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OBSERVED MAGNETIC DIPOLE TRANSITIONS IN THE GROUND TERMS OF Ti XIV, Ti XV, AND Ti XVII

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Observed Magnetic Dipole Transitions in

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Four observed spectrum lines in titanium-containing tokamak discharges have been identified as follows: TiXIV $2s^22p^5\ ^2P_{1/2} \rightarrow {}^2P_{3/2}$ at 2115.3 Å, TiXV $2s^22p^4\ ^3P_1 \rightarrow {}^3P_2$ at 2544.8 Å, TiXVII $2s^22p^2\ ^3P_2 \rightarrow {}^3P_1$ at 3834.4 Å and ${}^3P_1 \rightarrow {}^3P_0$ at 3371.5 Å. The identifications are based on observed time behavior and correlation with intensities of resonance lines of other titanium ions, and on general agreement with predicted wavelengths and intensities.

The forbidden (magnetic dipole) transitions in the $2s^2 2p^x$ configurations of iron ions have been extensively used[1-4] for local measurements of ion temperatures, plasma rotations, and radial ion density distributions in the PLT tokamak discharges. With the increasing use of titanium gettering[5-7] for the control of plasma density behavior and the exclusive use of titanium for construction materials for parts in direct contact with plasma in the PDX (Poloidal Divertor Experiment) tokamak,[8] it is of immediate interest to establish the wavelengths and relevant transition rates for the corresponding configurations in titanium. Since the ionization potentials of Ti ions are significantly different from the isoelectronic Fe ions, the addition of titanium also affords greater selection of radial locations (i.e. regions of different local electron temperature) for the diagnostics in discharges where both elements are present.

The energy levels[9] and corresponding transitions for the TiXIV-XVIII ground configurations are shown in Fig. 1. None of these transitions have been observed before; they are deduced from differences in shorter-wavelength resonance transitions,[10-13] semi-empirical extrapolations[14,15] or numerical ab initio calculations,[16] and therefore are subject to uncertanities of at least several Ångstroms. The four wavelengths in boxes represent our observations in tokamak discharges.

The 3834.4 ± 0.2Å line of Ti XVII was observed in the PLT tokamak, and has been used (in conjunction with detailed calculations[17] of the expected relative populations resulting from collisional and radiative transitions) to determine the titanium concentration in the PDX discharges.[18] The corresponding $^3P_2$-$^3P_1$ level separation is 26072 ± 2 cm^{-1}, and the simple L-S coupling magnetic dipole transition probability, based on this energy separation, is 239 sec^{-1}.

The other three lines, TiXIV 2115.3 ± 0.5 Å, TiXV 2544.8 ± 0.5 Å and TiXVII 3371.5 ± 0.5 Å were first observed in the PDX tokamak discharges (with somewhat less accurate instrumentation). The level separations and L-S transition probabilities are, respectively, 47260 ± 12 cm^{-1} and 1898 sec^{-1} for the $^2P_{1/2}$-$^2P_{3/2}$ of TiXIV; 39284 ± 8 cm^{-1} and 1363 sec^{-1} for the $^3P_1$-$^3P_2$ of TiXV; and 29652 ± 5 cm^{-1} and 469 sec^{-1} for the $^3P_1$-$^3P_0$ transition of TiXVII. All these numerical values are within expected uncertanities of the semi-empirical extrapolations of wavelengths,[14,15] and in good agreement with the calculated transition probabilities of Kastner et al.[16]

The identifications of the transitions are based on the time-dependence of the observed lines during the tokamak discharge and their absolute intensities, both compared with the corresponding behavior of the allowed resonance lines of adjacent titanium ions, TiXVII, XIX, and XX. A specific sample of results from a PDX discharge is shown in Fig. 2 (with peak intensities normalized to the same level to facilitate comparison). The time behavior of the 3371Å and 3834Å lines is indistinguishable, as expected and the time sequence of the others is consistent with the resonance lines of TiXIX and TiXX and the expected ionization times at the known electron temperature and density. The resonance line of OVI (the dominant impurity element in the discharge), which also resembles the time behavior of potential interfering lines and straylight, is clearly easily distinguishable. Typical oscillogram traces of the three lines are shown in the insets, together with a trace of the 309 Å line of TiXX (the time scale is 50 msec/div in one oscillogram and 100 msec/div in other).

The absolute peak intensities of the four forbidden lines, and the TiXIX resonance line are given in Fig. 3a. Figure 3b shows the calculated emissivity per titanium ion in the appropriate state of ionization by Feldman et al.[17] The calculations include all collisional and radiative transitions between all n = 2 levels (i.e. $2s^2 2p^x$, $2s2p^{x+1}$, $2p^{x+2}$ configurations). The proton collisions have only a minor effect on the relative intensities. The forbidden lines are all very nearly independent of electron density (for densities above 10^{13} cm^{-3}), whereas the allowed 169 Å line is proportional to electron density (2×10^{13} cm^{-3} both in the calculations and in the experiment at the time of the 169 Å line peak. The intensities are also practically idependent of electron temperature ($\sim$ 1.2 keV at 140 msec in the experiment), except insofar as it affects the time-dependence through ionization rates.

Figures 3a and 3b would be directly comparable if 1) all the important transition rates in the calculation are correct and 2) the number of ions (of each state of ionization) along the line of sight were the same at the time of measurement (the time of peak emissivity of each line in question). Comparison of the relative intensities of the five lines are regarded as a test of the adequacy of the calculations, whereas matching of the absolute ordinates constitutes a measurement of the titanium density in the plasma.

In the experiment the plasma density was slowly rising in time between 120-200 msec, and this may account for the slight discrepancy on the relative intensities between calculations and observations. If we were to assume a constant concentration of titanium in the plasma with a absolute value of 0.2% of electron density, or about 4×10^{10} Ti atoms/cm^3 at 200 msec) the calculated and measured intensities virtually coincide. We conclude that the rate-coefficients used in the calculations[17] are adequate for determination of the ion densities from absolute line intensity measurements.

Finally, we note that the predicted λ1776 Å line of TiXVIII and most of the intercombination lines should have readily measureable intensities in titanium-seeded tokamak plasmas. The establishment of their exact wavelengths and transition rates would be of interest both for detailed plasma diagnostics and for refinement of atomic physics calculations.

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Figure Captions

Fig. 1. Energy levels and transitions in the $2s^2 2p^x$ configurations of titanium. The wavelengths in parentheses have not yet been observed. IP indicates the ionization potentials of the ions.

Fig. 2. Time behavior of titanium ion lines, and an OVI resonance line in a PDX discharge. The insets show actual oscillograms of three of the forbidden lines and the TiXIX resonance line.

Fig. 3(a). Measured absolute intensities at the time of their maxima of various titanium lines in a PDX discharge, (b) calculated emissivity per ion of the same lines, at electron temperature and density close to experimental conditions.

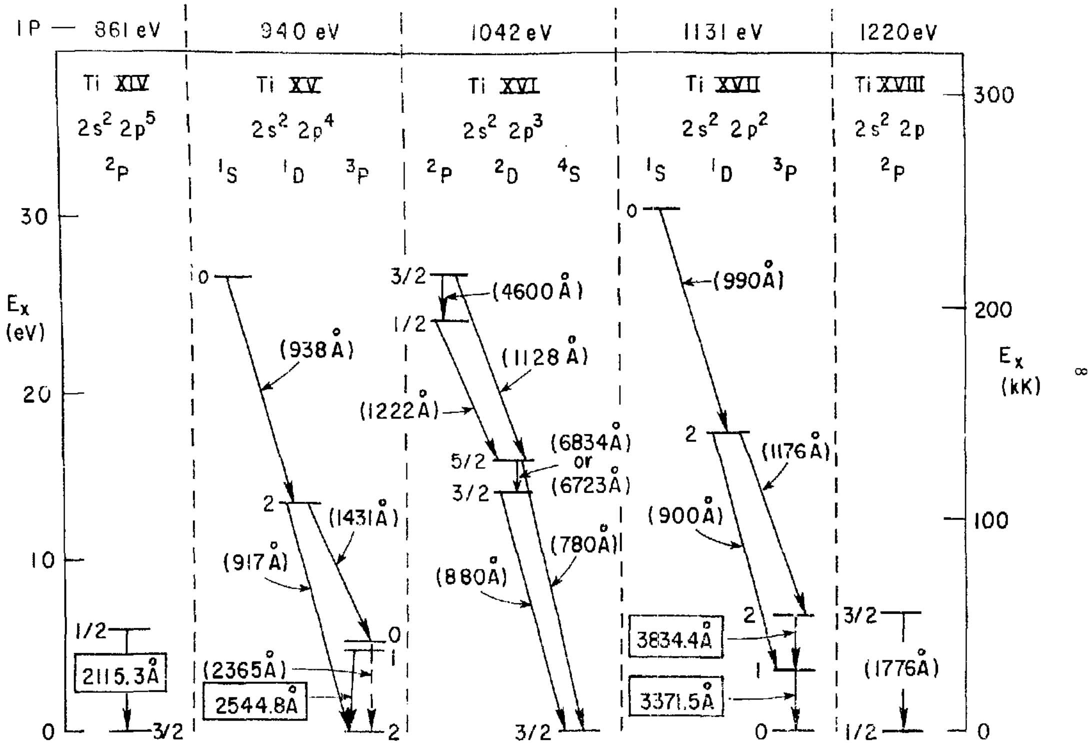
IP — 861 eV
940 eV
1042 eV
1131 eV
1220 eV
Ti XIV
2s² 2p⁵
²P
Ti XV
2s² 2p⁴
¹S ¹D ³P
Ti XVI
2s² 2p³
²P ²D ⁴S
Ti XVII
2s² 2p²
¹S ¹D ³P
Ti XVIII
2s² 2p
²P
Ex
(eV)
Ex
(kK)
(938Å)
(1431Å)
(917Å)
(2365Å)
2544.8Å
2115.3Å
(4600Å)
(1128Å)
(1222Å)
(6834Å)
or
(6723Å)
(780Å)
(880Å)
(990Å)
(1176Å)
(900Å)
3834.4Å
3371.5Å
(1776Å)
0
10
20
30
100
200
300

Fig. 1. 793582

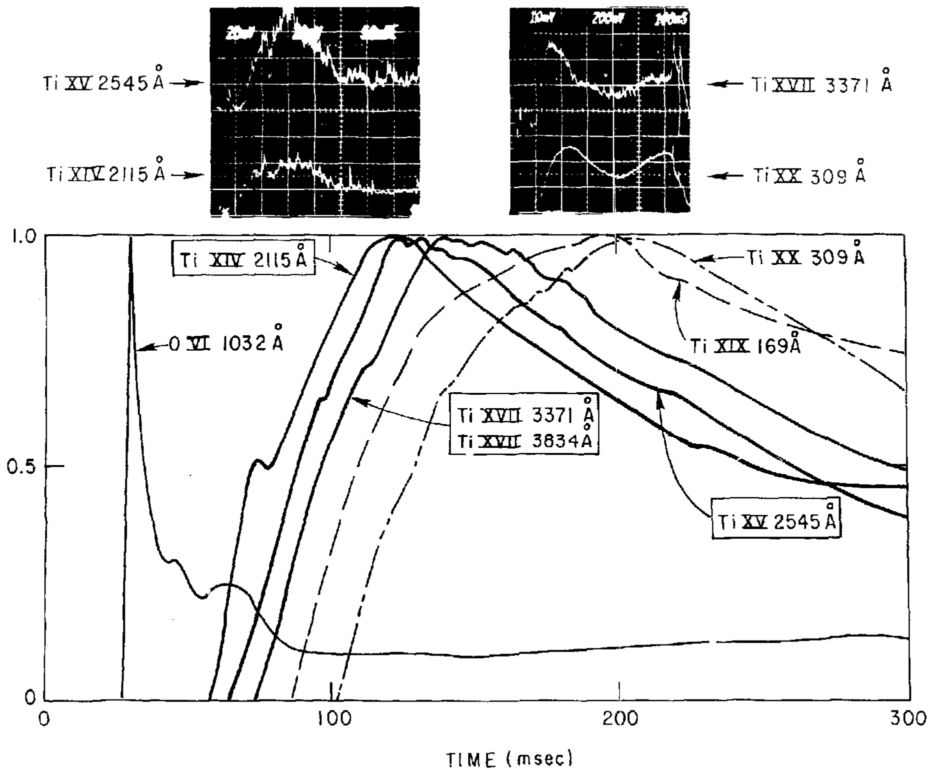
Ti XV 2545 Å
Ti XIV 2115 Å
Ti XVII 3371 Å
Ti XX 309 Å
1.0
0.5
0
Ti XIV 2115 Å
Ti XX 309 Å
O VI 1032 Å
Ti XIX 169 Å
Ti XVII 3371 Å
Ti XVII 3834 Å
Ti XV 2545 Å
0
100
200
300
TIME (msec)

Fig. 2. 793621

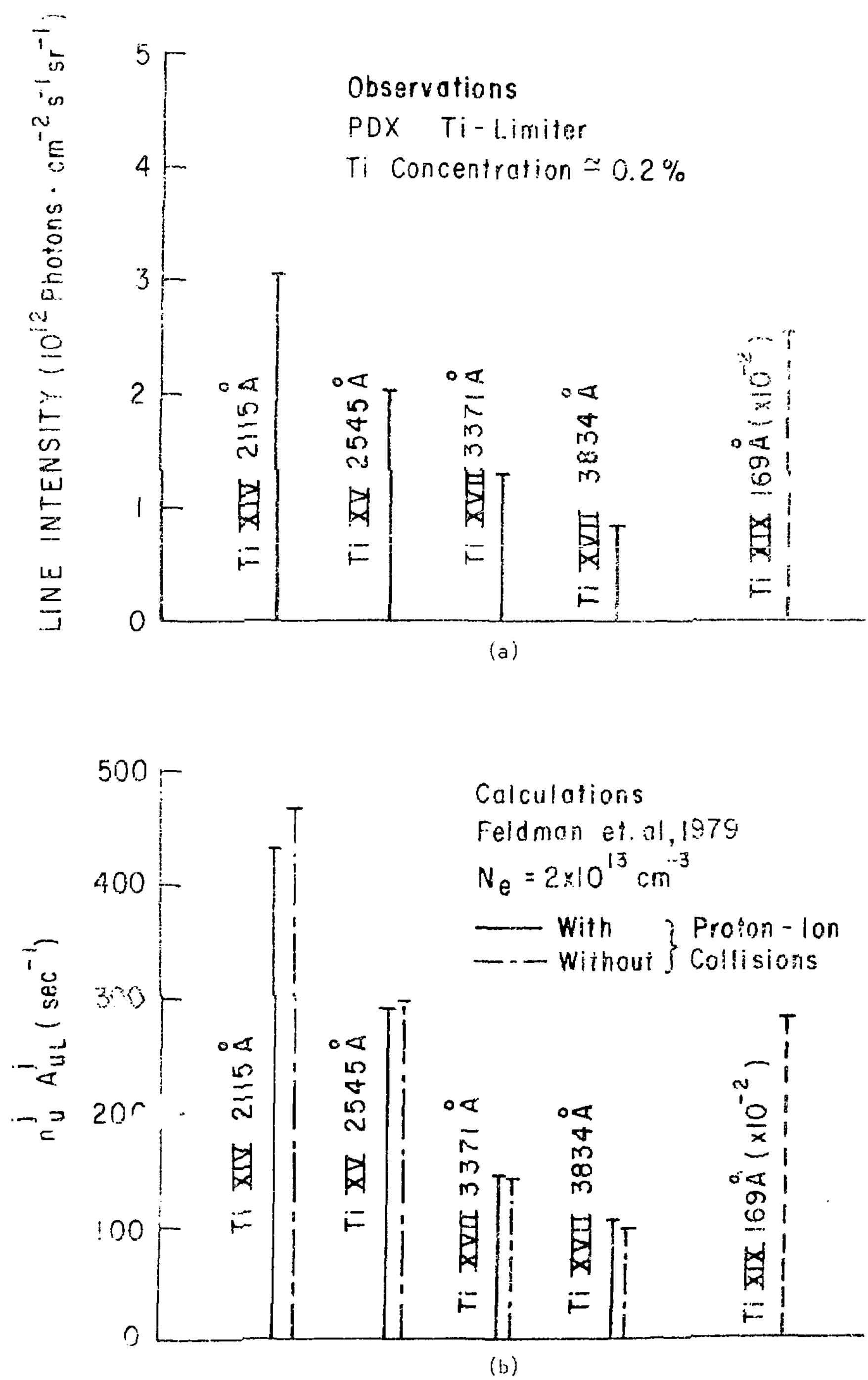
LINE INTENSITY (10^12 Photons · cm^-2 s^-1 sr^-1)
5
4
3
2
1
0
Observations
PDX Ti-Limiter
Ti Concentration ≃ 0.2 %
Ti XIV 2115 Å
Ti XV 2545 Å
Ti XVII 3371 Å
Ti XVII 3834 Å
Ti XIX 169 Å (x10^-2)
(a)
500
400
300
200
100
0
Calculations
Feldman et. al, 1979
Ne = 2x10^13 cm^-3
With
Without
Proton - Ion Collisions
Ti XIV 2115 Å
Ti XV 2545 Å
Ti XVII 3371 Å
Ti XVII 3834 Å
Ti XIX 169 Å (x10^-2)
(b)

Fig. 3. 793605