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Lifetime measurements in highly ionized silicon

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(Received 27 June 1991)

We report the measurement of excited-state lifetimes in highly ionized silicon atoms using multiplexed detection of a fast-ion beam source. Simultaneous lifetime measurements for resonance transitions and for Rydberg transitions in Si XI and Si XII have been performed. Comparisons with theoretical lifetimes are presented, and good agreement is obtained with a new relativistic many-body calculation of the $2p$ fine-structure-state lifetimes in lithium-like Si XII.

PACS number(s): 32.70.Fw, 32.30.Jc, 31.20.Tz, 31.30.Jv

Measurements of excited-state lifetimes in highly ionized atoms provide tests of relativistic atomic transition probability calculations [1]. The excitation of a fast-ion beam by a thin-foil target remains the only versatile method for direct measurement of such lifetimes [2,3]. The potential advantages of using position-sensitive photon detectors in fast-ion atomic physics studies have been recognized for some time [4,5]. We have applied position-sensitive detection of vacuum ultraviolet emission from excited fast-silicon ions to provide multiplexed measurements of excited-state lifetimes in highly ionized silicon atoms.

The spectra of Si^{10+} and Si^{11+} were produced by ionization and excitation of a beam of 42-MeV Si^{6+} ions from the Notre Dame Tandem Accelerator, by directing the ions through a thin-carbon-foil target of areal density 30 $\mu g/cm^2$. The fluorescent spectrum from the excited silicon beam was observed using a 1-m vacuum ultraviolet grating spectrometer that detected photons emitted perpendicularly to the beam direction. The spectrometer was refocused for the fast-ion source. The dispersed ultraviolet photons were detected using a photon-counting position-sensitive imaging detector consisting of a 1-in. wide windowless channeled electron multiplier array, in the chevron configuration, coupled with a resistive anode position sensor. The one-dimensional position decoding of the photon-induced electron pulses was obtained by comparison of the divided pulse charges appearing at the two ends of the anode. The position-dependent data were stored in the multichannel analyzer of a computer to accumulate the multiplexed wavelength spectrum.

An example of the measured spectrum of highly ionized silicon near 1000 Å is shown in Fig. 1. Transitions in lithium-like Si XII and beryllium-like Si XI are observed. The two strongest lines are the $1s^2 2s_{1/2} - 1s^2 2p_{3/2,1/2}$ fine-structure resonance transitions in Si XII at 499.4 Å and 520.7 Å, appearing in the second order of dispersion. The other two features are highly excited Rydberg transition complexes. The unresolved $n=5-6$ transition in Si XII appears at 517.7 Å (in second order), and the partially resolved $n=6-7$ transition in Si XI appears at ~1020 Å. The second-order linewidth of about 1.2 Å is a convolution of the chosen resolutions of the spectrometer and the detector. Simultaneous decay data for these transitions were obtained by measuring the spectrum at several different distances along the beam from the target foil, normalizing to the ion charge collected in a Faraday cup beam stop. The intensity decay data typically consisted of multiplexed spectra at each of about 20 spatial positions over a total

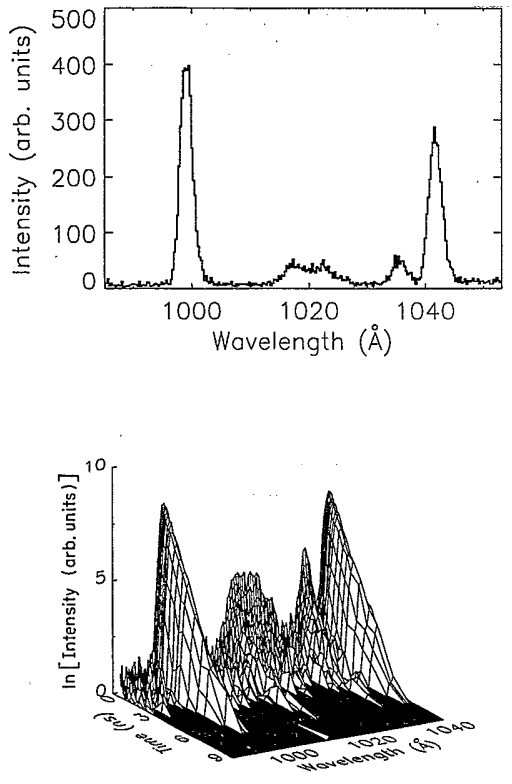

FIG. 1. The wavelength spectrum of highly ionized silicon near 1000 Å, shown (upper) as a single multiplexed spectrum and (lower) as a superposition of multiplexed spectra for a sequence of times after excitation, plotted semilogarithmically.

distance of 10 cm. The ion velocity was corrected for energy loss in the foil of $\sim 1\%$ to become $\beta = v/c = 0.0566$ ($v = 17.0$ mm/ns). Several multiexponential fits for up to three exponential components were attempted for each transition decay. The multiplexed data was binned in various ways before fitting in order to look for possible systematic discrepancies, such as variations between the high-wavelength and the low-wavelength portions of a given peak.

The decay data for the $2s$-$2p$ fine-structure transitions in Si XII support only single-exponential fits, as is expected since the dominant cascading states into $2p$ are very short lived. We find the $2p_{3/2}$ lifetime to be 1.07 ± 0.04 ns and the $2p_{1/2}$ lifetime to be 1.20 ± 0.04 ns. The uncertainties account for statistical contributions, variations in small background corrections, and reproducibility among data sets. These lifetime results are consistent with a previous less-precise fast-ion measurement [6] for the $2p_{3/2}$ fine-structure component but not for the $2p_{1/2}$ component (see Table I). Our measurements show unambiguously that the $J = \frac{3}{2}$ lifetime is shorter than the $J = \frac{1}{2}$ lifetime, in contrast to the results in Ref. [6]. Comparison with an early multiconfiguration Dirac-Fock (MCDF) calculation [8] provides agreement only if experimental transition energies [11] are applied in place of the theoretical energies in the E^3 relation between line strength and transition probability. Our lifetime results

TABLE I. Lifetimes (in ns) of the $1s^2 2p_{1/2,3/2}$ states in lithium-like Si XII.

$2p_{1/2}$	$2p_{3/2}$	Method
1.121	1.021	Z expansion[a]
1.158	1.020	MCDF[b], theoretical energies
1.176	1.035	MCDF[b], experimental energies
1.181	1.046	NBS tables[c]
1.188	1.044	CAHS[d], experimental energies
1.00±0.08	1.12±0.08	Fast-ion[e]
	1.01±0.10	Fast-ion[f]
1.186±0.002	1.042±0.002	MBPT[g], experimental energies
1.20±0.04	1.07±0.04	Fast-ion[g]

[a]Cohen and Dalgarno [7].
[b]Cheng, Kim, and Desclaux [8].
[c]Wiese and Martin [9].
[d]Theodosiou, Curtis, and El-Mekki [10].
[e]Träbert, Heckmann, and v. Buttlar [6].
[f]D. J. Pegg *et al.*, Phys. Scr. **18**, 18 (1978).
[g]This work.

agree well with new relativistic many-body perturbation theory (MBPT) [12] calculations that we have performed for this work. The MBPT calculations include correlation corrections to dipole matrix elements through third order, as well as an estimate of the lowest-order Breit correction. The convergence of MBPT for the dipole matrix elements is rapid: We find $D^{(1)}+D^{(2)}+D^{(3)}+D^{\text{Breit}} = (0.34413-0.00121-0.00019+0.00010)$ a.u. for $2s$-$2p_{1/2}$ and $(0.48766-0.00171-0.00027+0.00007)$ a.u. for $2s-2p_{3/2}$. The theoretical uncertainty in Table I follows from assigning (somewhat conservatively) an error to the dipole matrix element equal to $D^{(3)}$, the highest-order MBPT term calculated. We note that the calculation to first order alone provides nearly exact agreement with the MCDF values. Also, the MBPT transition energies [12] are sufficiently accurate such that even without QED corrections they change the theoretical lifetimes by less than 1% from the values obtained using experimental energies. Our lifetime results are also consistent with new calculations using the semiempirical Coulomb approximation with a Hartree-Slater model potential (CAHS) [10]. Finally, we can compare the ratio of our fine-structure-state lifetimes with the ratio of the theoretical line strengths. This provides a more precise comparison through the cancellation of small systematic effects that are present in the simultaneously measured lifetimes. Our ratio of experimental lifetimes is 1.121 ± 0.025, where the reduced cumulative uncertainty reflects the improved reproducibility among similarly constrained pairs of data fits for the two lifetimes. This lifetime ratio is equivalent to a line-strength ratio of 1.979 ± 0.044, which agrees with the MBPT line-strength ratio of 2.007 ± 0.003 as well as with the MCDF ratio of 2.005 and the CAHS ratio of 2.007.

Our measurements of the Rydberg state decays for $n = 6$ in Si XII and for $n = 7$ in Si XI display a multiexponential nature characteristic of strong cascading effects that result from population of high-angular-momentum states in the ion-foil excitation [13]. The $n = 5$–6 transition in lithium-like Si XII possesses unresolved angular-

momentum structure with our resolution (see Fig. 1), which further complicates the multiexponential character due to the L dependence of lifetimes. Our three-exponential decay fits yield a primary component of ≤ 0.10 ns, with long-lived components of ~ 1.2 ns and > 15 ns. The theoretical hydrogenic lifetime is ≤ 0.03 ns for the L states of $n = 6$. In contrast, the $n = 6$–7 transition in beryllium-like Si XI is expected to display a widely dispersed angular-momentum structure as a result of strong core polarization and configuration mixing effects that are characteristic of four-electron systems [14]. In Fig. 1 we show our measured partially resolved structure for this transition spread over some 10 Å near 1020 Å. We have performed multiconfiguration Dirac-Fock calculations [15] for the $n = 6$–7 transition in Si XI that predict the structure to be dominated by the highest angular-momentum components of the $2s6l$–$2s7l'$ transition below 1019 Å and by the highest angular-momentum components of the core-excited (or displaced) $2p6l$–$2p7l'$ transition above 1019 Å. Therefore we have applied separate decay fits to the corresponding wavelength regions of the observed $n = 6$–7 transition structure. Our multiexponential fits yield consistent primary decay components of ~ 0.15 ns for each of the $n = 7$ states, which compare with the theoretical hydrogenic lifetime of ≤ 0.09 ns. The longer-lived components in the fits are found to be ~ 1.5 ns and > 10 ns for the $2s7l$ decays, whereas only a single weaker component of > 1.0 ns appears in the $2p7l$ decays. This partial suppression of cascading in the core-excited $n = 7$ Rydberg states may reflect the effects of (nonradiative) autoionization for higher $2pnl$ states, which for $n > 8$ lie above the $1s^2 2s$ first ionization limit in Si XI. Calculations of autoionization rates for core-excited Rydberg states in highly ionized beryllium-like atoms are clearly needed in order to establish the relative importance of radiative decay branches for such states.

This work was supported in part by the University of Notre Dame Faculty Research Fund and by the U.S. Department of Energy, Fundamental Interactions Branch, Office of Basic Energy Sciences, Division of Chemical Sciences, under Contract Nos. DE-FG05-88ER13958 (L.J.C.), W-31-109-ENG-38 (H.G.B.), and W-7405-ENG-48 (S.A.B.). It is a pleasure to acknowledge stimulating discussions with W. R. Johnson and the assistance of E. D. Berners, J. LaVerne, and K. Kukla, as well as the excellent facilities of the Notre Dame Accelerator Laboratory.

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