Measurement of the contributions of high-n satellite lines to the $K\beta$ lines of He-like Ar^{16+}

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We have measured the contributions from high-n dielectronic satellite lines to the $1s^2$–$1s3p\ ^1P_1$ resonance line of heliumlike Ar^{16+}. Using a high-resolution crystal spectrometer to analyze the x-ray emission of ions trapped and excited in an electron-beam ion trap, contributions from satellite levels of the type $1s3lnl'$-$1s^2nl'$, for $n=3,4,5$ and $n\geqslant 6$, have been recorded. The resonance strength of the $n=3$ satellites was measured to be $(4.65\pm 0.67)\times 10^{-21}\ \mathrm{cm}^2$ eV. The resonance strength of the $n=4$ satellites was determined to be larger than that of the $n=3$ satellites and that of the $n=5$ satellites was found to be nearly equal to the resonance strength of the $n=3$ satellites. The n^{-3} dependence of resonance strengths expected from the n scaling of the Auger rates is thus shown to not be valid for the satellites studied in our measurements. [S1050-2947(96)08206-6]

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I. INTRODUCTION

X-ray emission from intermediate-Z atoms such as Ar^{16+} is used extensively as electron temperature (T_e) and electron density (n_e) diagnostics for inertial confinement fusion (ICF) plasmas. The argon is usually added as dopant (0.1 at. %) to the solid fuel. The electron temperature is deduced from the intensity ratio of transitions between $n=3$ and 1 levels in hydrogenic and heliumlike ions, $I_{\mathrm{Ly}\beta}/I_{K\beta}$ (equivalently denoted by $I_{\mathrm{H}\beta}/I_{\mathrm{He}\beta}$); the electron density is derived from Stark broadening of the $K\beta$ line [1]. In considering the $K\beta$ line profiles, one must take into account contributions from Li-like satellite lines of the form $1s3lnl'$-$1s^2nl'$ for $n\geqslant 2$ to the $1s^2$–$1s3p^1P_1$ $K\beta_1$ line, since observed line profiles show an asymmetry on the long-wavelength side due to blending with Li-like satellites [2] and the observed $K\beta$ linewidths are grossly overestimated if satellite contributions are ignored. These satellite contributions are usually derived from theoretical considerations and so far these theoretical models have included only the $n=2$ and 3 satellites [2–4]. Stark broadened profiles for these satellites and for the Ar $K\beta$ line are calculated and summed to give a composite profile that is fitted to the experimental data. The full width at half maximum (FWHM) of the resonance line with no satellites included is 13 eV at $n_e=2\times 10^{24}\ \mathrm{cm}^{-3}$ and $T_e=1000$ eV [3]; this width increases by as much as 20 eV when the $n=2$ and 3 satellites are included in the composite line profile [2]. The intensity of one part of the $1s3l3l'$ satellite lines has been measured in a low-density, tokamak plasma environment [5]; by contrast, we know of no previous measurements of high-n satellite contributions ($n\geqslant 4$) to the $K\beta$ line intensity. Because of the potentially large effects on the $K\beta$ line shape and intensity, it is very important to measure high-n satellite contributions in a controlled environment and to take the correct amount of satellite contributions into account if reliable estimates of plasma parameters are to be obtained from $K\beta$ line profiles.

In this study, we report a measurement of the contributions from high-n lithiumlike satellites to the resonance lines of heliumlike Ar^{16+}. In particular, we have measured line positions relative to $K\beta 1$ and contributed intensities from transitions of the type $1s3lnl'$-$1s^2nl'$ for $n=3$–5, and $n\geqslant 6$. Our results indicate that the contributions made by the n=4, 5, and $n\geqslant 6$ satellites with a combined resonance strength of $16.0\times 10^{-21}\ \mathrm{cm}^2$ eV in the immediate neighborhood of the $K\beta$ line are more than three times as large as the contribution of the $n=3$ satellite with a resonance strength of $4.65\times 10^{-21}\ \mathrm{cm}^2$ eV. These results are consistent with previous measurements [6,7], which measured high-n contributions to the $K\alpha$ line of heliumlike ions and found significant contributions from satellites of the form $1s2lnl'$-$1s^2nl'$ with $n\geqslant 3$. However, the measurement by Beiersdorfer *et al.* [7], which resolved the contributions from different principal quantum numbers, found a strong decrease of the resonance strength as n increased in accordance with the predicted n^{-3} scaling [8] arising from the n dependence of the Auger rates. Our results for the $K\beta$ satellites do not agree with this scaling for $n=3$, 4, and 5. In what follows we describe the present measurement and present a comparison of the results with theoretical predictions.

II. EXPERIMENT

The measurements were carried out with the Lawrence Livermore National Laboratory electron-beam ion trap (EBIT), a machine that uses an intense electron beam to ionize, trap, and excite ions in high charge states [9]. The electron-ion interactions in the EBIT are monitored through observation of x rays emitted at 90° to the electron beam. A ring of six observation ports provide access to monitoring radiation from the trap. The electron energy distribution is monoenergetic with a spread of typically 50 eV FWHM [10].

The x-ray spectra were recorded with a high-resolution Bragg-crystal spectrometer in the von Hámos geometry [11]. A LiF(200) crystal with a $2d$ spacing of 4.027 Å and bent to a radius of 75 cm was used. The crystal was centered at 3.4 Å, a Bragg angle of 57.6°, and a nominal resolving power of $\lambda/\Delta\lambda=12\,300$. In EBIT measurements that involve dielec-

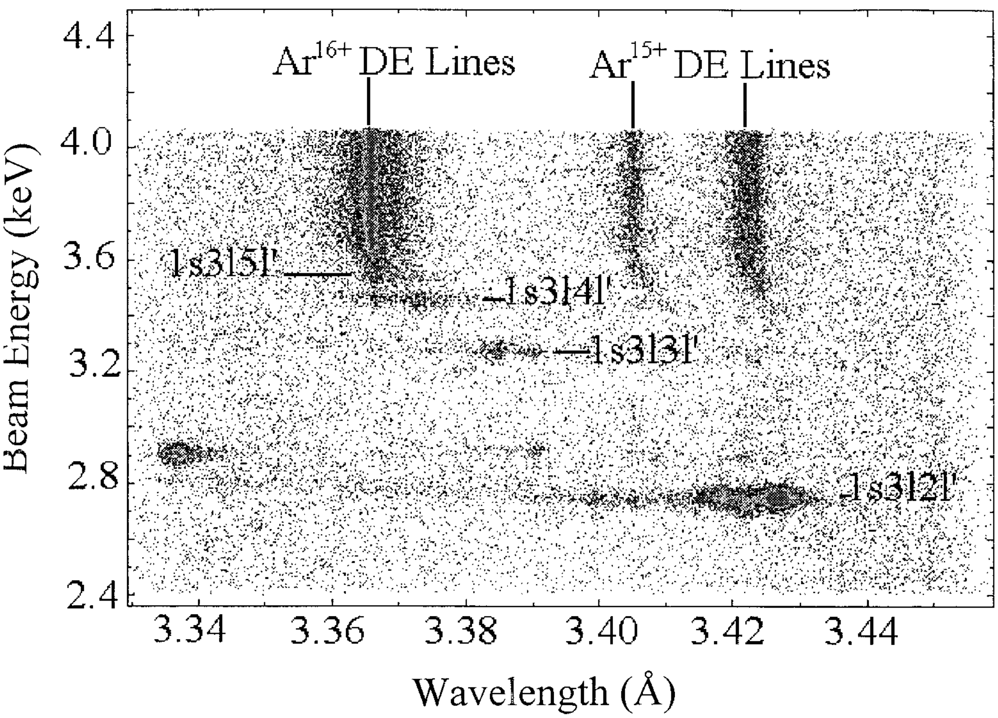

FIG. 1. Event mode data from the EBIT high-resolution Bragg crystal spectrometer showing the x-ray intensity distribution vs the x-ray energy and electron-beam energy. The Ar $K\beta_1$ ($1s^2$–$1s3p\ ^1P_1$) and $K\beta_2$ ($1s^2$–$1s3p\ ^3P_1$) direct excitation (DE) lines and the associated satellites of the type $1snl3l'$, $n=2$–5 and $n\geqslant 6$, have been labeled. Also shown are Ar^{15+} DE lines and their satellites. The feature at 3.34 Å arises from a dielectronic resonance in impurity ions indigenous to EBIT.

tronic recombination (DR), a resonant process, care must be taken to ensure that the electron-beam energy does not remain at the resonant value for long periods of time. This is because the cross sections for DR on resonance are very large and the charge balance is quickly destroyed when the electron beam is on a DR resonance. In our measurement, the electron beam was first maintained at an ionization potential of ~4 kV to produce mostly Ar^{16+} ions. Following this ''cooking'' period the electron beam was quickly swept over the interaction energy range from 4.0 kV (which is well above the direct excitation threshold) to 2.4 kV (this is just above the *KLL* resonance) and back again. The time for each back and forth sweep was 16 ms. In between sweeps the beam energy stayed at the ionization voltage to ensure that the charge balance is maintained. This electron-beam energy range produces the $K\beta$ lines by direct excitation (DE) and the associated (DR) satellite lines from the *KLM*, *KMM*, *KMN*, and *KMP* resonances, but misses the *KLL* resonance.

Data acquisition has been carried out in a mode in which we recorded for each x-ray event the beam energy, photon energy, and time of the event. Figure 1 shows a typical x-ray distribution in which each event is represented by a dot at the appropriate beam and photon energies. On this plot, events aligned in vertical lines represent DE bound-state transitions. Each bound-state transition clearly shows a threshold in beam energy. Associated with the DE lines are tails that occur below the threshold, curve towards longer wavelengths, and represent dielectronic recombination contributions.

In Fig. 1 we note the two $K\beta$ lines $1s^2$–$1s3p\ ^1P_1$ and $1s^2$–$1s3p\ ^3P_1$ near 3.370 Å . The wavelength of the $1s^2$–$1s3p\ ^1P_1$ $K\beta_1$ resonance line has been measured to be $3.365\,51\pm0.000\,12$ Å [12]. In the following, the positions of all the features were determined relative to the $K\beta_1$ wavelength. The corresponding threshold for excitation of the $K\beta_1$ line is 3683.96 eV. The DR lines associated with $K\beta$ have been labeled. The contributions from transitions $1snl3l'$-$1s^23l'$ for $n=2$–5 are excited at beam energies of 2.55, 3.27, 3.47, and 3.54 keV, respectively. The contributions for $n\geqslant 6$ occur between 3.55 and 3.68 keV. Also seen in Fig. 1 are DE lines for Ar^{15+} with associated dielectronic satellites lines; these occur at around 3.405 and 3.420 Å [5].

Spectra of interest are obtained from these data by taking appropriate horizontal projections, while excitation functions are represented by vertical projections. To evaluate the contributions of high-n satellites to the $K\beta$ lines we have made horizontal cuts around all the distinguishable satellite contributions and projected the data onto the x-ray energy axis. We show in Fig. 2 these high-n contributions as a function of wavelength (mÅ) measured relative to the line position of the $K\beta_1$ line. Figures 2(a), 2(b), 2(c), and 2(d) show the contributions from the satellites $1snl3l'$ for $n=3$, $n=4$, $n=5$, and $n\geqslant 6$, respectively.

We have least-squares fitted the spectra resulting from horizontal projections of contributions from each satellite to obtain the positions and intensities of individual high-n satellite contributions. These intensities have been normalized to the cross sections for direct excitation at threshold, $\sigma_{K\beta 1}=2.64\times10^{-22}$ cm^2, multiplied by the branching ratio of 94.6%. The cross section was calculated using a distorted-wave code of Zhang, Sampson, and Clark [13]; the uncertainty of this number is estimated to be 15%. We arrive at this estimate by comparing various cross sections calculated with this code to various EBIT measurements [14]. The resonance strengths for the different DR lines obtained in this manner have been corrected for polarization and anisotropy of EBIT x rays and are shown in Table I.

X rays from the EBIT are linearly polarized and the crystals used act as polarizers, selectively reflecting x rays polarized with the electric field parallel to the electron beam. Using the distorted-wave code of Zhang, Sampson, and Clark [13], we calculated the polarization of $K\beta_1$ at threshold to be

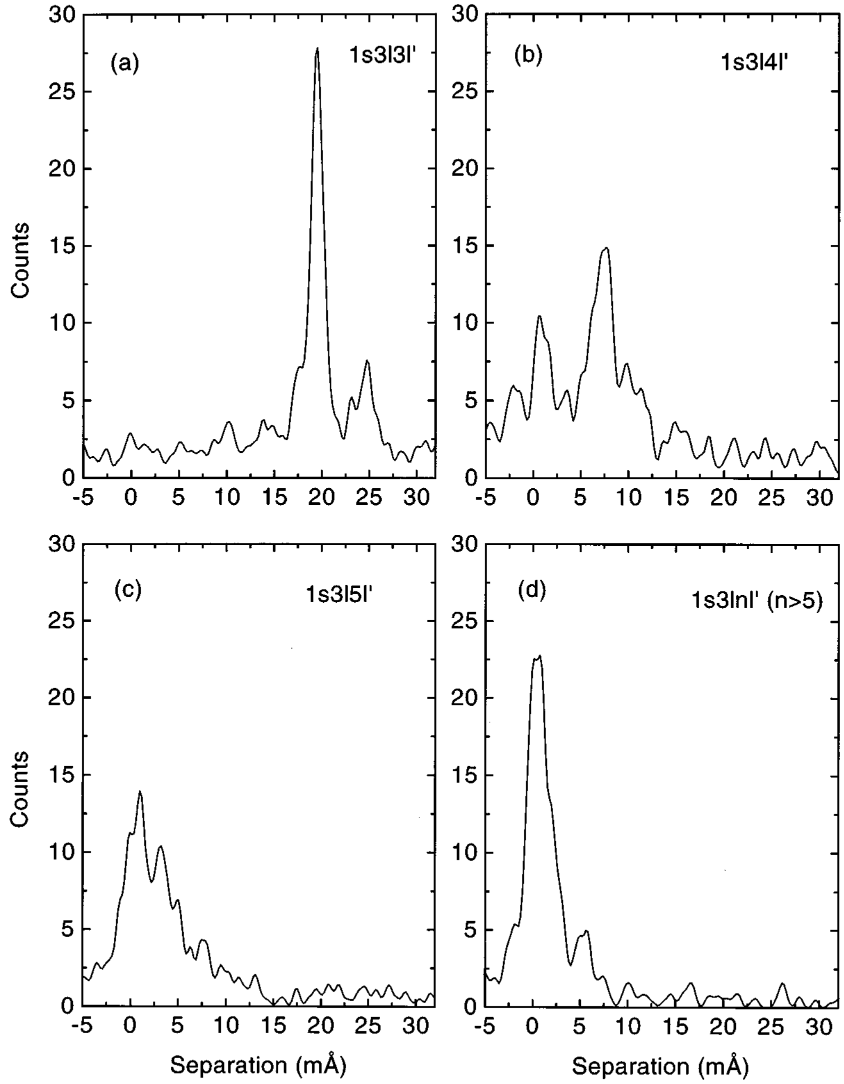

FIG. 2. Intensities of high-n satellites to $K\beta_1$ and $K\beta_2$ transitions of Ar^{16+}. Shown in (a), (b), (c), and (d) are contributions from the satellites $1s3lnl'$ for $n=3$, $n=4$, $n=5$, and $n\geqslant 6$, respectively. The satellite positions are given relative to that of $K\beta_1$.

62.7%. The polarizations of the satellites with $n=3$, 4, and 5 have also been calculated from a perturbation theory using multiconfiguration Dirac-Fock method [15] to be 35%, 27%, and 19%, respectively. We have assumed a value of 19% for the polarization of $n\geqslant 6$ satellite. We have used these polarizations and a value $f_\perp/f_\parallel=0.35$ for the ratio of the reflectivities of the crystal for x rays perpendicular to and parallel to the electron beam. This value is appropriate for LiF(200) at an x-ray energy of 3670 eV [16]. Thus we have corrected [10,17] the measured resonance strengths shown in Table I for polarization and anisotropy.

III. RESULTS AND DISCUSSION

Figure 2(a) shows that the total contribution from $n=3$ comes from two peaks (a larger peak at 18 mÅ and a smaller peak at 24 mÅ), whereas the $n=4$ contribution comes from several smaller peaks covering a total area comparable to or larger than that covered by the $n=3$ peaks. Since the measured resonance strengths are proportional to the areas under the curves, we find similar resonance strengths for $n=3$ and 4. In fact, the observed ratio of the resonance strength of the $n=4$ satellites to that of the $n=3$ is 1.25, i.e., the resonance strength of the $n=4$ satellites is larger than that of the $n=3$ satellites (see Table I). The size of the $n=5$ satellites is also nearly equal to that of the $n=3$ satellites. This is surprising when considering the behavior of the $1s^2nl'$-$1s2lnl'$ dielectronic satellites. The resonance strength of these satellites diminishes rapidly with n [7], in good agreement with the well-known n^{-3} scaling [8,18]. The behavior of the $K\beta$ satellites can be understood, however, by noting that the resonance strength of the $n=3$ satellites is diminished by L-shell Auger decay. Autoionizing levels of the type $1s3l3l'$ can decay by Auger decay to the excited levels $1s2l$, i.e.,

$$1s3l3l' \rightarrow 1s2l + e^-.$$

The result is resonant excitation of the heliumlike $K\alpha$ lines. This decay branch for the $1s3l3l'$ levels strongly diminishes the dielectronic recombination branch observed in the present measurement. The dielectronic recombination branches for $n\geqslant 4$ are also affected by such Auger channels, albeit to a lesser degree. The presence of this Auger branch destroys adherence to the n^{-3} scaling of the dielectronic resonance strengths. For $1s2snl$ autoionizing levels, this

TABLE I. Measured resonance strengths (S) of lithiumlike satellites to the He β line. The resonance strengths have been corrected for polarization and anisotropy of EBIT x rays and their uncertainties are given in parentheses. The position of the individual satellite feature is given relative to the position of the $K\beta_1$ line.

Feature	Relative position (mÅ)	$S_{\rm expt}$ (10^{-21} cm^2 eV)	$S_{\rm theor}$ [a] (10^{-21} cm^2 eV)	$S_{\rm theor}$ [b] (10^{-21} cm^2 eV)
		$1s3l3l'$-$1s^23l'$		
1	19.60	2.91(0.28)		3.160
2	24.8	0.54(0.14)		0.756
sum		4.65(0.67)	4.495	
		$1s3l4l'$-$1s^24l'$		
1	0.97	1.39(0.17)		
2	7.45	2.21(0.22)		
3	10.27	0.66(0.15)		
sum		5.80(0.82)	5.99	
		$1s3l5l'$-$1s^25l'$		
1	0.77	2.08(0.22)		
2	3.55	1.58(0.19)		
sum		4.32(0.73)	4.41	
		$1s3lnl'$-$1s^2nl'$		
1	0.72	4.32(0.23)		
2	5.39	0.57(0.11)		
sum		5.87(0.63)		

[a]Present calculation.
[b]Reference [5].

branch does not exist, for $1s2pnl$ autoionizing levels it exists only for very high n values, hence the n^{-3} scaling is intact.

In Table 1 we summarize the results of our measurements and list results from our calculation for comparison. There is, in general, agreement between measured and calculated values and also agreement with earlier calculations from Ref. [5]. A discrepancy of 50% between the measured and predicted ratio of the $1s3l3l'$ satellite and $K\beta_1$ was noted in Ref. [5]. Our results indicate that this discrepancy is not due to errors in the calculation of resonance strengths. This discrepancy may instead arise from temperature profile effects not accounted for in the analysis of [5].

The $1s3l3l'$ and the $1s2l3l'$ satellite are the only satellites taken into consideration in the model calculations used to make corrections to $K\beta_1$ line profiles for ICF density and temperature diagnostics [2–4]. Our measurements show that the resonance strength of the $1s3lnl'$ satellites with $n>3$ is more than three times larger than that of the $1s3l3l'$ satellites. The large size of the $n>3$ satellites suggests that it may be important to include these high-n satellites in the analysis of the $K\beta$ line profiles, especially when using the $K\beta$ line shapes for extracting diagnostic information on ICF plasmas.

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[1] B. A. Hammel, C. J. Keane, D. R. Kania, J. D. Kilkenny, R. W. Lee, R. Pasha, R. E. Turner, and N. Delamater, Rev. Sci. Instrum. **63**, 5017 (1992); B. A. Hammel, C. J. Keane, T. R. Dittrich, D. R. Kania, J. D. Kilkenny, R. W. Lee, and W. K. Levedahl, J. Quantum Spectrosc. Radiat. Transfer **51**, 113 (1994).
[2] R. C. Mancini, C. F. Hooper, Jr., N. D. Delamater, A. Hauer, C. J. Keane, B. A. Hammel, and J. K. Nash, Rev. Sci. Instrum. **63**, 5119 (1992).
[3] C. J. Keane, B. A. Hammel, D. R. Kania, J. D. Kilkenny, R. W. Lee, A. L. Osterheld, L. J. Suter, R. C. Mancini, C. F. Hooper, Jr., and N. D. Delamater, Phys. Fluids B **5**, 3328 (1993).
[4] B. A. Hammel, C. J. Keane, M. D. Cable, D. R. Kania, J. D. Kilkenny, R. W. Lee, and R. Pasha, Phys. Rev. Lett. **70**, 1263 (1993).
[5] P. Beiersdorfer, A. L. Osterheld, T. W. Phillips, M. Bitter, K. W. Hill, and S. von Goeler, Phys. Rev. E **52**, 1980 (1995).
[6] M. Bitter, S. von Goeler, K. W. Hill, R. Horton, D. Johnson, W. Roney, N. Sauthoff, E. Silver, and W. Stodiek, Phys. Rev. Lett. **47**, 921 (1981); F. Bely-Dubau, P. Faucher, L. Steenman-Clark, M. Bitter, S. von Goeler, K. W. Hill, C. Camby-Val, and J. Dubau, Phys. Rev. A **26**, 3459 (1988); TFR Group, F. Bombarda, F. Bely-Dubau, P. Faucher, M. Cornille, J. Dubau, and M. Loulergue, Phys. Rev. A **32**, 2374 (1985).
[7] P. Beiersdorfer, M. B. Schneider, M. Bitter, and S. von Goeler,

Rev. Sci. Instrum. **63**, 5029 (1992).
[8] R. D. Cowan, *The Theory of Atomic Structure and Spectra* (University of California Press, Berkeley, 1981); J. Dubau and S. Volonté, Rep. Prog. Phys. **43**, 199 (1980); K. R. Karim and C. P. Bhalla, Phys. Rev. A **43**, 615 (1991).
[9] M. A. Levine, R. E. Marrs, J. R. Henderson, D. A. Knapp, and M. B. Schneider, Phys. Scr. **T22**, 157 (1988).
[10] P. Beiersdorfer, T. W. Philips, K. L. Wong, R. E. Marrs, and D. A. Vogel, Phys. Rev. A **46**, 3812 (1992).
[11] P. Beiersdorfer, R. E. Marrs, J. R. Henderson, D. A. Knapp, M. A. Levine, D. B. Platt, M. B. Schneider, D. A. Vogel, and K. L. Wong, Rev. Sci. Instrum. **61**, 2338 (1990).
[12] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, Phys. Rev. A **40**, 150 (1989).
[13] H. L. Zhang, D. H. Sampson, and R. E. H. Clark, Phys. Rev. A **41**, 2850 (1993).
[14] K. L. Wong, P. Beiersdorfer, M. H. Chen, R. E. Marrs, K. J. Reed, J. H. Scofield, D. A. Vogel, and R. Zasadzinski, Phys. Rev. A **48**, 2850 (1993).
[15] M. H. Chen, in *Recombination of Atomic Ions*, Vol. 296 of *NATO Advanced Study Institute, Series B: Physics*, edited by W. G. Graham, W. Fritsch, Y. Hahn, and J. A. Tanis (Plenum, New York, 1992), p. 61.
[16] B. L. Henke, E. M. Gullikson, and J. C. Davis, At. Data Nucl. Data Tables **54**, 181 (1993).
[17] A. J. Smith, P. Beiersdorfer, V. Decaux, K. Widmann, A. Osterheld, and M. Chen, Phys. Rev. A **51**, 2808 (1995).
[18] K. R. Karim and C. P. Bhalla, Phys. Rev. A **43**, 615 (1991).