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Dielectronic Satellite Spectrum of Helium like Iron (Fe XXV)

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ABSTRACT

Dielectronic satellite spectra of Fe XXV near 1.8500 Å have been observed from PLT (Princeton Large Torus) tokamak plasma discharges for electron temperatures in the range from 1.5 to 3 keV and an electron density of 2×10^{13} cm^{-3}. The electron temperature was independently determined from the electron cyclotron radiation emitted by the plasma. The quality of the spectra allows a detailed comparison with theoretical predictions, which is of importance in view of diagnostic applications.

The spectra of helium-like ions, which can be observed in stellar and laboratory plasmas, show in addition to the characteristic helium lines, a series of satellites due to transitions of the type $1s^2n\ell$ - $1s2pn\ell$ with $n \geq 2$. These lithium-like configurations are almost entirely formed by dielectronic recombination, the inverse process of autoionization. Exceptions are the $1s^22s$ - $1s2p2s$ satellites, which can also be produced by collisional inner shell excitation.[1,2]

In addition to providing information on fundamental aspects of atomic physics, the spectra of helium-like ions have important diagnostic applications. These include measurement of the electron temperature (T_e) and determination of the departure from ionization equilibrium using the intensity of appropriate satellites relative to the intensity of the helium-like resonance line. In a recent experiment[3] the resonance line of Fe XXV has also been used for Doppler-broadening measurements to determine the ion temperature (T_i) in the hot central core of PLT (Princeton Large Torus) tokamak plasma discharges.

A theory of the satellite spectrum of helium-like ions has been given by Gabriel[1] and Bhalla et al.[2] who performed wavelength and intensity calculations for the well resolved n = 2 satellites. In preparation for the Solar Maximum Mission orbiting flare study during 1979/80, the theory of the satellite spectrum of Fe XXV has recently been improved to include dielectronic satellites with n = 3-11.[4] Most of these satellites fall into the narrow wavelength range of 1.8500 ± 0.0010 Å and cannot be resolved from the helium-like resonance line. This leads to an apparent intensity increase of the resonance line, which must be taken into account for a correct evaluation of intensity ratios.

Experimental data on highly ionized high atomic number (Z) ions are rare due to the experimental difficulties of producing suitable high temperature plasma sources. Spectra of the high charge states of iron have been obtained from experiments on high current sparks[5,6] and earlier observations of solar flares[7] from the Intercosmos IV satellite. The quality of these spectra is, however, insufficient for a detailed comparison with theory.

In this paper we present measurements of the Fe XXV satellite spectrum from a well diagnosed iron seeded hydrogen tokamak plasma of large enough volume to significantly reduce effects of convective losses. The experiments were performed on PLT using a high resolution ($\lambda/\Delta\lambda$ = 15000 at 1.8500 Å) Bragg curved crystal spectrometer, which permits simultaneous measurement of all spectral lines in the wavelength range from 1.8480 to 1.8720 Å. The details of the spectrometer and the experimental arrangement have been described earlier.[3] The spectra were recorded from ohmically heated plasma discharges of electron temperatures in the range from 1.5 to 3 keV and an electron density of 2×10^{13} cm^{-3}, which is well below the threshold for collisional de-excitation.[1] The experimental results are, therefore, comparable with those expected from the solar corona. The reproducibility of the PLT discharges permitted us to record spectra with small statistical error and sufficient resolution for a detailed comparison with the most recent theoretical predictions.[4]

Figure 1 and Figures 2a-d show satellite spectra of Fe XXV obtained for central electron temperatures of 1.65, 1.80, 2.10, 2.30, and 2.45 keV, respectively. The electron temperature was determined from the electron-cyclotron radiation emitted by the plasma.[8] The raw data for each of these spectra were recorded during a period of 250 msec of a PLT discharge pulse when the electron temperature was constant (steady state conditions) and were accumulated over typically 10 discharges with identical parameters. The quality of the experimental data allowed determination of the position, intensity, and width of the spectral lines from a least squares fit of Voigt functions.[9] In order to determine these line parameters with minimum error, it was necessary to fit groups of usually two neighboring peaks simultaneously. An exception is the well isolated resonance line w, which was fitted as a single peak. The most prominent peaks have been identified as the helium-like lines w, x, y, and z, the lithium-like n = 2 satellites t, q, (k,r), and j, and the beryllium-like line β. The key letters used for line identification are explained in Table 1 and agree with Gabriel's notation.[1] The strong features of the collisionally excited satellite q, and the helium-like intercombination (x,y), and forbidden (z) lines are expected for high-Z ions, like iron, because of the breakdown of L-S coupling. As is most obvious from Figure 1, the spectra also show a fine line structure between some of the most prominent peaks and on the long wavelength side of the resonance line w. This structure disappears with increasing electron temperature and is ascribed to weak n=2 satellites, such as a, and to n = 3 satellites, respectively.

Experimental and theoretical wavelengths are listed in Table I for comparison. For most of the lines the agreement is within the estimated error of 0.0005 Å of the theoretical calculations.[2] The experimental accuracy is 0.0001 Å. As expected,[2] the experimental results for the helium-like lines x, y, and z agree better with the wavelength calculations of Ermolaev et al.[10] than with those of Gabriel.[1]

Figures 3a-d show the observed intensities of the lines j, x, y, z, q, β relative to that of the resonance line w for the experimental values of T_e. The relative intensity of the satellite j is a function of T_e alone and can, in principle, be used as a diagnostic of the electron temperature.[2] Figure 3a presents *the experimental results for* I_j/I_w *together with predictions of* the earlier theory[1,2] (solid curve) and the new theory[4] (dashed curve) which takes into account the apparent intensity increase, $\Delta I_w = \alpha(T_e)I_w$, of the resonance line due to unresolved dielectronic satellites with $n \geq 3$. The experimental results are very close to the most recent predictions.[4] The agreement may be further improved by taking the value of the oscillator strength f_w, which has been considered as an adjustable parameter,[1] to be 0.6 instead of 0.55 which was used for the predictions.

Figure 3b shows the observed relative intensities for the intercombination (x,y) and forbidden (z) lines. For comparison, the relative intensity predictions at T_e = 2.7 keV are 0.35, 0.25, and 0.41 for x, y, and z, respectively.[14]

Figures 3c,d show the observed intensity ratios for the collisionally excited satellites q and β.[15] The intensity ratios,

$\frac{I_q}{I_w}$ and $\frac{I_\beta}{I_w}$ are proportional to the abundances of Fe XXIV and Fe XXIII relative to Fe XXV and can be used for determination of the charge-state distribution.[2] Interpretation of the results requires knowledge of the equilibrium distribution. Shown are predictions based on the coronal equilibrium calculations of Jordan[11] (curve 1) and Summers[12] (curve 2). The observed discrepancies of the various predictions and the experimental results indicate that the theoretical model for the ionization equilibrium of a tokamak plasma or for the excitation rates needs improvement.

Further experimental evidence of unresolved dielectronic satellites is obtained from an investigation of the resonance line w. Figures 4a,b,c present on an expanded scale part of the spectrum of Figure 1 and Figures 2a,b, respectively. The experimental points have been connected by solid curves to accentuate an internal line structure indicated by the raw data. Both the internal structure and the well resolved dielectronic n = 3 satellites on the long wavelength side of the resonance line disappear with increasing electron temperature. This suggests that the internal structure is also due to dielectronic satellites. It seems that the internal structure also contributes to the line broadening. The apparent T_i values obtained from Voigt-function fits to the line profiles in Figures 4a,b,c are 1395, 1326, and 1260 eV, respectively.

In conclusion, high resolution satellite spectra of Fe XXV have been obtained from tokamak discharges during the period of steady state conditions. The quality of the spectra and independent electron temperature measurements have permitted the first detailed comparison with theory. This comparison is important because theories for high Z ions, like iron, depend on accurate calculations of the autoionization and collisional inner shell excitation rates, which are complicated due to the breakdown of L-S coupling. The relative intensities of the $n = 2$ dielectronic satellites are in good agreement with the most recent theory. The relative intensity of the satellite j can thus be used as a reliable electron-temperature diagnostic. At low electron temperatures a small correction to the values of T_i determined from Doppler broadening of the resonance line is required because of the excitation of unresolved satellites. With regard to the collisionally excited satellites q and β the observations are in disagreement with various predictions based on coronal equilibrium. Improvements should be made to the theory of the ionization balance of iron. For the case of tokamak plasmas, effects due to radial impurity transport should be included in calculations of the ionization balance. These results show the importance of the dielectronic Fe XXV satellite spectrum for diagnostic applications to fusion and astrophysical plasmas and should stimulate further theoretical investigations.

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[15]It has been suggested by Gabriel that dielectronic recombination from FeXXIV and inner shell ionization of FeXXII might also contribute to excitation of line β.

TABLE I

Key	Transition	λ exp. (Å)	λth[1] (Å)	λth[10] Å
w	$1s^2(^1S_o) - 1s2p(^1P^o_1)$	1.8500	1.8500	1.84992
x	$1_s{}^2(^1S_o) - 1s2p(^3P^o_2)$	1.8553	1.8551	1.85519
t	$1s^22s(^2S_{1/2}) - 1s2p(^3P)2s(^2P^o_{1/2})$	1.8568	1.8570	
y	$1s^2(^1S_o) - 1s2p(^3P^o_1)$	1.8595	1.8591	1.85947
q	$1s^22s(^2S_{1/2}) - 1s2p(^1P)2s(^2P^o_{3/2})$	1.8612	1.8604	
a	$1s^22p(^2P^o_{3/2}) - 1s2p^2(^2P_{3/2})$	1.8618	1.8618	
{k	$1s^22p(^2P^o_{1/2}) - 1s2p^2(^2D_{3/2})$	{1.8637}	1.8631	
r}	$1s^22s(^2S_{1/2}) - 1s2p(^1P)2s(^2P^o_{1/2})$		1.8635	
j	$1s^22p(^2P^o_{3/2}) - 1s2p^2(^2D_{5/2})$	1.8662	1.8657	
z	$1s^2(^1S_o) - 1s2s(^3S_1)$	1.8687	1.8677	1.86801
β	$1s^22s^2(^1S_o) - 1s2s^22p(^1P_1)$	1.8712 —		1.8710[13]

Table I. Experimental and theoretical wavelengths of the observed spectral lines. The superscripts indicate the references from which the theoretical wavelengths were taken. The experimental wavelengths were normalized to the theoretical value[1] of 1.8500 Å for the resonance line w.

FIGURE CAPTIONS

Fig. 1 Dielectronic satellite spectrum of Fe XXV as recorded by a multi-channel analyzer from PLT for a central electron temperature of 1.65 keV. The photon energy decreases with increasing channel number. The conversion gain is 0.18 eV/channel. w indicates the Fe XXV Kα-resonance line at 1.85 Å. Also shown (solid curve) is the result of a least squares fit of Voigt functions to the raw data of the most prominent peaks.

Fig. 2a-d Dielectronic satellite spectra of Fe XXV for central electron temperatures of 1.80, 2.10, 2.30, and 2.45 keV, respectively. Otherwise, the conditions are the same as for Fig. 1.

Fig. 3 Observed line intensities relative to the intensity of the resonance line w as a function of T_e.

(a) Experimental results for the dielectronic satellite j and predictions of both the earlier[1,2] (—) and most recent[4] (--) theories.

(b) Observed relative intensities of the intercombination (x,y) and forbidden (z) helium-like lines. The dashed lines were drawn to aid the eye.

(c,d) Observed relative intensity of the satellites β and q and predictions based on calculations of Jordan[11] (curve 1) and Summers[12] (curve 2).

Fig. 4a-c Expanded profiles of the resonance line w from the spectra shown in Fig. 1 and Figs. 2a,b. The solid curves have been drawn to accentuate an internal line structure, indicated by the raw data.

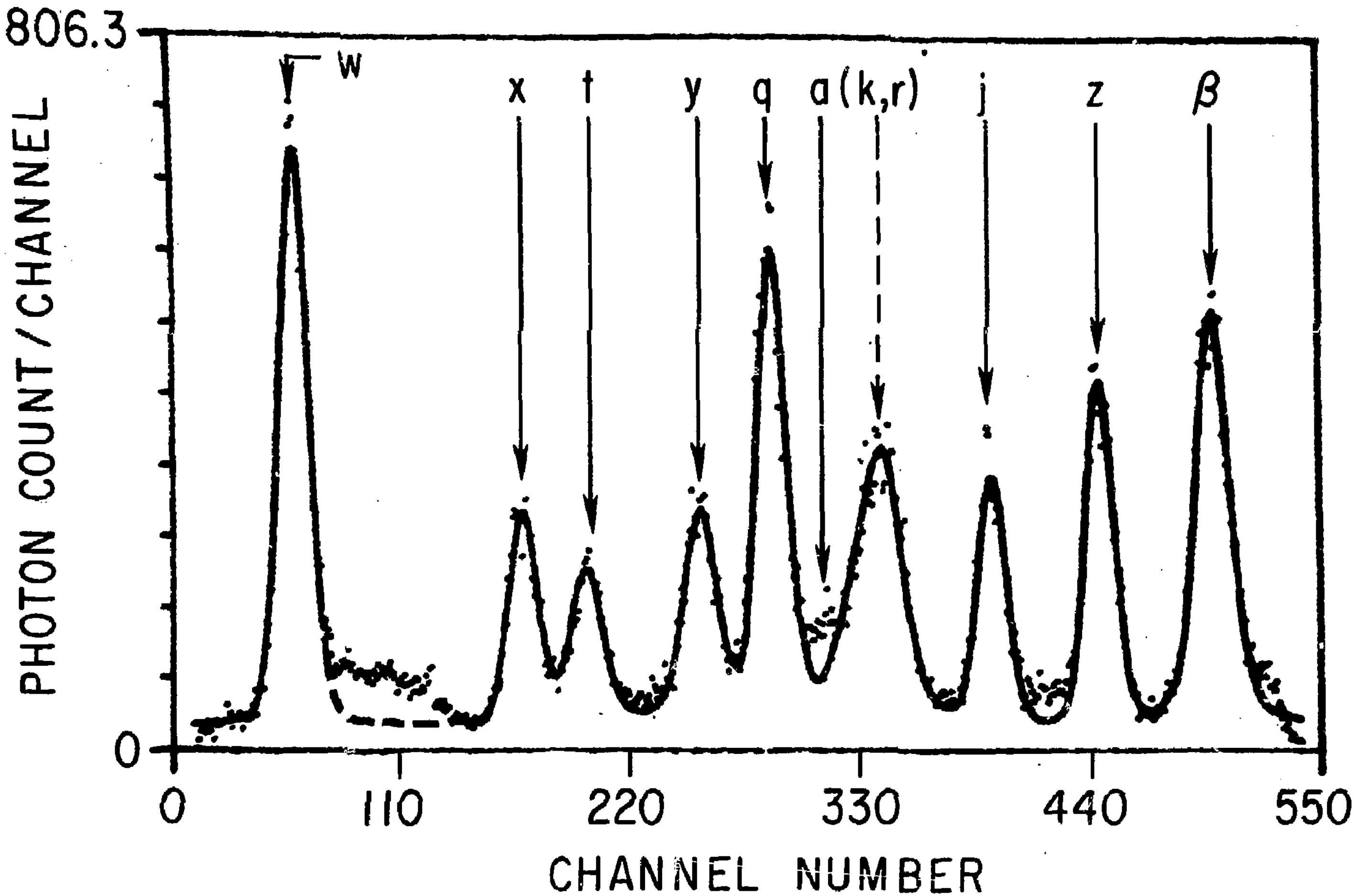
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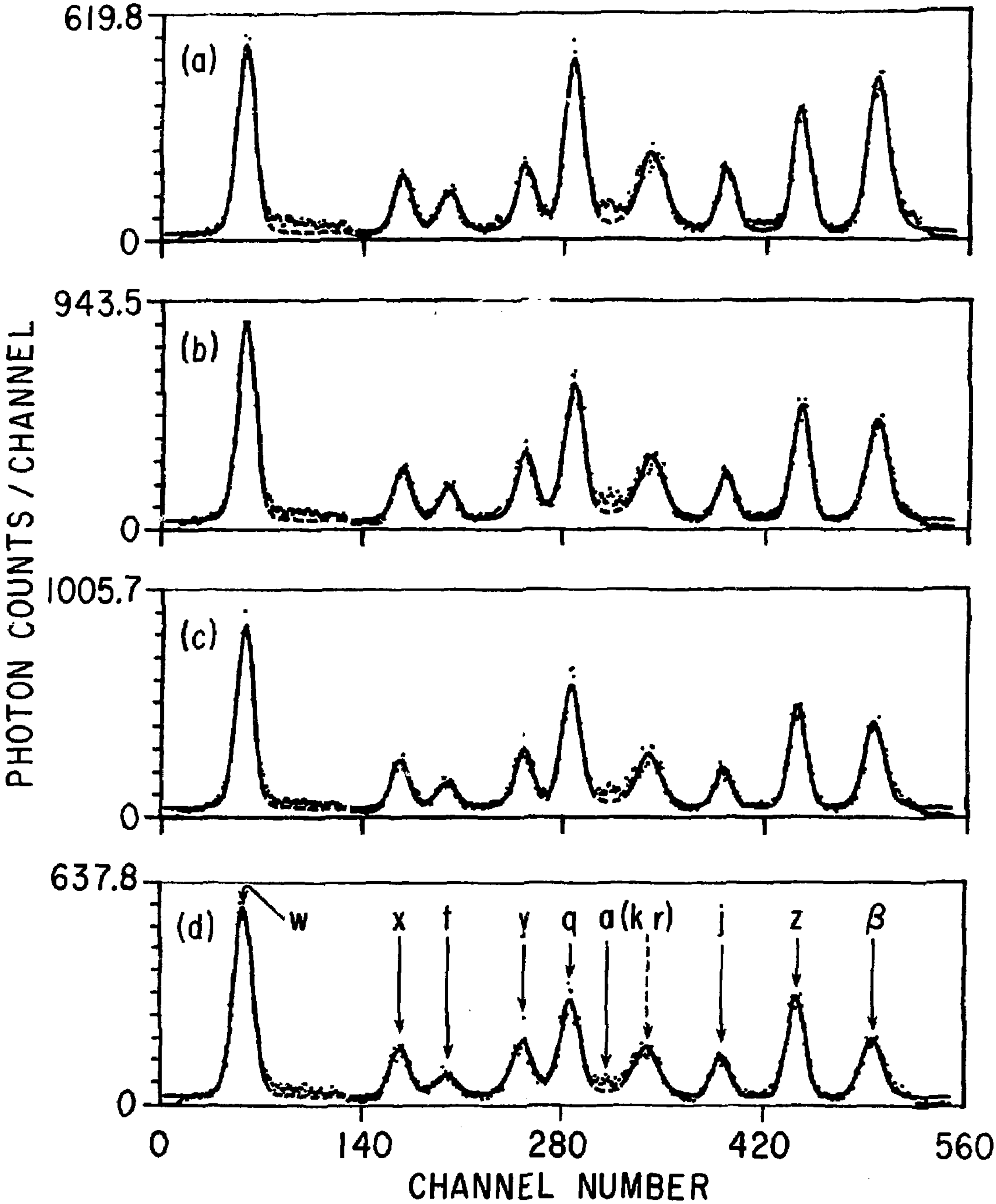
Fig. 1. 793153



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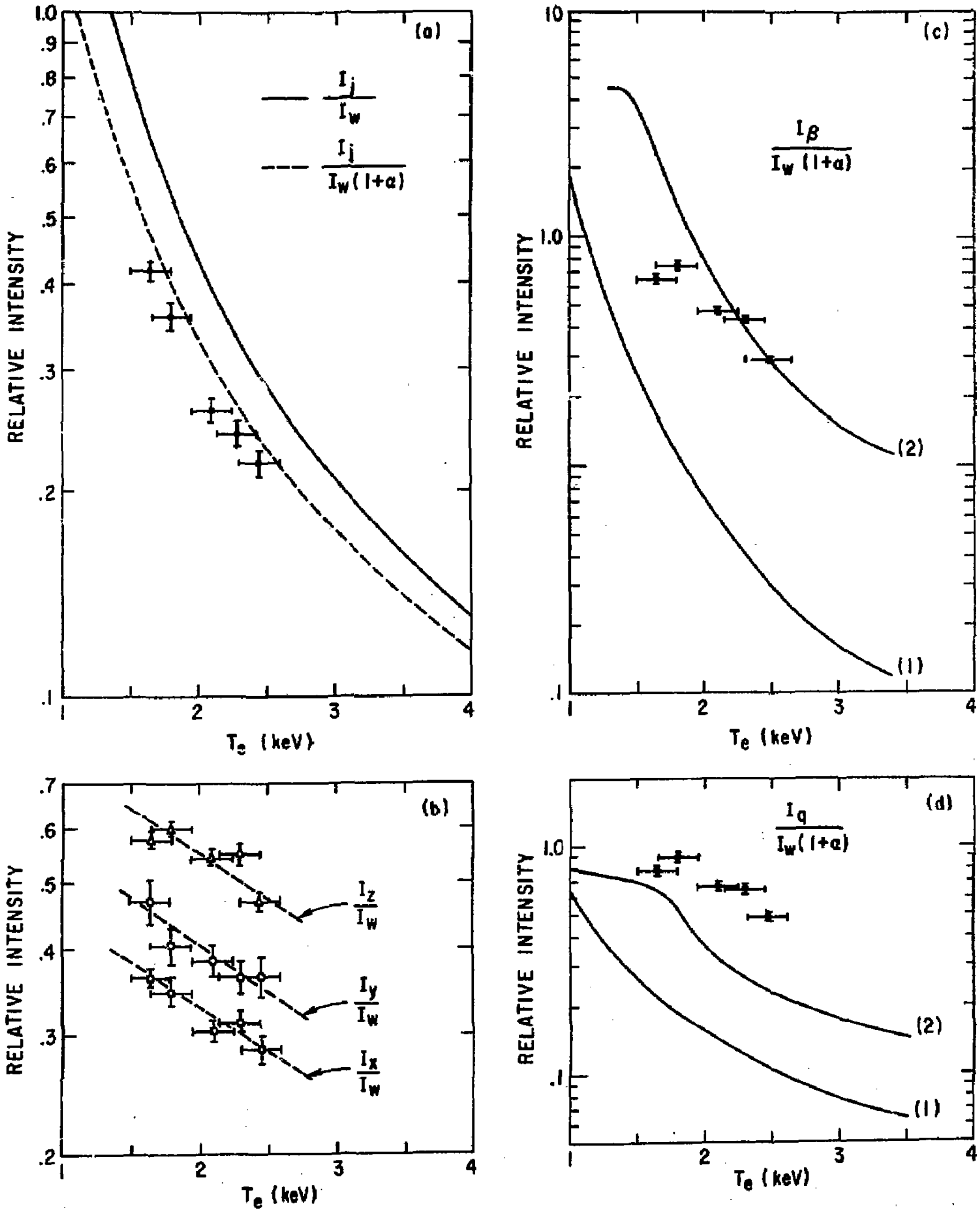

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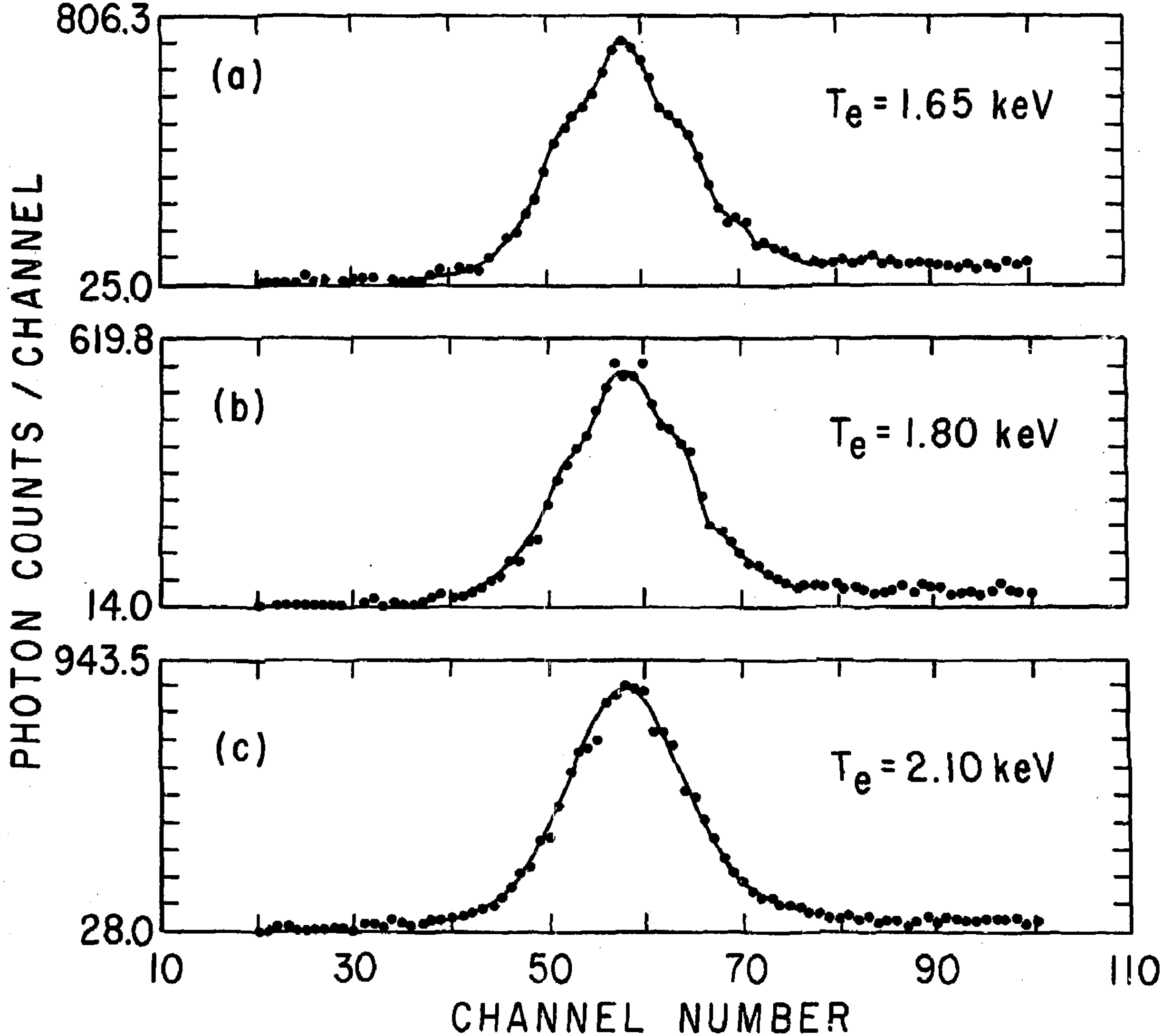

Fig. 4a-c. 793252

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