Unresolved Dielectronic Satellites of the Resonance Line of Heliumlike Iron (Fe XXV)

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High-resolution spectra of Fe XXV have been observed from Princeton Large Torus tokamak discharges and are used for a detailed comparison with theoretical predictions of Bely-Dubau, Gabriel, and Volonté for the ($1s^2nl$-$1s2pnl$, $n \geq 3$) dielectronic satellites at 1.85 Å. The theory predicts a significant apparent broadening of the resonance lines of high-Z heliumlike ions in high-temperature plasmas due to the dielectronic capture of electrons into outer atomic shells. The experimental results and theoretical predictions are in good general agreement.

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The resonance lines of heliumlike iron (Fe XXV) and titanium (Ti XXI), and their associated satellites which are due to transitions of the type $1s^2nl$-$1s2pnl$ with $n \geq 2$, have been observed in hot plasmas and have been used to diagnose solar flares[1-4] and tokamak discharges.[5,6] The diagnostic applications include measurements of the satellite-to-resonance line ratios for determination of the electron temperature (T_e) and the ionization equilibrium as well as Doppler-broadening measurements for determination of the ion temperature (T_i).

Recently, Bely-Dubau, Gabriel, and Volonté[7] showed that the contribution of satellites produced by dielectronic capture of an electron into an atomic level with main quantum number $n = 3$–11 can be effectively considered as a line-broadening mechanism for the resonance line. In essence, the $1s$-$2p$ transition is only slightly changed by the presence of an electron in the outer shells so that the satellite lines and the resonance line form an unresolvable blend. The calculations of Bely-Dubau, Gabriel, and Volonté[7] predict a significant increase of both the apparent width and intensity of the resonance line which must be taken into account for Doppler-broadening measurements and the evaluation of satellite-to-resonance line ratios. This new line-broadening mechanism occurs only in high-temperature plasmas where dielectronic recombination of high-Z ions gives a significant contribution to the line radiation. It is the aim of this paper to give a detailed comparison between experiment and the theory of Bely-Dubau, Gabriel, and Volonté[7] in order to establish a solid base for diagnostic applications, especially for the Doppler-broadening measurements which are of vital importance for tokamaks.

Figures 1(a), 1(b), and 1(c) show satellite spectra of Fe XXV which have been recorded with a curved crystal spectrometer[5,6,8] on the PLT (Princeton Large Torus) tokamak from discharges with central electron temperatures of 0.9, 1.2, and 1.5 keV, respectively. The data were accumulated from several, typically twenty, discharges with identical parameters to reduce the statistical error. In this range of electron temperatures, the dielectronic satellites are very prominent spectral features. The spectra show the resonance line at 1.85 Å and a kind of pedestal (features A, B, $d13$) on its long-wavelength side which is due to the presence of $n \geq 3$ dielectronic satellites.

The spectral lines in the wavelength range from 1.8540 to 1.8730 Å have been fitted by Voigt functions.[9] The structure in the wavelength range from 1.8480 to 1.8540 Å, which includes the unresolved satellites, has been fitted by the theoretical predictions of Bely-Dubau, Gabriel, and Volonté.[7] The theoretical predictions for the line spectrum are calculated by a computer code from the transition arrays given by Bely-Dubau, Gabriel, and Volonté. The electron temperature needed to calculate the excitation rates is taken from the laser scattering data. The ion temperature which determines the Doppler width is varied in the computer program until the variance between experimental data and theoretical predictions is minimized. A more detailed and expanded graph of this fit for the spectrum shown in Fig. 1(b) is presented in Fig. 1(d). The theoretical predictions of Bely-Dubau, Gabriel, and Volonté (curve I) are decomposed into the contributions from the resonance line (w) and dielectronic satellites with $n = 3$–11 (curve II). The features A, B, and $d13$ are essentially due to $n = 3$ satellites, whereas the remaining part of curve II underneath the resonance line is predominantly due to

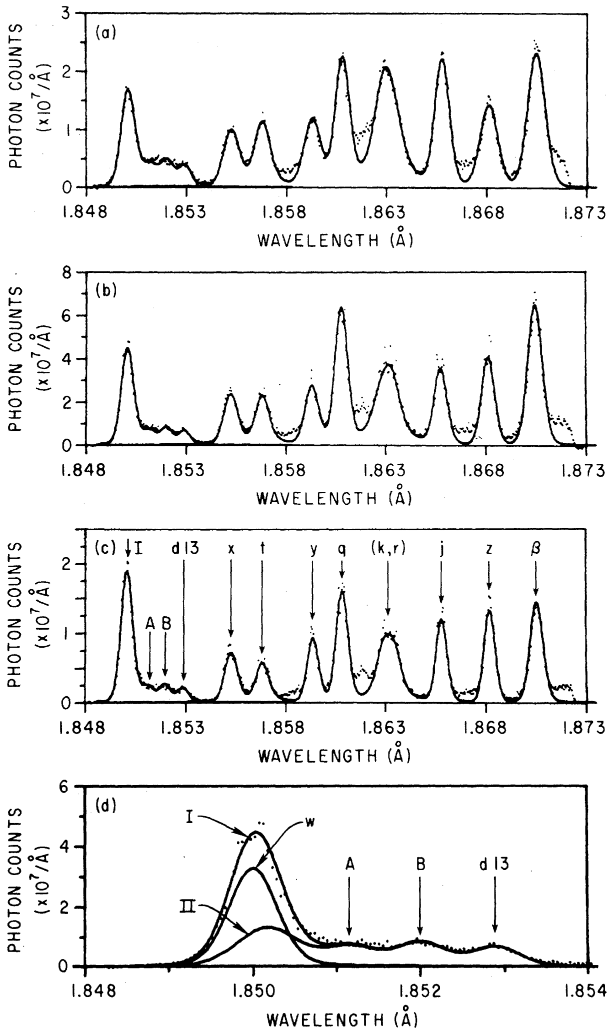

FIG. 1. Dielectronic satellite spectrum of Fe XXV. (a)–(c) Spectra obtained for central electron temperatures of 0.9, 1.2, and 1.5 keV and central electron densities of (9, 3, and 3) $\times 10^{13}$ cm^{-3}, respectively. (d) Experimental data of spectrum (b) near 1.8500 Å and predicted (Ref. 7) line structure (curve I) decomposed into resonance line (w) and contributions from satellites with $n = 3-11$ (curve II).

$n = 4-11$ satellites. It is the part which causes the apparent line broadening and intensity increase of the resonance line.

The satellites which, according to the theory,[7] mainly contribute to the spectral features on the long-wavelength side of the resonance line are given in Table I. These are the transitions for which the predicted relative intensities (I_s/I_w) at 20×10^6 K (≈ 1.7 keV) are larger than 1×10^{-3}. Table I shows that the experimental wavelengths for the $n = 3$ satellites are larger than the theoretical wavelengths by 0.0003 Å. This is within the reported error of 0.0005 Å of the theoretical predictions.[7] In the fit shown in Fig. 1(d) the Bely-Dubau wavelengths of the $n = 3$ satellites have been increased by 0.0003 Å. $d13$ is a well isolated $n = 3$ satellite, whereas A and B are composed of several lines. The features A, B, and $d13$ are well above the statistical error of 5% for a data point in the considered wavelength range. However, they are comparable in magnitude with small periodic variations of the detector efficiency which result from the finite spacing (1 mm) of the cathode wires in the multiwire proportional counter of the crystal spectrometer. The features are, therefore, partially masked by the detector efficiency oscillations if not properly corrected for. The accuracy in determining the shape of features A and B is thus limited. On the other hand, the long-wavelength wing of $d13$ is determined quite accurately.

TABLE I. Experimental and theoretical (Ref. 7) wavelengths for the observed spectral features A, B, and $d13$. Listed are the most intense transitions with relative intensities $I_s/I_w \geq 1\times10^{-3}$ at 20×10^6 K (Ref. 7).

Key	Transition	λ (Å)
A		1.8512[a]
$h9$	$1s^2 3d(^2D_{3/2})-1s2p3d(^2D_{5/2})$	1.8509[b]
$h15$	$1s^2 3d(^2D_{5/2})-1s2p3d(^2F_{7/2})$	1.8509[b]
9	$1s^2 4p(^2P_{3/2})-1s2p4p(^2D_{5/2})$	1.8509[b]
B		1.8520[a]
$a2$	$1s^2 3s(^2S_{1/2})-1s2p3s(^2P_{1/2})$	1.8513[b]
$h7$	$1s^2 3d(^2D_{5/2})-1s2p3d(^2D_{5/2})$	1.8514[b]
$a1$	$1s^2 3s(^2S_{1/2})-1s2p3s(^2P_{3/2})$	1.8515[b]
$d5$	$1s^2 3p(^2P_{3/2})-1s2p3p(^2P_{3/2})$	1.8516[b]
$d15$	$1s^2 3p(^2P_{1/2})-1s2p3p(^2D_{3/2})$	1.8518[b]
$d13$	$1s^2 3p(^2P_{3/2})-1s2p3p(^2D_{5/2})$	1.8529[a]
		1.8526[b]

[a]Experimental value.
[b]Theoretical prediction (Ref. 7).

Theoretical predictions for the relative intensities of the satellites and the resonance line cannot be directly compared with the measured intensities because of the blend of the resonance line with $n \geq 4$ satellites. However, the ratio of the intensity of features A and B and $d13$ relative to the intensity (I_w^*) of the apparent resonance line, which is defined as the line structure in the wavelength range from 1.8480 to 1.8510 Å,[7] can be accurately determined. These intensity ratios are listed in Table II. Figure 2(a) shows the ratio I_{d13}/I_w^* versus electron temperature, as well as the theoretical predictions.[7] The agreement between experiment and theory is within the error bar.

Of special interest is the intensity ratio of the satellites j and $d13$.[10] These satellites are both excited by dielectronic capture of electrons with kinetic energies of 4.694 and 5.815 keV, respectively. Therefore, the measurement of their relative intensity is not extremely sensitive to small errors in the determination of the electron temperature. Figure 2(b) shows the experimental results and the theoretical predictions for I_j/I_{d13}. The experimental values deviate slightly from the theoretical expectations. We do point out that the electron velocity distribution was very close to a Maxwellian for the investigated PLT discharges. The results are, therefore, not affected by runaway electrons.[10] Discrepancies between experiment and theory[11] are also observed for the intensity of the spectral lines x, y, and z. The intensity ratios in Table II should be useful for current theoretical work on the excitation rates for these forbidden lines.[12]

The line profile [as demonstrated in Fig. 1(d)] is in good agreement with the theory of Bely-Dubau, Gabriel, and Volonté.[7] The $n=3$ satellites which constitute the features A, B, and $d13$ are clearly resolved. The features due to the satellites with $n \geq 4$, which blend with the resonance line, should be detectable, in principle, as a deviation of the profile shape of the apparent resonance line from a Voigt function. However, in practice, the statistical error of the experimental data does not allow us to determine the contribution from $n \geq 4$ satellites with certainty. In other words, the data in the wavelength range from 1.8480 to 1.8510 Å can be fitted by the theoretical predictions of Bely-Dubau, Gabriel, and Volonté,[7] as well as by a Voigt function fit with a slightly higher ion temperature ($\tilde{T}_i$). For low electron temperatures, this $\tilde{T}_i$ value depends on the wavelength range which is used for the Voigt function fit, but its deviation from the Bely-Dubau result vanishes with increasing electron temperature. In fact, a Voigt function fit to only the data on the short-wavelength side of the resonance line gave practically the same ion temperatures as a Bely-Dubau fit. If, on the other hand, the Voigt function fit was extended to the half maximum on the long-wavelength side of the apparent resonance line, the deviation of the $\tilde{T}_i$ value from the Bely-Dubau result was 28% for the $T_e = 0.9$ keV case but less than 15% for electron temperatures in excess of 1.2 keV. This result is of practical interest because a fit with the theoretical predictions of Bely-Dubau, Gabriel, and Volonté,[7] which requires a special computer program, is not absolutely necessary for ion-temperature measurements. Since the features A, B, and $d13$ are well described by the theory,[7] it is very likely that the predictions for the $n = 4-11$ satellites are also

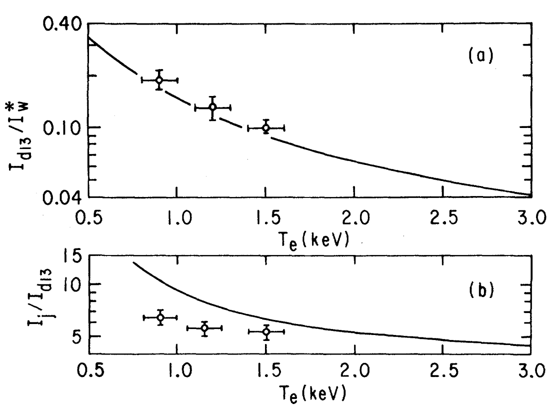

FIG. 2. (a) Intensity ratio of the satellite $d13$ and the apparent resonance line (structure in the wavelength range from 1.8480 and 1.8510 Å) vs electron temperature. (b) Intensity ratio of the dielectronic satellites j and $d13$ vs T_e. The solid lines represent the theoretical predictions of Bely-Dubau, Gabriel, and Volonté (Ref. 7).

TABLE II. Line intensities relative to the intensity (I_w^*) of the apparent resonance line (structure in the wavelength range from 1.8480 to 1.8510 Å). The values in columns (a), (b), and (c) were obtained from the spectra in Figs. 1(a), 1(b), and 1(c), respectively. Also listed are the ratios for the true and apparent resonance line (I_w/I_w^*) which have been deduced from the fit of the theoretical predictions of Bely-Dubau, Gabriel, and Volonté (Ref. 7) to the experimental data [Fig. 1(d)].

	(a)	(b)	(c)
$\Sigma I_s/I_w^*$ [a]	0.64	0.42	0.30
I_{d13}/I_w^*	0.20	0.13	0.10
I_x/I_w^*	0.60	0.52	0.38
I_t/I_w^*	0.82	0.65	0.39
I_y/I_w^*	0.72	0.60	0.44
I_q/I_w^*	1.24	1.37	0.82
$I_{(k,r)}/I_w^*$	2.32	1.71	0.10
I_j/I_w^*	1.22	0.74	0.55
I_z/I_w^*	0.93	0.84	0.60
I_β/I_w^*	1.61	1.60	0.82
I_w/I_w^*	0.532	0.652	0.727

[a]Relative intensity of the line structure in the wavelength range from 1.8510 to 1.8540 Å (features A, B, $d13$) and the apparent resonance line.

quite reliable although we were not able to confirm this. The Doppler ion temperatures are in reasonable agreement with the results from charge-exchange measurements.

In conclusion, the experimental results can be considered as a verification of the theory of Bely-Dubau, Gabriel, and Volonté[7] for the dielectronic satellites with $n \geq 3$ of the resonance line of heliumlike iron (Fe XXV). The theory predicts a significant broadening for the resonance lines of high-Z heliumlike ions in high-temperature plasmas on the basis of the fact that the $n \geq 3$ satellites are partially blended with the resonance line. Corrections for the additional broadening of the Fe XXV resonance line can be made quite accurately so that this line can be used for ion-temperature diagnostics even at low electron temperatures. Small deviations from the theoretical predictions[10] are observed for the intensity ratio of the dielectronic satellites j and $d13$. The results should be of interest for the interpretation of recently observed dielectronic satellite spectra of Fe XXV from solar flares.[2-4]

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