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# Lifetime Measurements for Allowed and Forbidden Transitions*

Dedicated to Prof. Dr. Karl-Heinz Schartner on the occasion of his 60th birthday

E. Jasper,[1] A. Vasilyev,[1] K. Kukla,[1] C. Vogel Vogt,[1] A. E. Livingston,[1] H. G. Berry,[1] S. Cheng,[2] L. J. Curtis[2] and R. W. Dunford[3]

[1]Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA
[2]Department of Physics and Astronomy, University of Toledo, Toledo, Ohio 43606, USA
[3]Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

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**Abstract**

Excited state lifetimes ranging in value from picoseconds to nanoseconds are reported for selected highly charged ions. The measurements utilize beam-foil excitation and photon-counting extreme ultraviolet spectroscopy with position sensitive detection. Lifetimes are reported for both allowed and forbidden transitions in several classes of highly charged ions.

## 1. Introduction

The time-resolved nature of the fast beam emission source provides the capability of measuring excited state lifetimes ranging from picoseconds to hundreds of nanoseconds in highly charged ions. Photon counting spectroscopy in the extreme ultraviolet (EUV) wavelength region (~30–1000 Å, or ~10–300 eV) using microchannel plate position-sensitive detectors (MCP/PSD) allows the efficient and simultaneous detection of a wide bandwidth of atomic transitions with high sensitivity, high resolution, and low background. We have applied these techniques in beam-foil spectroscopy experiments on selected atomic systems at the Notre Dame Tandem and the Argonne ATLAS accelerator facilities . We report here excited state lifetime measurements involving allowed and forbidden transition rates for the ions $P^{13+}$, $Br^{24+}$, and $Kr^{32+,33+}$. Comparison is made with recent relativistic many-body calculations.

## 2. Lithium-like and Beryllium-like Krypton

We have studied the beam-foil spectra of highly-charged krypton ions in the EUV region at the Argonne ATLAS accelerator facility. We have measured the excited state lifetimes for $n = 2$ states in Li-like $Kr^{33+}$ and Be-like $Kr^{32+}$ by monitoring the time-delayed spectra along a beam of 9.5 MeV/u krypton ions. The EUV emission was dispersed by a 2.2 meter grazing incidence spectrometer and the spectrum was detected using a 2 cm wide MCP/PSD. This allowed the simultaneous detection of about a 60 Å section of the spectrum for each position of the PSD. The wavelength resolution achieved was about 1 Å. The PSD data were particularly useful for analyzing decays of closely spaced features, using selective data binning. An auxiliary spectrometer entrance slit was situated very close to the beam to provide a spatial resolution of about 100 μm. This enabled lifetimes ranging from 10 ps to 3 ns to be measured in this work.

Figure 1 shows a sequence of time-delayed spectra for one position of the PSD. The prompt decays of most of the $n = 2 - 2$ transitions and all of the Rydberg transitions are distinguished from two prominent longer decays. These two decays represent the $2s_{1/2}$ - $2p_{1/2}$ fine structure transition at 174 Å in Li-like krypton and the spin-forbidden intercombination transition $2s^2\ ^1S_0 - 2s2p\ ^3P_1$ at 170 Å in Be-like krypton.

Table I summarizes our lifetime measurements in $Kr^{32+}$ and $Kr^{33+}$. The lifetime results show generally good agreement with previous measurements and with theoretical calculations. The three $1s^22p^2\ ^3P$ fine structure lifetimes have not been measured previously. All the $2p^2$ lifetimes are consistent with the early relativistic Hartree-Fock calculations of Cheng *et al.* [4]. The Be-like intercombination transition lifetime for the $1s^22s2p\ ^3P_1$ state of about 2.5 ns is consistent with the trend of previous measurements and recent calculations for this spin-forbidden transition in other high-Z Be-like ions. The Li-like $2p_{1/2}$ and $2p_{3/2}$ fine structure lifetimes differ by a factor of seven, primarily as a result of the large fine structure splitting. Our lifetime results are in good agreement with a recent relativistic many-body perturbation theory calculation [5].

## 3. Hyperfine Quenched Transition Rates in Helium-like $P^{13+}$

The hyperfine interaction for nonzero nuclear spin induces small $1s2p\ ^{1,3}P_1$ admixtures into the $1s2p\ ^3P_{0,2}$ wave functions for He-like ions. This enables forbidden E1 transitions from $1s2p\ ^3P_{0,2}$ to the $1s^2\ ^1S_0$ ground state to become allowed, resulting in differentially reduced (quenched) $^3P_{0,2}$ lifetimes. We have measured the $1s2p\ ^3P_{0,2}$ lifetimes in He-like $P^{13+}$ in a beam-foil experiment at the Notre Dame Tandem accelerator facility. Spectra of highly charged phosphorus ions were detected using a normal incidence spectrometer and an MCP/PSD detector for prompt and sequentially delayed positions along the 80 MeV ion beam. Analysis of the $1s2s\ ^3S_1 - 1s2p\ ^3P_{0,2}$ transition decays at 813 Å and 740 Å yielded the $^3P_{0,2}$ fine structure state lifetimes listed in Table II.

* Dedicated to Professor Dr. Karl-Heinz Schartner on the occasion of his 60th birthday.
Author for correspondence: Livingston.2@nd.edu

 

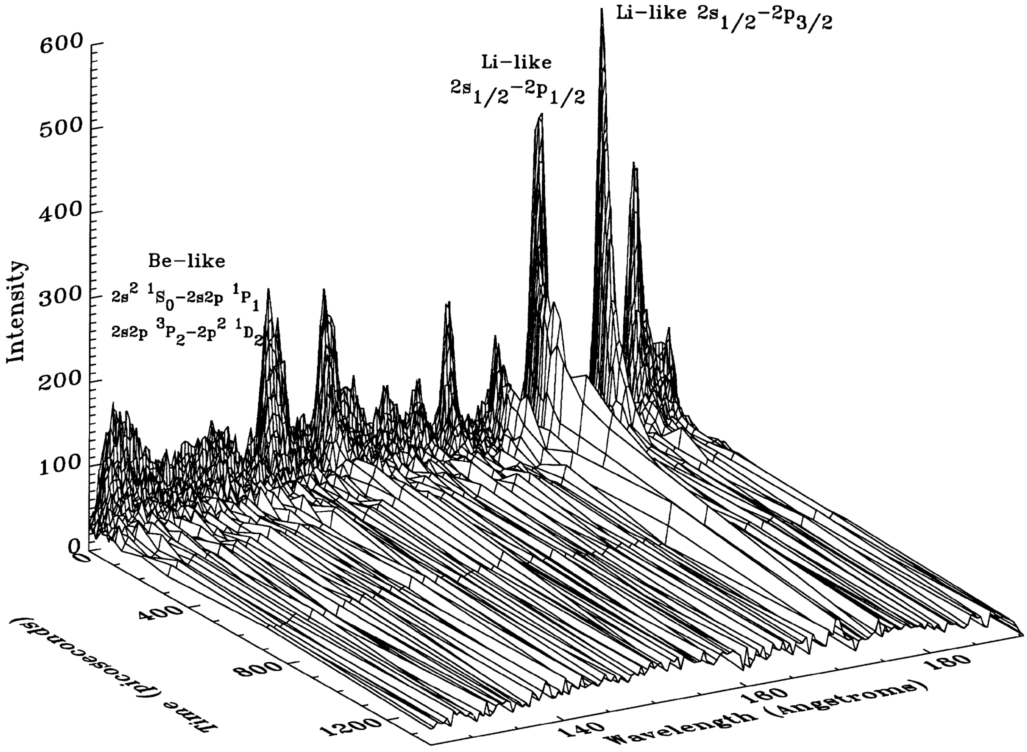


*Fig. 1.* Sequence of time-delayed krypton spectra.

Table I *Lifetimes (ps) in Highly-Ionized Krypton*

| State | Experiment | Theory |
|---|---|---|
| $1s^22p\ ^2P_{1/2}$ | **365(23)**$^*$<br>320(30)$^a$ | 357.5$^b$<br>356.0$^c$<br>359.8$^d$ |
| $1s^22p\ ^2P_{3/2}$ | **50.7(9)**$^*$<br>52(3)$^a$<br>49.5(1.5)$^e$ | 49.64$^b$<br>49.70$^c$<br>49.93$^d$ |
| $1s^22s2p\ ^3P_1$ | **2560(240)**$^*$<br>2300(300)$^a$ | 2480$^c$<br>2420$^f$<br>2370$^g$ |
| $1s^22s2p\ ^1P_1$ | 17.5(1.5)$^e$ | 17.2$^c$<br>18.5$^f$ |
| $1s^22p^2\ ^3P_0$ | **47.4(4.7)*** | 48.0$^c$ |
| $1s^22p^2\ ^3P_1$ | **21.0(1.7)*** | 22.7$^c$ |
| $1s^22p^2\ ^3P_2$ | **29.1(2.6)*** | 30.8$^c$ |
| $1s^22p^2\ ^1D_2$ | **19.9(1.2)***<br>19(2)$^e$ | 18.6$^c$ |
| $1s^22p^2\ ^1S_0$ | **10.6(1.0)***<br>10.5(1.0)$^e$ | 10.0$^c$ |

(*) Beam-Foil Spectroscopy (**This Work**).
(a) Beam-Foil Spectroscopy (Dietrich, *et al.*-1980) [1].
(b) Semi-empirical (Theodosiou, *et al.*-1991) [2], (Curtis, *et al.*-1995) [3].
(c) Relativistic Hartree-Fock (Cheng, *et al.*-1979) [4].
(d) Relativistic Many-Body Perturbation Theory (Johnson, *et al.*-1996) [5].
(e) Beam-Foil Spectroscopy (Träbert, *et al.*-1995) [6].
(f) Systemized Interpolation (Curtis & Ellis-1996) [7].
(g) $Z$-expansion (Ralchenko & Vainshtein-1995) [8], [see also Ynnerman & Froese Fischer-1995] [9].

For the $^3P_0$ ($F$ = 1/2) state, our measured lifetime shows good agreement with the 20% reduction in lifetime calculated for the influence of hyperfine structure. For the $^3P_2$ ($F$ = 3/2) state, the hyperfine structure effect is only about 3%, and the $F$ = 5/2 state is unquenched. Our measurement of the two unresolved hyperfine decay components of the $^3P_2$ state reflects the weighted mean of the $F$ = 3/2 and $F$ = 5/2 lifetimes (3.40 ns), and is just sensitive to the hyperfine quenching effect. In both fine structure components, our results are in agreement with recent hyperfine quenching calculations of Johnson *et al.* [11].

## 4. The 3p $^2P_{3/2}$ Lifetime in Sodium-like Bromine

Recent relativistic many-body calculations [5] for transition rates in Na-like ions have improved the theoretical accuracy in this alkali-like system. For the first

Table II *Lifetimes (ns) in Helium-like $P^{13+}$*

| Theory | $1s2p\ ^3P_2$ | $1s2p\ ^3P_0$ |
|---|---|---|
| No hfs | 3.44$^a$ | 6.06$^a$ |
| $F$ = 1/2 | | 4.83$^b$<br>4.84$^c$<br>4.85$^d$ |
| $F$ = 3/2 | 3.36$^b$<br>3.34$^c$ | |
| $F$ = 5/2 | 3.44$^b$<br>3.44$^c$ | |
| **Experiment** | **3.36 ± 0.05** | **4.88 ± 0.09** |

(a) Many-body perturbation theory (Johnson, Plante, Sapirstein-1995) [10].
(b) Independent particle approximation (Berry-1997, **This Work**).
(c) Radiation damping theory (Johnson, Cheng, Plante-1997) [11].
(d) $1/Z$-expansion method (Mohr-1976) [12].

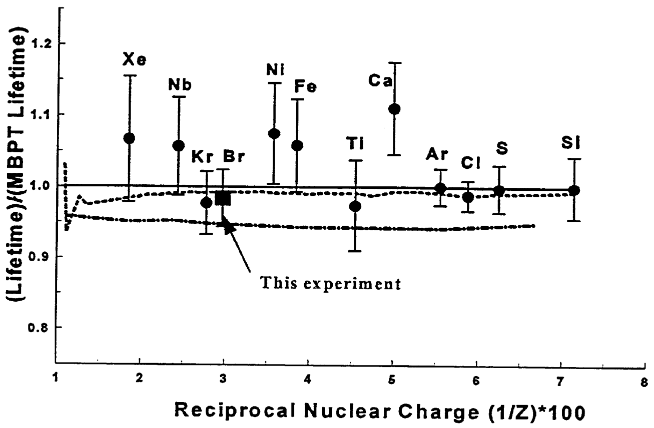


*Fig. 2.* Isoelectronic comparison of experimental and theoretical lifetimes for the $3p_{3/2}$ state in Na-like ions. The *x*-axis represents the relativistic many-body values [5]. See Ref. [14] for further experimental and theoretical references.

excited states 3p $^2P_{1/2,3/2}$, experiment and theory are in good agreement for light Na-like ions ($Z < 20$). However, most subsequent measurements at higher $Z$ for the 3p $^2P_{3/2}$ state suggest a systematic 5–10% discrepancy toward longer lifetimes than the many-body values. The 3p $^2P_{1/2,3/2}$ states are influenced by strong cascade feeding from the 3d $^2D_{3/2,5/2}$ states. Although recent high-Z measurements all used a correlated cascade analysis technique (ANDC), the most recent measurement of the 3p $^2P_{3/2}$ lifetime for $Kr^{25+}$ [13] applies a more stringent ANDC analysis with good statistics and agrees with theory. We have performed a comparable measurement of the 3p $^2P_{3/2}$ lifetime in Na-like $Br^{24+}$.

A beam-foil excitation of 190 MeV bromine ions was performed at the ATLAS facility, and the spectrum of highly-charged bromine was detected with an MCP/PSD detector mounted on a grazing incidence spectrometer. Further experimental details have been reported in a recent publication of this work [14]. We measured the simultaneous decays of the transitions 3s $^2S_{1/2}$ – 3p $^2P_{3/2}$ (189 Å) and 3p $^2P_{3/2}$ – 3d $^2D_{5/2,3/2}$ (167 Å, 172 Å) in $Br^{24+}$ on the PSD. Accurate cascade correction was accomplished using an integral form of the ANDC technique, and avoiding data smoothing processes used in the previous analyses. Our lifetime result for 3p $^2P_{3/2}$ in $Br^{24+}$ is 49.6 ± 2.0 ps. This value is in isoelectronic agreement with the most recent measurement in $Kr^{25+}$ [13], and it is in excellent agreement with the relativistic many-body calculation [5] (see Fig. 2).

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