Line ratios and wavelengths of helium-like argon $n = 2$ satellite transitions and resonance lines

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The characteristic x-ray emission from helium-like argon was investigated as a mean to diagnose hot plasmas. We have measured the radiation from $n = 2 - 1$ parent lines and from KLn dielectronic recombination satellites with high wavelength resolution as function of the excitation energy using the Berlin Electron Beam Ion Trap. Values of wavelength relative to the resonance and forbidden line are tabulated and compared with references. The line intensity observed over a wide range of excitation energies is weighted with a Maxwellian electron-energy distribution to analyze line ratios as function of plasma temperature. Line ratios $(j+z)/w$ and k/w compare nicely with theoretical predictions and demonstrate their applicability as temperature diagnostic. The ratio $z/(x+y)$ shows not to depend on the electron density.

1. Introduction

The measurement of the radiation pattern from helium-like ions, dominated by the 4 parent lines, conventionally labelled w, x, y, and z, and the associated dielectronic recombination (DR) satellites provides a mean to diagnose hot laboratory-fusion plasmas or the plasma of astrophysical objects, which are not accessible for direct measurements [1,2]. The intensity of these resonant satellites is strongly affected by the local plasma properties through electron recombination. From the intensity ratio of certain line combinations information on electron temperature or density, transport or spatial distribution of impurities or possible deviations from the Maxwellian energy distribution by polarization spectroscopy can be derived. Even though the helium-like ion system is known to a fair degree and atomic recombination and ionization rates can be calculated for a wide range of plasma conditions this basic theoretical data needs to be checked with experimental observations of wavelength, excitation energy and line strength.

Argon serves as a favorable diagnostic tool of various plasmas, owing to its properties of controllable injection into and efficient pumping out of fusion devices. He-like argon has a significant abundance in a plasma with electron temperatures in the range between $T_e = 0.5$ to 3.5 keV. This T_e range prevails in the outer region of large tokamak machines, where argon is employed as coolant or in the center of smaller devices, where it serves as a tracer of plasma conditions [3].

The dielectronic satellites j and k are especially useful for diagnostic purposes, since they cannot be populated directly from the ground state of the Li-like ion through the promotion of an inner-shell electron and since their resonance strengths are observed as large. Unfortunately, for the argon system investigated here, the line j and z blend with an unresolvable 0.2 mÅ separation. This blend of lines is a typical situation in a plasma, where the excitation follows from a broad energy distribution (usually Maxwell-Boltzmann) and leads to simultaneous emission of directly excited lines as well as dielectronic satellites. EBIT, however, with it's mono-energetic electron beam, offers, in conjunction with high-resolution spectroscopy, the opportunity to investigate collisionally excited emission spectra differentially as function of wavelength and electron-

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excitation energy [4]. Thereby, level-specific information on wavelength, excitation energy and strength of individual transitions can be gained.

2. Experimental method

The x radiation of helium-like argon was collected at the Berlin Electron Beam Ion Trap with a vacuum flat-crystal spectrometer. The dispersing quartz-crystal and the position-sensitive proportional detector reach a resolving power > 2000. Neutral argon is continuously fed into EBIT, which ionizes and confines the ions with its 70-μm-diameter electron beam. Operating at 5-keV-energy and 90-mA-electron current the charge-state distribution is dominated by Ar^{16+} after 200 ms. This prepares the experiment sequence in which the nearly mono-energetic (50 eV spread) electron-beam energy is linearly ramped during a period of 20 ms from 1.9 to 3.9 keV probing He-like argon ions and simultaneously recording x rays emitted during recombination processes with the beam electrons. For every detected x-ray event the corresponding excitation energy of the electron beam is registered. The resulting information is presented as a scatter plot in Fig. 1.

The rapid switching of the electron-beam energy and a re-ionization period following the sampling period ensures that the trapped ion abundance is not altered. After repetition of the sequence for 3 s the ion inventory is expelled and a fresh argon-ion ensemble is prepared preventing the accumulation of high-Z background ions. To probe the smoothly varying radiation emitted after direct excitation over an extended energy range, the electron-beam energy was raised in 8 steps from 3.8 to 15.8 keV during a second experiment sequence.

Quickly sweeping EBIT's electron-beam energy, we can measure the rate of a process by analyzing the recorded intensity normalized to the electron and ion density as function of excitation energy for a given ion population. To compare with a plasma the measured excitation function has to be folded with the wide energy distribution of the exciting electrons, which commonly follows a Maxwell-Boltzmann distribution.

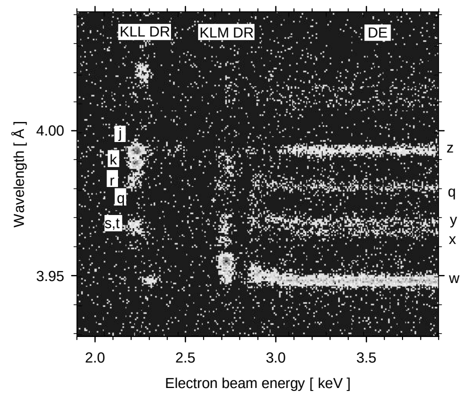

Figure 1. Scatter plot of x rays from He- and Li-like argon showing wavelength- and excitation-energy-resolved individual satellites from KLn dielectronic recombination as distinct spots and direct excitation as horizontal lines.

We note, however, that the spectral information obtained with EBIT can be weighted with any energy-distribution function and in this respect deviations from a Maxwellian can be studied. To the weight function we combine the variation of the electron density with beam energy, caused by the fact that, during the beam-energy ramp, we keep the electron-beam current constant.

To circumvent the problems of absolute line-intensity measurements the rate coefficient exciting a dielectronic satellite is related to the rate coefficient of the w-resonance line, which is the brightest of the spectrum and proportional to the number of excited He-like argon ions from which the satellites originate. The measured line radiation has to be corrected for the experimental situation of anisotropic electric-dipole radiation due to directed electron-beam excitation expressed by the polarization and the detection properties of the crystal and the recording device, which can be summarized in an instrumental response function.

Table 1
Experimental and theoretical wavelengths of $n = 2$ dielectronic satellite transitions lithium-like argon in [Å]. bl marks an unresolved blend of lines.

label	Transition	BerlinEBIT	Tarbutt [6]	TFR [3]	Chen [7]	Bhalla [8]	Vainstein [9]	Phillips [2]
q	$1s2p(^3P)2s\ ^2P_{3/2} - 1s^22s\ ^2S_{1/2}$	3.98155(15)	3.98134(10)	3.9813(1)	3.9827	3.9785	3.9806	3.9801
r	$1s2p(^3P)2s\ ^2P_{1/2} - 1s^22s\ ^2S_{1/2}$	3.98433(39)	3.98355(10)	3.9833(2)	3.9851	3.9807	3.9827	3.9823
j	$1s2p^2\ ^2D_{5/2} - 1s^22p\ ^2P_{3/2}$	3.99417(28)	3.99392(11)	3.9943	3.9940	3.9899	3.9932	3.9906
k	$1s2p^2\ ^2D_{3/2} - 1s^22p\ ^2P_{1/2}$	3.98986(25)	3.98999(12)	3.9900(2)	3.9900	3.9864	3.9892	3.9875
m	$1s2p^2\ ^2S_{1/2} - 1s^22p\ ^2P_{3/2}$	3.96625(39)	3.96580(15)	3.9656	3.9647	3.9616	3.9651	3.9744
s	$1s2p(^1P)2s\ ^2P_{3/2} - 1s^22s\ ^2S_{1/2}$	3.96625(50)	3.96891(20)	3.9676	3.9680	3.9639	3.9669	3.9673
t	$1s2p(^1P)2s\ ^2P_{1/2} - 1s^22s\ ^2S_{1/2}$	bl	bl	3.9688	3.9685	3.9650	3.9677	3.9683
u	$1s2p(^3P)2s\ ^4P_{1/2} - 1s^22s\ ^2S_{1/2}$	4.01084(40)	4.01012(20)	-	4.0165	4.0123	4.0141	4.0095
v	$1s2p(^3P)2s\ ^4P_{3/2} - 1s^22s\ ^2S_{1/2}$	bl	bl	-	4.0176	4.0139	4.0152	4.0109

Table 2
Wavelengths of lithium-like argon $n = 3$ and $n = 4$ dielectronic satellites observed as strong. Wavelengths are given in [Å] and compared to theoretical predictions.

Transition	BerlinEBIT	Safronova [10]	Bhalla [8]	TFR [3]	Chen [7]
$1s2p3d\ ^2F_{7/2} - 1s^23d\ ^2D_{5/2}$	3.95217(17)	3.9522	3.9491	3.9479	3.9526
$1s2p3d\ ^2D_{5/2} - 1s^23p\ ^2P_{3/2}$	3.95591(18)	3.9564	3.9523	3.9529	3.9542
$1s2p3s\ ^2P_{3/2} - 1s^23s\ ^2S_{1/2}$	3.96318(15)		3.9633	3.9628	3.9635
$1s2p3p\ ^2D_{5/2} - 1s^23p\ ^2P_{3/2}$	3.96686(18)		3.9640	3.9643	3.9688
$1s2p4p\ ^2D_{5/2} - 1s^24p\ ^2P_{3/2}$	3.95150(19)		3.9499	3.9487	

3. Wavelengths

For the observed dielectronic satellites shown in Fig. 1, wavelengths were determined by calibrating the spectrum to theoretical values for the w and the z line calculated by Drake [5]. The results are summarized in table 1 for the KLL DR and for the KLM and KLN DR in table 2. The uncertainty origins from non-linearities of the interpolation between w and z, the spectrometer response and statistics. The data is compared with recent measurements of Tarbutt et al. [6], values from the TFR tokamak and theoretical calculations using different methods [7–9,2,10].

4. Line ratios

4.1. Density-sensitivity

To extract information on the electron density from x-ray spectra of He-like ions it is common to relate the intensity of the forbidden line z to the intercombination lines x and y. This sensitivity is caused by the collisional transfer from the metastable $^3S_1$ to the ^3P_J level, which is observed as efficient for light elements. For He-like argon we compare our measurement of $R = z/(x + y)$ in Fig. 2 with values from other EBIT facilities [11,12], the Alcator C tokamak [1], and theoretical predictions. The theoretical value using excitation rates by Pradhan [1] and the predictions by HULLAC collisional radiative rate coefficients with modifications including the two-photon decay of the $1s\,2s\,^1S_0$ level (HULLAC w 2hν) or a variation of the collisional data (HULLAC col) demonstrate the insensitivity of the ratio R for argon.

4.2. Temperature-dependent ratios

The relative ratio of dielectronic satellites to the resonance line is sensitive to the electron temperature of the plasma. The strong j satellite blended by the z line frame with the w line the He-like argon spectrum and can already be clearly distinct with modest detection effort. We have measured this ratio $(j + z)/w$ and plotted it together with a data point from TFR tokamak [3] and a calculated value in Fig. 3 showing the weak temperature dependence of the ratio above

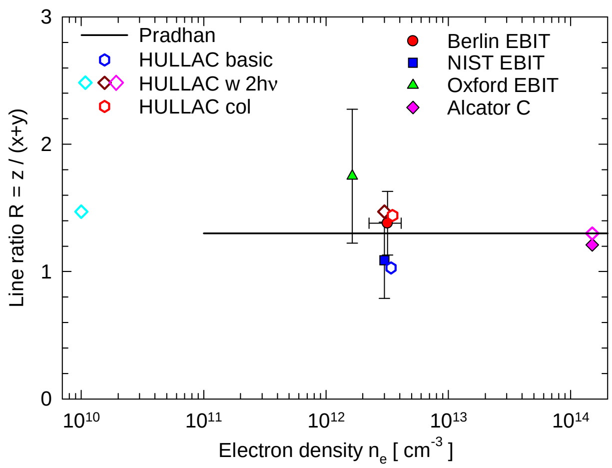

Figure 2. Line ratio $R = z/(x+y)$ for He-like argon arranged according to the electron density. In the EBIT experiment the electron-beam energy is $7keV$ and the density is calculated from the electron current and the estimated beam radius. For the tokamak value and the theoretical predications the plasma temperature is about $2keV$.

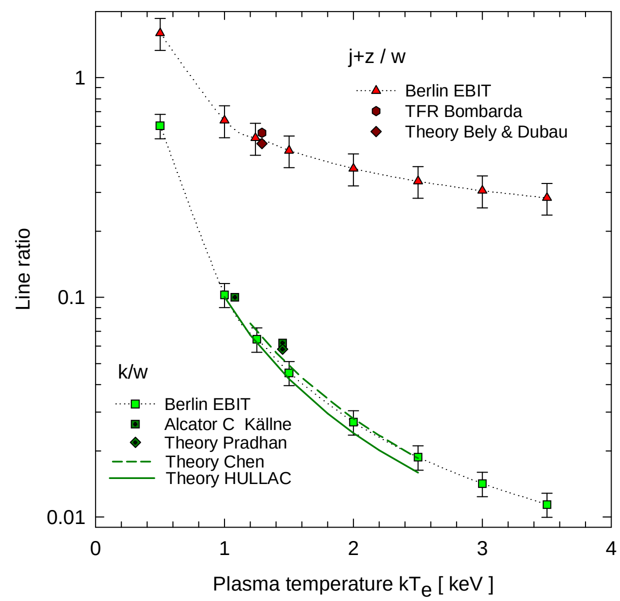

Figure 3. Line ratio of $(j+z)/w$ and k/w for He-like argon as function of the electron temperature. Experimental values from the Berlin EBIT are compared with measurements at TFR and Alcator C tokamak and theoretical predictions.

$T_e = 1\,keV$. The experimental uncertainty adds statistics, variations in the polarization, crystal reflectivity and changes in the electron beam ion overlap.

Further, we have extracted the line ratio of the k satellite, which is well resolved from other lines, and the parent w resonance. In Fig. 3 the k/w ratio is plotted as function of plasma temperature and compared to tokamak values from Alcator C and a calculated data point [1]. The functional trend is supported by theoretical calculations using the HULLAC-package and dielectronic recombination data by Chen [7]. Modifications to the HULLAC-predicted [4] collisional excitation rates or variations of the electron density show only a minor influence on the line ratio, indistinguishable within the experimental uncertainty. The steep temperature dependence of the k/w ratio allows a more accurate determination of T_e from the measured line ratio, which is important for the application as plasma-temperature diagnostic.

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