Master

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

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ABSTRACT

$(1s^2 n\ell - 1s2pn\ell,\ n \geq 3)$ dielectronic satellites of the resonance line of Fe XXV at 1.85 Å have been observed from PLT (Princeton Large Torus) tokamak discharges and are used for a detailed comparison with theory. The necessary corrections for Doppler broadening measurements are discussed, and accurate satellite to resonance line ratios allowing for a determination of the total dielectronic recombination rate of Fe XXV are derived.

The resonance lines of the heliumlike ions of iron (Fe XXV) and titanium (Ti XXI), and their associated satellites which are due to transitions of the type $1s^2n\ell$ - $1s2pn\ell$ with $n \geq 2$ have been observed in hot plasmas and have been used to diagnose solar flares[1] and tokamak discharges.[2-4] These diagnostic applications include measurements of the electron temperature (T_e) and the ionization equilibrium from satellite to resonance line ratios, as well as determination of the ion temperature (T_i) from Doppler broadening. In particular, the ion temperature determination is of vital importance for the diagnostic of tokamak discharges.[2]

In a recent paper[5] Bely-Dubau <u>et al</u>. presented an improved theory of the dielectronic satellite spectrum of Fe XXV including ($1s^2n\ell$ - $1s2pn\ell$) satellites with n = 3-11. Since most of these satellites fall into the narrow wavelength range from 1.8480 to 1.8540 Å and are partially blended with the resonance line, they can cause a significant increase of the apparent intensity and width of the resonance line which must be taken into account for evaluation of satellite to resonance line ratios as well as for Doppler broadening measurements. It is the purpose of this paper to give a detailed comparison between experiment and theory in order to establish a solid base for diagnostic applications.

Figures 1a, b, and c show satellite spectra of Fe XXV for electron temperatures of 0.9, 1.2, and 1.5 keV, respectively. In this temperature range the dielectronic satellites are a most prominent spectral feature. The data were recorded from PLT (Princeton Large Torus) tokamak discharges during the period (250 ms) of steady-state conditions with use of a high resolution ($\lambda/\Delta\lambda$ = 15000 at λ = 1.8500 Å) Bragg curved crystal spectrometer and were accumulated over typically 20-30 discharges with identical parameters in order to reduce the statistical error. The details of the experimental arrangement have been described earlier.[2,3] The spectra in Figures 1b and c were recorded from ohmically heated discharges, whereas the spectrum in Fig. 1a was observed from a discharge with auxiliary ion cyclotron heating. Radial profiles of the electron temperature and density were obtained from laser Thomson scattering.[6] The spectra have been corrected for constant background ($\approx 10^6$ photon counts/Å) and small periodic variations of the detector efficiency which are due to the finite spacing (1 mm) of the cathode wires in the multiwire proportional counter. The period of these detector-efficiency oscillations is smaller than the Doppler width of the observed spectral lines, and therefore this correction does not impair the accuracy of the results. The solid curves represent theoretical predictions[5] for the line structure in the wavelength range from 1.8480 to 1.8540 Å, and in the wavelength range from 1.8540 to 1.8730 Å, least squares fits of Voigt functions to the experimental data.

The spectral lines have been identified using the notation of Gabriel[7] and Bely-Dubau <u>et al</u>.[5] The features in the wavelength range from 1.8540 to 1.8730 Å have been discussed in an earlier paper.[3] They represent the intercombination (x, y) and forbidden (z) lines of Fe XXV, the lithiumlike n = 2 satellites t, q, (k,r), and j, and the berylliumlike line β. Of most interest is the line structure in the vicinity of the resonance line at 1.85 Å.

on an expanded scale Figure 1d shows the experimental data in the wavelength range from 1.8480 to 1.8540 Å for the spectrum of Fig. 1b. The theoretical line structure (curve I) has been decomposed according to Bely-Dubau et al.[5] into contribution from the heliumlike resonance line (w) and the dielectronic satellites with n = 3-11 (curve II). According to Ref. 5, the relative intensity of the n = 3-11 satellites (curve II) and the resonance line (w) is determined only by the electron temperature; we used the central T_e obtained from the laser scattering. The ion temperature was adjusted for a best fit to the experimental data in the considered wavelength range. To obtain agreement between observations and predictions it was necessary to increase the theoretical wavelengths for the n = 3 satellites by 0.0003 Å, which is within the theoretical error of 0.0005 Å. Table 1 lists the experimental and theoretical wavelengths for the $n \geq 3$ satellites which mainly contribute to the spectral features observed on the long wavelength side of the resonance line. d13 is a well isolated n = 3 satellite, whereas A and B are composed of several spectral lines. 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 the variation of the detector efficiency and are masked by the detector-efficiency oscillations if not properly corrected for. The accuracy in determining the shape of features A and B is not very good. However, the long wavelength wing of d13 is determined quite accurately. The variation of the intensity of n = 3 dielectronic satellites and the n = 2 dielectronic satellites, j and (k, r), with electron temperature is obvious from Fig. 1.

The value for the resonance line intensity (I_w) derived from the fit in Fig. 1a has then been used for evaluation of satellite to resonance line ratios (I_s/I_w). These are listed in Table 2. The relative intensity of the dielectronic satellites j and d13 is a function of T_e alone and can be used as an electron temperature diagnostic. Values of 1.020 and 0.840 keV, respectively, have been obtained from the relative satellite line intensities, I_j/I_w and I_{d13}/I_w, of the spectrum in Fig. 1a; these are in excellent agreement with the central values of the electron temperature profile observed by laser scattering shown in Fig. 2. This can be considered as an experimental proof of the theory of Ref. 5.

We have also investigated the effect of the presence of unresolved $n \geq 3$ satellites on the apparent profile of the resonance line, which is important for Doppler broadening measurements. Table 3 compares ion temperatures ($T_i^{(1)}$, $T_i^{(2)}$, $T_i^{(3)}$) obtained from various fits to the observed line profiles of Figs. 1a, b, and c. The ion temperature results ($T_i^{(1)}$) were determined from a fit of the theoretical predictions[5] (curve I) to the observed line structure. The $T_i^{(2)}$- and $T_i^{(3)}$- values were obtained from the fits of a Voigt function to the data on the short wavelength side in the range from 1.8490 to 1.8501 Å, and the data in the wider range from 1.8490 to 1.8508 Å, respectively. The difference between the $T_i^{(2)}$- and $T_i^{(3)}$- values, which is obviously due to the asymmetry of the apparent resonance line profile, becomes less pronounced with increasing electron temperature. The results from Table 3 can be summarized in the following way: Clearly, a fit using the theory of Bely-Dubau et al. gives the correct result. In case that such a fit is not available a Voigt function fit can be performed to the wing on the short wavelength side which gives practically identical results. Even if the Voigt function fit is extended beyond the half maximum on the long wavelength side, one obtains results which agree within 15% with the correct ion temperature for electron temperatures above 1.2 keV. The Doppler ion temperatures are in reasonable agreement with the results from charge exchange measurements.

The dielectronic recombination rate (R_d) associated with 1s - 2p transitions is proportional to the relative intensity of all dielectronic satellites,

$$R_d = C(T_e) \sum I_s/I_w \quad ,$$

where $C(T_e)$ is the collisional excitation rate for the 1s - 2p resonance transition.[5] This represents 90% of the total recombination rate of Fe XXV.[5] $\sum I_s/I_w$ has been determined from the intensity ratios in Table 2, incorporating a correction of the n = 2 satellite t and r for intensity contribution from collisional excitation.[7,8] The resulting dielectronic recombination rate is shown in Fig. 3 as a function of T_e. Also included are results obtained from spectra presented in our previous paper.[3] The error bars shown in Fig. 3 result from the experimental error for T_e as determined from dielectronic satellite to resonance line ratios and independent electron temperature diagnostics.[6,9] The agreement with the theoretical prediction[5] (solid curve) is excellent.

Discrepancies between experiment and theory still exist for the satellite to resonance line ratios of the lithiumlike satellite q and the heliumlike lines x, y, z. (These lines are not produced by dielectronic recombination.) The experimental values for I_q/I_w, which is proportional to the relative abundance $n_{Fe\ XXIV}/n_{Fe\ XXV}$, are larger than predicted for coronal equilibrium.[10] These deviations are observed to depend on the electron density and may be explained by radial transport of Fe XXV ions.[4] The intensity of the heliumlike intercombination (x, y) and forbidden (z) lines relative to the resonance line (w) is observed to vary with electron temperature, contrary to theoretical predictions. Also the intensities are larger than expected.[11]

In conclusion, dielectronic satellite spectra of Fe XXV have been observed from PLT tokamak discharges for central electron temperatures in the range from 0.9 to 1.5 keV, where the process of dielectronic recombination is the dominant mechanism of line excitation. The experimental results permitted a detailed comparison with the predictions for $n \geq 3$ satellites in the immediate neighborhood of the resonance line and can be considered as an experimental verification of the theory of Bely-Dubau et al.[5] Corrections for the additional broadening of the resonance line due to dielectronic satellites with $n \geq 3$ can, therefore, be made quite accurately, so that this line can be used for ion temperature diagnostics even at low electron temperatures. The intensity ratios of the satellite lines and the true resonance line have been determined and have been used to deduce the part of the dielectronic recombination rate, which is associated with the

1s-2p transition. Discrepencies between experiment and theory exist for the intensity (relative to the resonance line) of spectral lines which are not excited by dielectronic recombination. These include the helium-like intercombination and forbidden lines and the lithium-like satellite q. The observed intensity ratios should be useful for current theoretical work on excitation rates and the ionization equilibrium in tokamak discharges.

Acknowledgment

We gratefully acknowledge discussions with F. Bely-Dubau, A. H. Gabriel, J. Dubau, and S. Volonté. We also gratefully acknowledge the assistance of J. Gorman and J. Boychuk in the construction of the device, A. Greenberger and R. Persons for interfacing the pulse-height analyzer, the data acquisition group under F. Seibel for analysis and display software, the PLT support staff under W. Mycock, and the PLT research staff for support and discussions.

This work was supported by U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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[11]It has been suggested by J. Dubau (private communication) that the forbidden line might also be excited by inner-shell ionization of Fe XXIV ions.

TABLE CAPTIONS

Table 1. Experimental and theoretical[5] wavelengths for the observed spectral features A, B, and d13.

Table 2. Satellite to resonance line ratios and relative abundances of Fe XXIV and Fe XXV. The experimental values in column (a), (b), and (c) were obtained from the spectra in Fig. 1a, b, and c respectively.

Table 3. Ion temperature results obtained from various fits to the apparent resonance line profiles in Figs. 1a, b and c. $T_i^{(1)}$ has been determined from a fit of the theoretical predictions of Bely-Dubau *et al.*[5] to the observed line structure. $T_i^{(2)}$ and $T_i^{(3)}$ were obtained from a Voigt function fit to the data in the range from 1.8490 to 1.8501 Å, and the data in the range from 1.8490 to 1.8508 Å, respectively.

FIGURE CAPTIONS

Figure 1. Dielectronic satellite spectrum of Fe XXV. (a,b,c) Spectra obtained for central electron temperatures of 0.9, 1.2 and 1.5 keV, and central electron densities of 9 and 3×10^{13} cm^{-3}, respectively. (d) Experimental data of spectrum (b) near 1.8500 Å, and predicted[5] line structure (curve I) decomposed into resonance line (w) and contributions from satellites with n = 3-11 (curve II).

Figure 2. Electron temperature profile obtained from laser Thomson scattering during observation of the Fe XXV satellite spectrum shown in Fig. 1a.

Figure 3. Experimental results and predictions[5] for the dielectronic recombination rate, Rd, as a function of T_e.

TABLE 1

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

TABLE 2

	OBSERVED RELATIVE LINE INTENSITIES		
	(a)	(b)	(c)
$\Sigma^* I_s/I_w$	1.95	1.14	0.80
I_{d13}/I_w	0.37	0.20	0.14
I_x/I_w	1.12	0.79	0.52
I_t/I_w	1.54	1.00	0.53
I_y/I_w	1.36	0.92	0.60
I_q/I_w	2.32	2.10	1.13
$n_{Fe\ XXIV}/n_{Fe\ XXV}$	3.0** (2.3)***	2.8** (0.9)***	1.5** (0.5)***
$I_{(k,r)}/I_w$	4.36	2.62	1.39
I_j/I_w	2.30	1.14	0.75
I_z/I_w	1.74	1.29	0.83
I_β/I_w	3.03	2.45	1.12

*Relative intensity of dielectronic satellites with $n = 3$-11 in the wavelength range from 1.8480 to 1.8540 Å

**Deduced from the observed intensity ratio I_q/I_w.

***Predicted for coronal equilibrium.

TABLE 3

	Ion Temperature Results		
	$T_i^{(1)}$ (keV)	$T_i^{(2)}$ (keV)	$T_i^{(3)}$ (keV)
(a)	1.4	1.51	1.78
(b)	1.1	1.03	1.22
(c)	1.0	.96	1.24

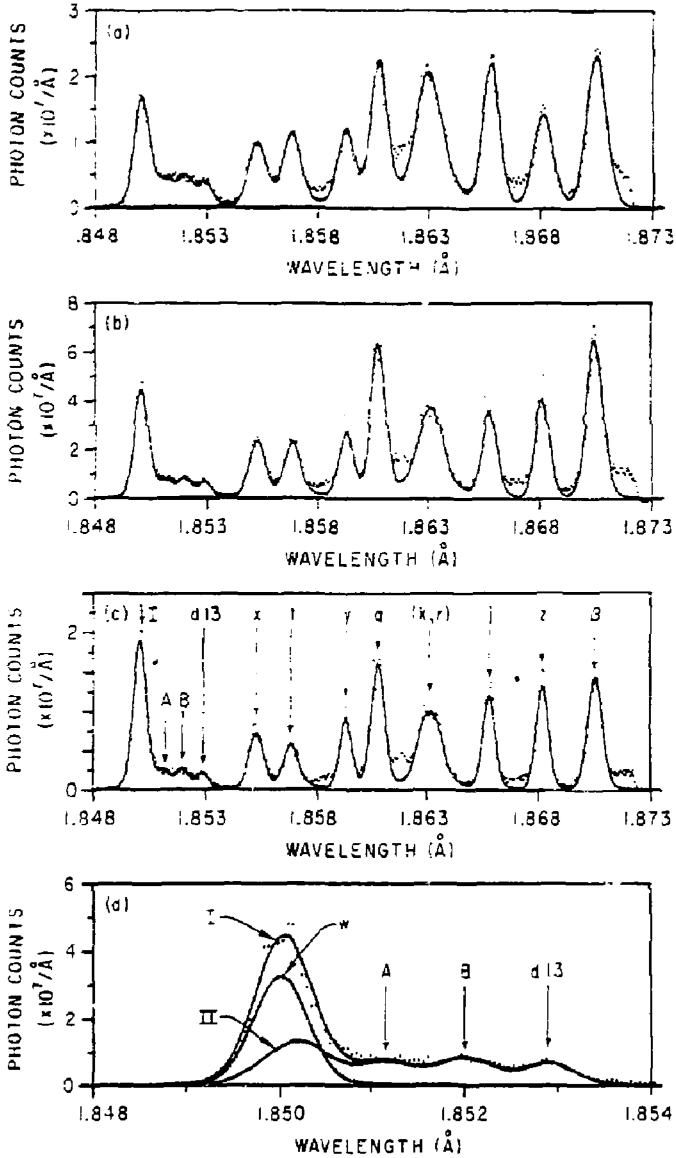

Fig. 1. (PPPL-806549)

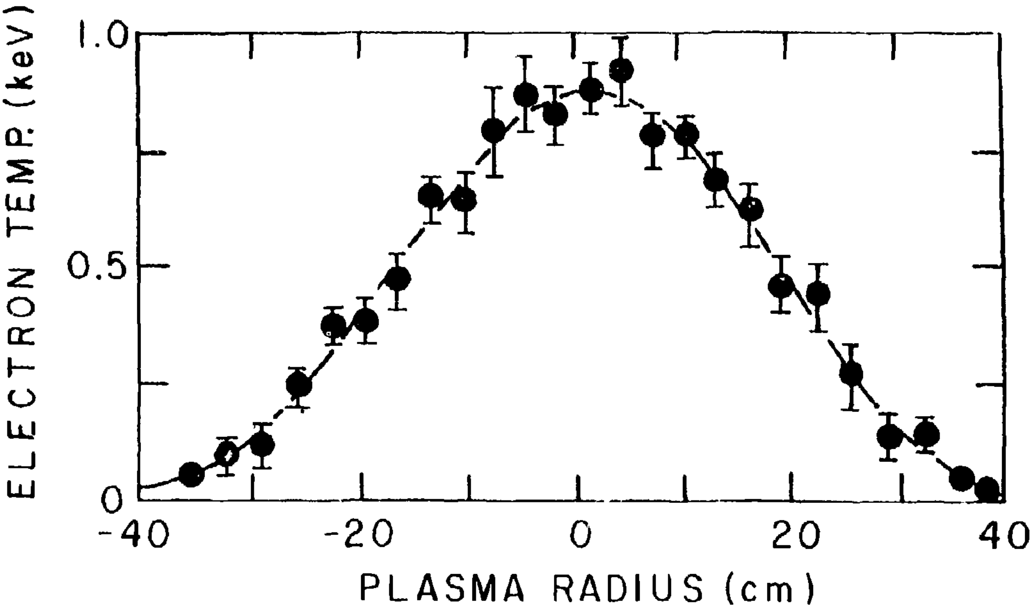

Fig. 2. (PPPL-809146)

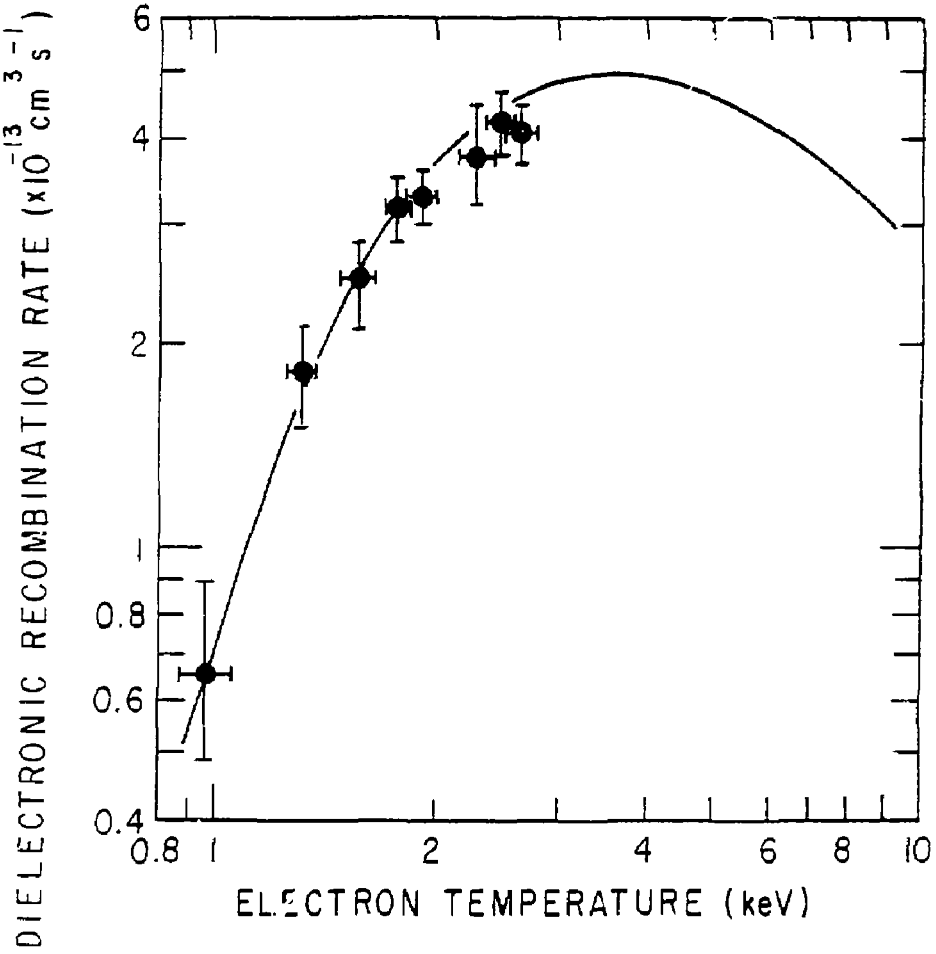

Fig. 3. (PPPL-809145)