Experimental $M1$ transition rates in K XI, K XV, and K XVI

E. Träbert,* P. Beiersdorfer, G. V. Brown, H. Chen, E. H. Pinnington,† and D. B. Thorn
Department of Physics and Space Technology, Lawrence Livermore National Laboratory, Livermore, California 94550-9234
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Transition probabilities of three magnetic dipole ($M1$) transitions in multiply charged ions of potassium have been measured using the Livermore electron beam ion trap EBIT-2. Our results for the atomic level lifetimes are 4.44 ± 0.10 ms for K XI (F-like) $2s^2 2p^5\,{}^2P^o_{1/2}$, 4.47 ± 0.10 ms for K XV (B-like) $2s^2 2p\,{}^2P^o_{3/2}$, and 7.6 ± 0.5 ms for K XVI (Be-like) $2s2p\,{}^3P^o_2$. The results confirm the accuracy of most predictions to within 3% of ground-state and 7% of excited-state transitions.

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I. INTRODUCTION

Electric dipole forbidden transitions, that is, magnetic dipole ($M1$) and electric quadrupole ($E2$) transitions, between the fine structure levels of multiply charged ions are the origin of many of the solar coronal lines and are of great interest for plasma diagnostics. Their transition rates are used to determine species densities in astrophysical plasmas and are needed in the modeling of the plasma edge in fusion test devices. B- and F-like ions feature just a single such line each, corresponding to the transitions $2s^2 2p\,{}^2P^o_{1/2}$–${}^2P^o_{3/2}$ and $2s^2 2p^5\,{}^2P^o_{3/2}$–${}^2P^o_{1/2}$, respectively, within the ground term. The simplest system with such (measurable) $M1$ transitions in an excited configuration is the four-electron (Be-like) ion. For low-charge-state ions, the $2s2p\,{}^3P^o_2$-level predominantly decays via a 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 [1–3].

For $M1$ and $E2$ transitions, the transition probability depends mostly on angular coupling factors and the energy interval. However, recent experimental transition rate data for argon ($Z=18$), an element with prominent coronal lines arising from all three aforementioned transitions, do not all agree with each other [4–8], and only some of them are compatible with theory. In order to improve on the understanding of systematic errors, we studied the same transitions in a neighboring element, potassium ($Z=19$). Such ions with odd atomic numbers have a relatively low cosmic abundance and consequently are not prominent in solar spectra, but the wavelengths of the transitions of interest [9] are well suited for the sensitivity range of our detectors. The expected lifetimes are shorter than those in argon by a factor of 2, which is beneficial for precise measurements by our experimental techniques.

*Also at IPNAS, Université de Liège, B-4000 Liège, Belgium. Permanent address: Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany. Email address: traebert@ep3.ruhr-uni-bochum.de

†Permanent address: Department of Physics, University of Alberta, Edmonton AB, T6G 2J1, Canada.

II. EXPERIMENT

The measurements were carried out at Lawrence Livermore National Laboratory, using the electron beam ion trap EBIT-2. The actual ion trap region was imaged by two $f/4$ 10-cm-diameter quartz lenses onto the photodetector, a low-dark-rate, half-inch-diameter, end-on-cathode photomultiplier (Hamamatsu type R2557 with a 401K spectral sensitivity curve). Filters centered at wavelengths 345 nm (bandpass of 5 nm full width at half maximum), 425 nm (bandpass 11 nm), and 465 nm (bandpass 10 nm) let pass (with about 70% transmission) the light of the three transitions of interest, at 344.8 nm K^{14+} (K XV), 425.6 nm K^{10+} (K XI), and 463.5 nm K^{15+} (K XVI), respectively, while rejecting other lines and most of the background light (for example, scattered light from the hot filament of the electron gun). Since $M1$ transitions usually dominate the optical spectra of electron beam ion traps [8,10,11], the use of such interference filters was deemed sufficient.

Potassium vapor was diffused into the trap from an oven. The gas load caused no notable change in the vacuum readings. The presence of potassium in the trap was ascertained by producing K x rays in He-like potassium ions with an electron beam energy set at the KLL dielectronic resonance near 2500 eV.

For the lifetime measurements, the electron beam ion trap was operated in a cyclic mode. The data were sorted into 0.1-ms-wide time bins and accumulated over up to 23 h per transition. About every 0.24 s the accumulated ion cloud was purged from the trap. The electron beam was switched on for about 0.18, ionizing and exciting the ion cloud in the trap. Then the electron beam was switched off for about 60 ms, which let the ion cloud expand to a new equilibrium at a somewhat larger diameter, but still held the ions in the so-called magnetic trapping mode [12]. The switching time of the electron beam was 30 μs. The electron beam energies were chosen about 100 to 300 eV above the respective production thresholds.

The signal rate (above background) in the decay part of the data sets ranged from 5 to 50 counts per minute for K XI and K XV, but reached only 2 counts per minute for K XVI. A total of three such curves was collected for K XV, three curves for K XI, and two data sets for K XVI. The ratio of the curve maximum to the tail (background only) reached 30 for K XI and 60 for K XV, but was as low as 2 for K XVI. This

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ratio reflects the combination of excitation efficiency, filter transmission, and photomultiplier response relative to the (constant) detector dark rate. The excitation efficiency is different for ground-state and excited-state configurations. It also varies with the electron beam energy in relation to the production threshold, as does the charge state distribution in the trap. The quality of the various data sets is, of course, reflected in the statistical errors obtained from their analyses.

The measured value for the intensity decay rate is modified by the underlying loss rate of ions from the observation zone (by thermal evaporation of the ion cloud along the magnetic field, charge-changing collisions with the neutral rest gas, or diffusion across the magnetic field). The loss rate needs to be measured in order to derive the atomic lifetime from the apparent lifetime. Temporal developments in several charge states of multiply charged ions are best studied in the x-ray range, where spectral lines from several charge states can be detected simultaneously with an energy-dispersive detector. However, owing to the filled K shell, the Be-, B-, and F-like ions of present interest feature no x-ray transitions. In order to obtain an estimate of the ion loss rates, we resorted to charge exchange (CX) measurements on more highly charged ions that have x-ray decay channels. With electron beam energies of about 10 kV, bare, H-, and He-like ions of potassium were easily produced and their x-ray emission after electron capture detected by a germanium (EG&G Ortec IGLET) detector that viewed essentially the same volume as the optical detector. The charge states of the ions observed in the x-ray range are not very different from the ones that are important for our optical measurements, so that rather similar confinement times are expected. Nevertheless, we associate an uncertainty of 50% with the magnitude of this small correction to our optical decay rates.

After the electron beam is switched off, the ion cloud as a whole develops toward lower ionization stages. CX processes may feature different time histories depending not only on ion velocity, collision cross section, and density of the neutral gas (the main collision partner), but also on the rank of a given charge state fraction in the charge state distribution. This dilemma ideally requires one to measure the CX processes for each charge state of interest, which is not generally possible in an electron beam ion trap. With a relatively shallow trap (150 V nominal potential difference between middle and end drift tubes), the measured ion storage time constant varied from 220 ms to 500 ms. With a deeper trap (350 V), an additional fast component with a time constant of order 25 ms appeared in the x-ray data. However, optical data of the various potassium ions recorded with shallow or deep traps show little difference. Thus the fast component must relate to contaminants of other (usually heavy) ion species that are easily captured in a deep trap. Only the slow component was used for the correction of the optical lifetime results. In the optical data curve with the best contrast of signal to background and with the highest counting statistical reliability, a weak slow second decay component showed with the same time constant as the ion storage lifetime determined in the x-ray channel. We ascribe this decay component to CX events (electron capture by ions in a higher charge state) that then, after a radiative cascade, repopulate the level of interest.

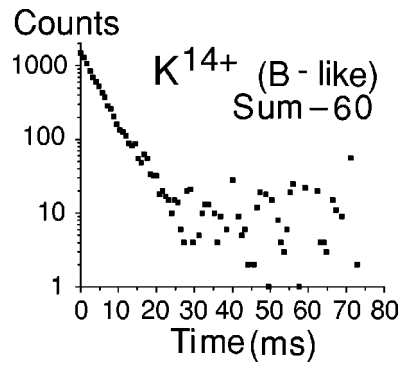

FIG. 1. Photon signal (logarithmic scale) obtained with K XV, after the electron beam in EBIT-2 is switched off (magnetic trapping mode). A background contribution of 60 counts per channel has been subtracted from the data.

III. DATA ANALYSIS AND RESULTS

Sample data are shown in Fig. 1. In the decay curve analysis, the background was treated as flat, while one to three exponentials were used to describe the primary decay and any additional components associated with either spectral blends or cascade transitions (including those introduced by CX processes). Data evaluation was restricted to the part of the decay curves after 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 trapping times were measured in alternation with the optical decay curves and forced systematic corrections of the raw lifetime results by 1–2 %, and half of this correction was assumed as the uncertainty of the correction.

In order to test for the influence of transients and background fluctuations, data sets were truncated at the beginning or tail. Cutting off early data points beyond the switching time caused a rapid increase of the statistical uncertainty, but no significant change of the mean lifetime value. In contrast, cutting off the background-dominated tail of the data curves resulted (in some cases) in variations of the primary lifetime result that exceeded the statistical uncertainty of the lifetime value determined from the full curve. This implies that the background itself may be structured and, in its temporal shape, may depend on the operating conditions. Because of this systematic error, we increased the 1σ error estimates of the primary atomic lifetime results for K XI and K XV to about twice the purely statistical value (of about 1%) appropriate for the evaluation of the individual full curves.

Because of the weaker photon signal for K XVI, the statistical uncertainty of the background dominates the error budget in this case, rendering the aforementioned systematic error problem insignificant. We thus find lifetimes of 4.44 ± 0.10 ms for K XI (transition rate $224 \pm 6\ \mathrm{s}^{-1}$) and of 4.47 ± 0.10 ms for K XV (transition rate $226 \pm 6\ \mathrm{s}^{-1}$). For K XVI, our analysis yielded an atomic lifetime (after ion storage time correction) of 7.6 ± 0.5 ms (transition rate 131

TABLE I. Comparison of predicted and measured lifetimes τ for the upper levels of the ground states in K XI and K XV.

τ (ms)	Reference
K XI $2s^2 2p^5\,{}^2P^o_{1/2}$	
Theory	
4.33	[15]
4.35	[16]
4.30[a]	[16]
4.27	[9]
Experiment	
4.44±0.10	This work
K XV $2s^2 2p\,{}^2P^o_{3/2}$	
Theory	
4.50	[16]
4.57[a]	[16]
4.52	[17]
4.57	[9]
4.58	[18]
4.56	[19]
Experiment	
4.47±0.10	This work

[a]Theoretical results adjusted for experimental transition energy.

±9 s^{-1}). All results are presented in Table I together with the various theoretical predictions.

IV. DISCUSSION

The general interest in the transitions studied here is reflected in a number of calculations. In Tables I and II, we compare our results only with calculations that explicitly provide transition rates for potassium. (For more references on similar transitions in other ions, see [8].) For all 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 three orders of magnitude, and we disregard the $E2$ contribution. The present lifetime results for K XI and K XV are compatible with the theoretical expectations (after correction for experimental transition energies), and they also fit the same isoelectronic trend as do the results of heavy-ion storage ring work [13,14] and data from the EBIT-2 trap for other elements [see Figs. 2(a) and 2(b)].

TABLE II. Predicted and measured lifetime data for the $2s2p\,{}^3P^o_2$ level in K XVI. The (0.8%) $M2$ ground state decay rate [1] has been added where needed for determining the predicted lifetime.

A (s^{-1})	τ (ms)	Reference
	Theory	
140	7.14	[1]
134	7.40	[20]
155	6.40	[21]
131	7.57	[9]
223	4.46	[22]
136	7.29	[2]
	Experiment	
131±9	7.6±0.5	This work

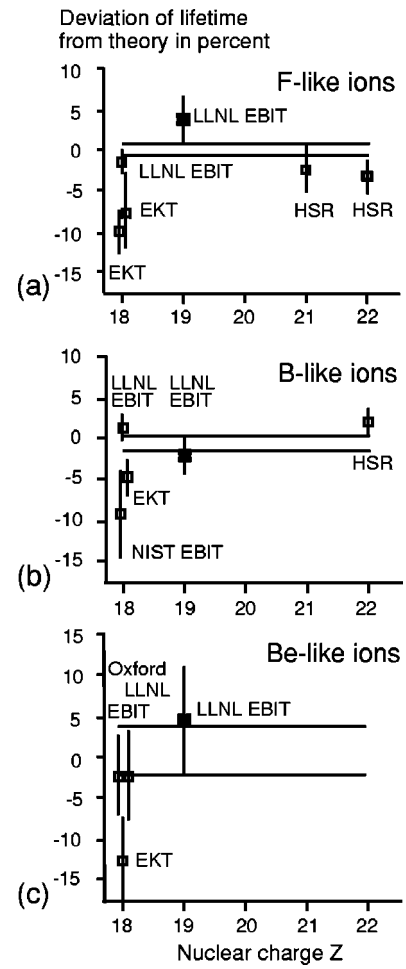

FIG. 2. Lifetime data for the transition in (a) the $2s^2 2p^5\,{}^2P^o_{1/2}$ level in the ground state of F-like ions, (b) the $2s^2 2p\,{}^2P^o_{3/2}$ level in the ground state of B-like ions, and (c) the $2s2p\,{}^3P^o_2$ excited level of Be-like ions. In (a) and (b), all data are normalized to the theoretical results given by Cheng *et al.* [16] after semiempirical correction for experimental transition energies. In (c), the data are normalized to the theoretical results given by Safronova *et al.* [2]. The horizontal bars indicate the scatter range of selected predictions (the predictive uncertainties are much larger). The experimental data are from an electrostatic Kingdon trap (EKT) [4,5], from the NIST, Oxford and LLNL EBITs [[6–8] and this work (full symbols)], and from a heavy-ion storage ring (HSR) [13,14].

The predictions for the $M1$ decay rate of the K XVI $2s2p\,{}^3P^o_2$ level cluster near 140 s^{-1}. Our experimental result overlaps (within the error bar) with most of the calculational results (Table II), including the latest and probably most elaborate ones [2]. The previously claimed 3σ discrepancy of Ar XV experiments with theory [5], which had already been contradicted by electron beam ion trap results from two different experiments [7,8], is, therefore, not sub-

stantiated by our data on K XVI either [Fig. 2(c)].

Ignoring the calculational results in [21], which differ by a factor of 2 from our results, theory is corroborated at the 7% level of our present experiment for an excited configuration, and to better than 3% for the ground-state complex in K XI and K XV. Evidently, the usual theoretical uncertainty estimates of 10–20 % are rather conservative. Further improvements of the precision of electron beam ion trap lifetime measurements in the visible range, beyond the present 3% uncertainty, will require charge-state- if not level-specific measurements of charge exchange processes and their influence on decay curves much beyond the time range in which the optical decay signal dominates. Such studies, however, will have to use elements that are more readily introduced into an electron beam ion trap than potassium.

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