Lifetime of the $3p\ ^2P_{3/2}$ level in Na-like Kr^{25+}

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We have measured the lifetime of the $3p\ ^2P_{3/2}$ level in Na-like Kr^{25+}, using beam-foil excitation and cascade-corrected analysis. Our result, $\tau=45.2\pm2$ ps, has half the uncertainty of previous experimental data for highly ionized Na-like ions, and permits an important test of theoretical methods. Recently, Hutton *et al.* [Phys. Rev. A **51**, 143 (1995)] pointed out a seemingly systematic one-standard-deviation difference between theoretical and experimental f values of $3s\ ^2S_{1/2}-3p\ ^2P_{3/2}$ transitions for Na-like ions with $Z>20$. Our more precise result indicates that these small differences are coincidental and insignificant, confirming the reliability of theoretical calculations for this system. [S1050-2947(97)03804-3]

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I. INTRODUCTION

During the past decade there has been both experimental and theoretical activity in the specification of low-lying transitions in Na-like ions. These essentially one-electron systems usually produce strong and well-isolated spectral lines that are well suited to experimental measurement, and these data are needed in many specific applications. Because of their relatively simple structure, these systems are also of fundamental importance for testing the reliability of atomic structure calculations.

Experimental data for lifetimes of the $3p$ levels (and thus for the $3s$-$3p$ oscillator strengths) are available for many Na-like ions through Au^{68+}. The result for neutral Na has been of particular interest because of the high quoted accuracy (0.18%) to which it had been measured by beam-laser methods [1], and the fact that it differed from elaborate theoretical calculations [2] by more than five times the quoted uncertainties. Recently this discrepancy has been resolved by a new beam-laser experiment [3], a precise linewidth determination [4], and by measurements which use the alternative approaches of photoassociative spectroscopy of ultracold atoms [5]. The oscillator strength for the Na $3s$-$3p$ transition deduced from these measurements agrees very well with theoretical calculations [2], but the methods are not applicable to highly ionized systems. In the case of Mg^+ there is good agreement between the results of a beam-laser study [6] and theoretical predictions. For multiply charged Na-like ions all existing experimental results were obtained by beam-foil excitation. In contrast to the selective nature of the beam-laser excitation process, decay curves obtained from beam-foil excitation must be analyzed for the effects of cascade repopulation. Inaccuracies can occur if cascading is heavy and the analysis is made solely by multiexponential curve fitting. However, by measuring the decay curves of the primary level and all levels that significantly replenish its population, it is possible to make a joint analysis by the arbitrarily normalized decay curve (ANDC) method [7] that greatly reduces or totally eliminates the effects of cascading. By the use of ANDC methods the lifetimes of the $3p$ levels have been determined for several Na-like ions between Si and Cu [8–16]. In this context, Hutton *et al.* [16] reported results for $Z=22$–29 which showed an unexpected deviation from relativistic Hartree-Fock calculations [17]. This result stimulated new calculations, using the semiempirical Coulomb approximation with a Hartree-Slater core [18], relativistic many-body perturbation theory [19] and the relativistic distorted-wave approximation [20]. For the $3s\ ^2S_{1/2}$-$3p\ ^2P_{1/2}$ f values, all of these new calculations were in agreement with the experimental results (including subsequent measurements in Xe^{48+}, Au^{68+} [21], and Nb^{29+} [22]). However, for the $3s\ ^2S_{1/2}$-$3p\ ^2P_{3/2}$ transitions in Na-like Fe, Ni, Nb, and Xe the experimental f values were consistently 10% lower than theoretical calculations. Although these differences are systematic, they are comparable to the quoted accuracies of the individual measurement, and thus inconclusive at this level of precision. In order to provide a definitive comparison between experiment and theory, we have carried out a measurement of the $3s\ ^2S_{1/2}$-$3p\ ^2P_{3/2}$ oscillator strength in Na-like Kr^{25+} (which lies in a gap in existing high Z measurements). Our measurement is accurate to within 4%, and agrees well with theoretical calculations, and conclusively demonstrates the reliability of theoretical calculations for this system.

II. EXPERIMENT

The measurements were made at the Institute of Physical and Chemical Research (RIKEN), using the RILAC heavy-ion accelerator and a standard beam-foil setup. Beams of Kr^{13+} ions, accelerated to an energy of 168 MeV, were sent through a 40 $\mu g/cm^2$ carbon foil. Typical ion currents, measured with a Faraday cup on the downstream side of the foil, were 100–150 nA (4–6 particle nA). The light emitted by

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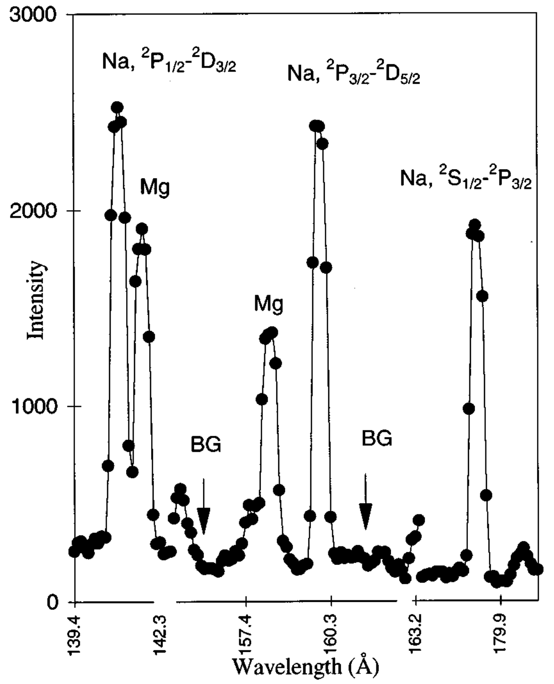

FIG. 1. Three sections of a beam-foil spectrum of Kr (168.4 MeV). The lines belonging to Na-like Kr^{25+} are indicated, together with two transitions in Mg-like Kr^{24+}. *BG* indicates the places where the background decay was measured.

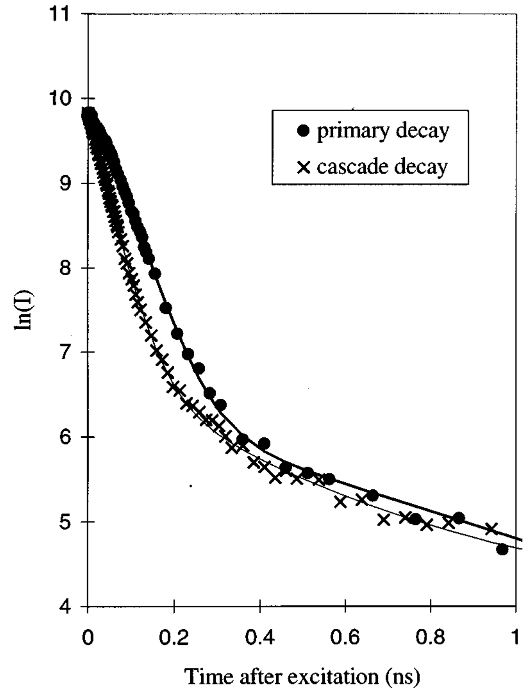

FIG. 2. The beginning of the primary $3p\ ^2P_{3/2}$ and cascade $3d\ ^2D_{5/2}$ decay curves, together with DISCRETE fits. The decay curves were followed for 2 ns.

the excited ions was dispersed by a 2.2 m McPherson, NIKON grazing incidence spectrometer, equipped with a 600 lines/mm grating and a channel electron multiplier detector. The spectrometer viewed the beam at an angle of 90°, and its entrance slit was placed close to the beam (10 mm from the center of its 6 mm diam) in order to maximize the time resolution of the system (important because of the short lifetimes studied). Using 50 μm spectrometer slits, linewidths full width at half maximum (FWHM) of about 0.4 Å were obtained in the region studied (140–180 Å). Beam-foil spectroscopy at ion energies above approximately 100 MeV is hampered by the comparatively high beam-dependent background caused by, e.g., x rays and electrons striking the entrance slit. Techniques employing electric fields (with added refinements to the methods described in Ref. [22] were used to reduce these backgrounds close to the foil. Thus, for the strongest lines, signal-to-noise ratios (S/N) close to 15 were obtained, 4–5 times higher than those obtained for earlier experiments of this type. All decay data were corrected for background through a subtraction of the intensity decay curve in the region between the spectral lines studied.

III. RESULTS AND DISCUSSION

The $3s$-$3p$ and $3p$-$3d$ transitions in Na-like Kr were readily identified in our beam-foil spectra using the accurate wavelengths given by Reader *et al.* [23]. In the spectral region of interest we also observed intense lines belonging to Mg-like Kr, classified by Sugar *et al.* [24]. A partial spectrum is depicted in Fig. 1.

In our experiment the decay curve of the $3p\ ^2P_{3/2}$ level is influenced by cascading, mainly from the $3d\ ^2D_{3/2}$ and $^2D_{5/2}$ levels. Cascading from $4s\ ^2S$ and $4d\ ^2D$ is also possible, but it can be neglected in the present case. The $\Delta n = 1$ transitions in very highly charged Na-like ions are orders of magnitude faster than $3p$ lifetimes and their repopulation does not affect the lifetime determination of $3p$ [9,11]. In particular, the theoretical lifetimes of the $4s$ and $4d$ levels in Kr^{25+} are 0.58 ps and 0.32 ps, respectively [20], and their decay takes place very close to the foil, in a region not included in our decay-curve analyses. We measured the decay of the primary transition $3s\ ^2S_{1/2}$-$3p\ ^2P_{3/2}$ (178.994 Å) and those of the cascades from $3d\ ^2D_{3/2}$ (140.891 Å) and $3d\ ^2D_{5/2}$ (159.920 Å). Examples of decay curves are shown in Fig. 2. Note that these two curves, representing $3p\ ^2P_{3/2}$ and $3d\ ^2D_{5/2}$ levels, follow quite similar patterns.

After subtraction of ''background decay,'' which was measured in line free regions of spectra (*BG* in Fig. 1), the first step in analyzing the decay curves was to perform a multiexponential fitting with the program DISCRETE [25]. Because of vignetting by the foil and the high background rate close to the foil, it was necessary to omit the first few points from the analysis. The results were relatively insensitive (less than 1%) to the points excluded in this truncation. The values obtained in this manner yielded a primary decay time of 56.4±3.4 ps, a growing-in cascade of 38.6 ps, and a long-lived cascade of 630 ps. While these values serve primarily as a high-frequency filter to prepare the data for analysis by the ANDC method, the growing-in value shows reasonable agreement with theoretical lifetimes [18] of the $^2D_{3/2}$ (26.74 ps) and $^2D_{5/2}$ (36.44 ps) levels as well as with our experimental values for these levels (see below). The long-lived component is probably an effective manifold of cascades from higher levels.

The next step was to analyze the $3p\ ^2P_{3/2}$ decay by the ANDC method through the implementation of the computer

TABLE I. Experimental and theoretical $3p\ ^2P_{3/2}$ lifetimes and $3s\ ^2S_{1/2}$-$3p\ ^2P_{3/2}$ oscillator strengths in Na-like Kr^{25+}.

Level	Lifetimes (ps) Experiment	Theory	Oscillator strength Experiment	Theory
$3p\ ^2P_{3/2}$	45.2 ± 2[a]	45.86[c]	0.2126 ± 0.009	0.20946[c]
		45.43[d]		0.2133[d]
	56.4 ± 3.4[b]			
	$(-38.6;630)$[b]			

[a]ANDC, recommended experimental value.
[b]Results of the multiexponential fit, cascade lifetimes in the parentheses. A negative sign denotes a growing-in cascade.
[c]Theodosiou and Curtis [18].
[d]Sampson, Zhang, and Fontes [20].

program CANDY [26]. As in all Na-like ions, the decay times of the $3p$ and $3d$ decay curves are quite close in value, so it is necessary that both be incorporated into the analysis. In situations such as this, multiexponential fits are unreliable, whereas ANDC analysis can produce quite accurate results [16,22,26].

The ANDC analysis indicated that the $3d\ ^2D_{5/2}$ level was the dominant source of cascade repopulation, and a reliable result could be obtained by including only this cascade. However, when cascades from both the $3d\ ^2D_{5/2}$ and $3d\ ^2D_{3/2}$ levels were included the uncertainties were reduced. The resulting value for the $3p\ ^2P_{3/2}$ lifetime, 45.2 ps (see Table I), is about 20% shorter than the value that was obtained by multiexponential fitting. This is typical for an ANDC analysis in cases where the lifetimes of the primary and cascading levels are close to each other. The ANDC value was only weakly sensitive to the choice of the fit region, showing a deviation about the mean value of less than 2%. This, together with the uncertainty in the time base associated with the beam velocity (below 1%), is the main source of uncertainty in the measurement. Since the ANDC method is based on relationships among measured decay curves, it makes no assumptions regarding the multiexponential representation of the decay curve, and provides a test of its validity through the requirement that the extracted lifetime be independent of the fitting region selected. For completeness, the decay times of the $3d\ ^2D_{5/2}$ and $3d\ ^2D_{3/2}$ levels obtained from multiexponential fits are also mentioned here. However, these values (31.0 and 46.1 ps, respectively) are significantly longer than theoretical predictions [18] quoted above. The fits are undoubtedly distorted by cascade repopulation along the yrast chain ($3d$-$4f$-$5g$-$6h$, etc). However, this indirect cascading is automatically included in the ANDC analysis of the $3p\ ^2P_{3/2}$ level.

Table I lists our $3p\ ^2P_{3/2}$ lifetime, its corresponding f value, and theoretical results [18,20]. The statistical uncertainty is ±0.9 ps whereas the total error estimate is ±2 ps. Our result is in excellent agreement with theoretical values [18,20], and from this fact we must conclude that the apparent systematic trend (in which the measured f values in the four ions, Fe, Ni, Nb, and Xe, all lie one standard deviation below the theoretical estimates) is coincidental, and not indicative of a discrepancy between experiment and theory. The situation for the Na-like ions is illustrated in Fig. 3 (an updated version of a similar figure in Ref. [27]). The experimental line strengths are here compared with straight lines that connect the low Z values to the hydrogenic limits (108 and 216) at infinite Z. In making this extrapolation, we have accounted for small deviations from the linearity of the line strengths at extremely high Z by using a correction factor C ($C=0.9964$ in Kr) obtained from the relativistic formulation of hydrogenlike line strengths (for details see Ref. [27]).

IV. CONCLUSION

We thus conclude that no discrepancy between theory and experiment exists for f values for the $3s\ ^2S_{1/2}$-$3p\ ^2P_{3/2}$ transition in highly charged Na-like ions. Higher precision was required for this verification than was necessary for

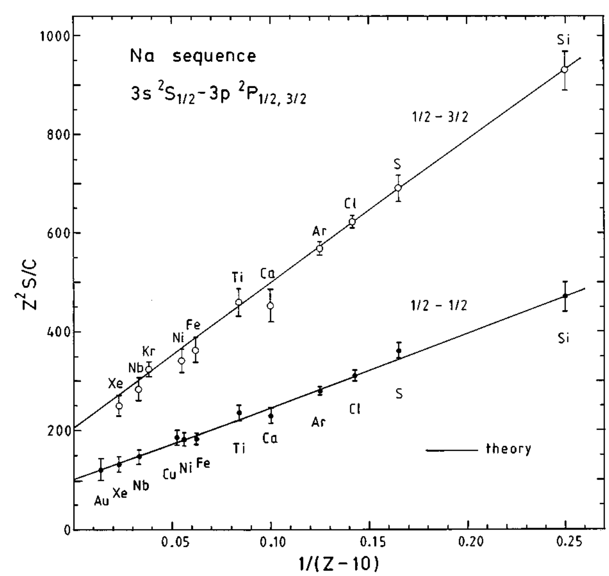

FIG. 3. The transition probabilities for the $3s$-$3p$ resonance lines in Na-like ions. The quantity Z^2S/C (where S is the line strength in a.u. and C a relativistic correction, see text) is plotted vs $1/(Z-10)$. The experimental data are from Refs. [8–16, 21, 22] and this work, whereas the lines connect the theoretical values, based on the Coulomb approximation Hartree-Slater (CAHS) method [18,27].

the $3s\ ^2S_{1/2}$-$3p\ ^2P_{1/2}$ transition because the $3p\ ^2P_{1/2}$ lifetime is significantly longer that those of the $3p\ ^2P_{3/2}$ level and the $3d\ ^2D_{3/2}$, $3d\ ^2D_{5/2}$ cascade levels. The reliable determination of the $3p\ ^2P_{3/2}$ lifetime made more stringent demands on the experimental time resolution, and required a thorough ANDC analysis, both of which were carried out in our measurement.

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