Observed magnetic dipole transitions in the ground-state terms of Ti XIV, Ti XV, and Ti XVII

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Four observed spectrum lines in titanium-containing tokamak discharges have been identified as follows: Ti XIV $2s^22p^5\ ^2P_{1/2}\to{}^2P_{3/2}$ at 2115.3 Å, Ti XV $2s^22p^4\ ^3P_1\to{}^3P_2$ at 2544.8 Å, Ti XVII $2s^22p^2\ ^3P_2\to{}^3P_1$ at 3834.4 Å and $^3P_1\to{}^3P_0$ 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 $2s^22p^x$ 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 Princeton Large Torus (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 Poloidal Divertor Experiment (PDX) 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 Ti XIV-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] semiempirical extrapolations,[14-15] or numerical *ab initio* calculations,[16] and therefore are subject to uncertainties of at least several angstroms. The four wavelengths in boxes in Fig. 1 represent our observations in tokamak discharges.

The 3834.4 ± 0.2-Å 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

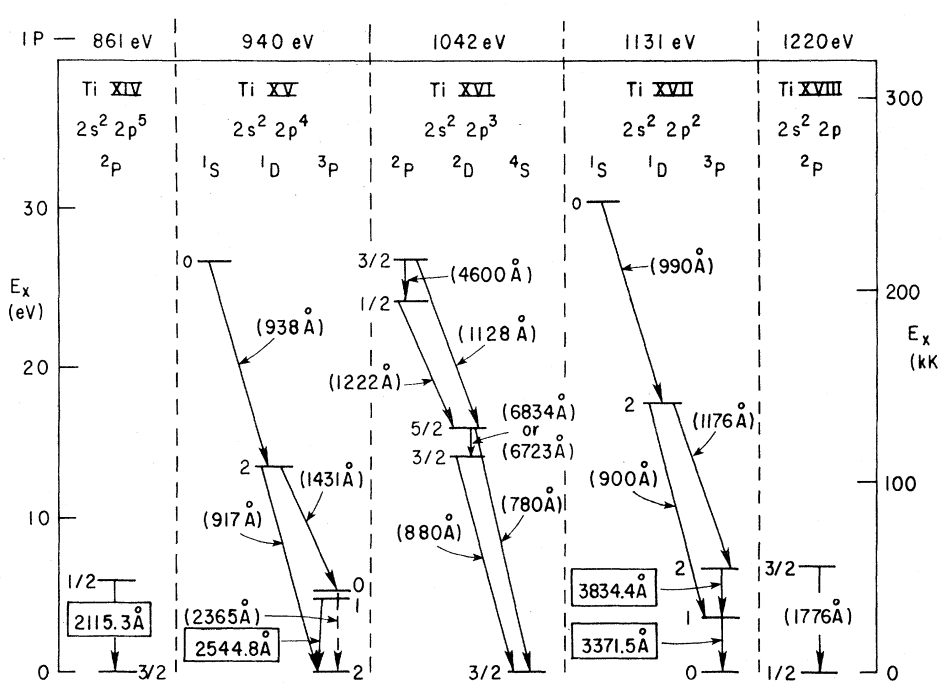

FIG. 1. Energy levels and transitions in the $2s^22p^x$ configurations of titanium. Wavelengths in parentheses have not yet been observed. IP indicates the ionization potentials of the ions.

concentration in the PDX discharges.[18] The corresponding $^3P_2$-$^3P_1$ level separation is 26 072 ± 2 cm^{-1}, and the simple *LS* coupling magnetic dipole transition probability based on this energy separation is 239 sec^{-1}.

The other three lines, Ti XIV 2115.3 ± 0.5 Å, Ti XV 2544.8 ± 0.5 Å, and Ti XVII 3371.5 ± 0.5 Å, were first observed in the PDX tokamak discharges (with somewhat less accurate instrumentation). The level separations and *LS* transition probabilities are respectively 47 260 ± 12 cm^{-1} and 1898 sec^{-1} for the $^2P_{1/2}$-$^2P_{3/2}$ of Ti XIV, 39 284 ± 8 cm^{-1} and 1363 sec^{-1} for the $^3P_1$-$^3P_2$ of Ti XV, and 29 652 ± 5 cm^{-1} and 469 sec^{-1} for the $^3P_1$-$^3P_0$ transition of Ti XVII. All these numerical values are within expected uncertainties of the semiempirical 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, Ti XVII, 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 3371- and 3834-Å lines is indistinguishable, as expected, and the time sequence of the others is consistent with the resonance lines of Ti XIX and XX and the expected ionization times at the known electron temperature and density. The resonance line of O VI (the dominant impurity element in the discharge), which also resembles the time behavior of potential interfering lines and stray light, 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 Ti XX (the time scale is 50 msec/div in one oscillogram and 100 msec/div in the other).

The absolute peak intensities of the four forbidden lines and the Ti XIX resonance line are given in Fig. 3(a). Figure 3(b) shows the calculated emissivity per titanium ion in the appropriate state of ionization by Bhatia, Feldman, and Doschek.[17] The calculations include all collisional and radiative transitions between all $n = 2$ levels (i.e., $2s^22p^x$, $2s2p^{x+1}$, and $2p^{x+2}$ 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. The intensities are also practically independent of electron temperature (~1.2 keV at 140 msec in the experiment), except insofar as it affects the time dependence through ionization rates.

Figures 3(a) and 3(b) would be directly comparable if (1) all the important transition rates in

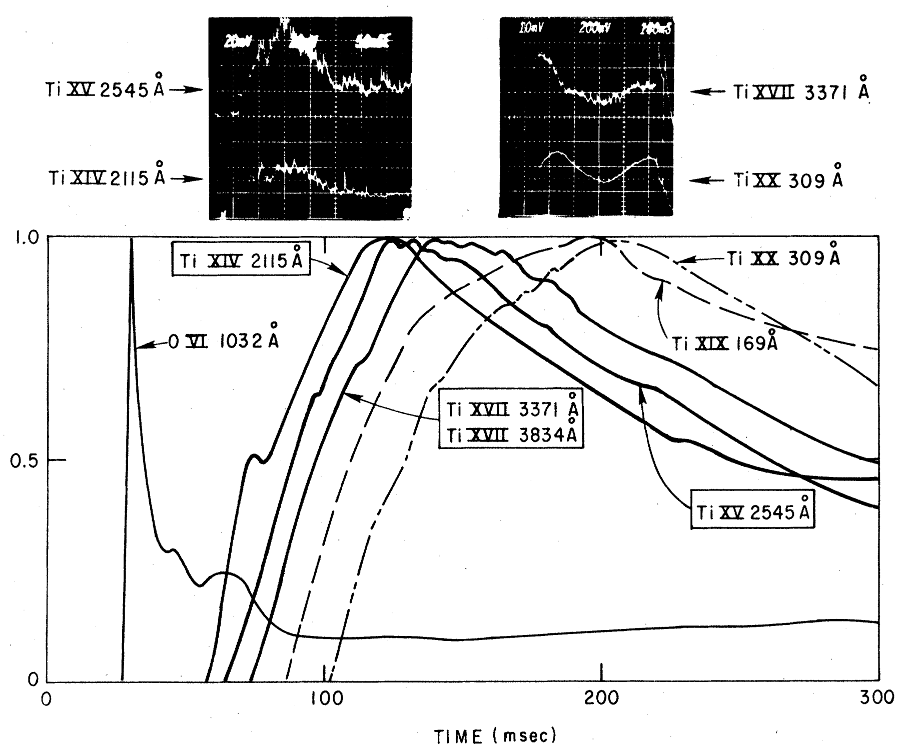

FIG. 2. Time behavior of titanium ion lines, and an O VI resonance line in a PDX discharge. Insets show actual oscillograms of three of the forbidden lines and the Ti XX resonance line.

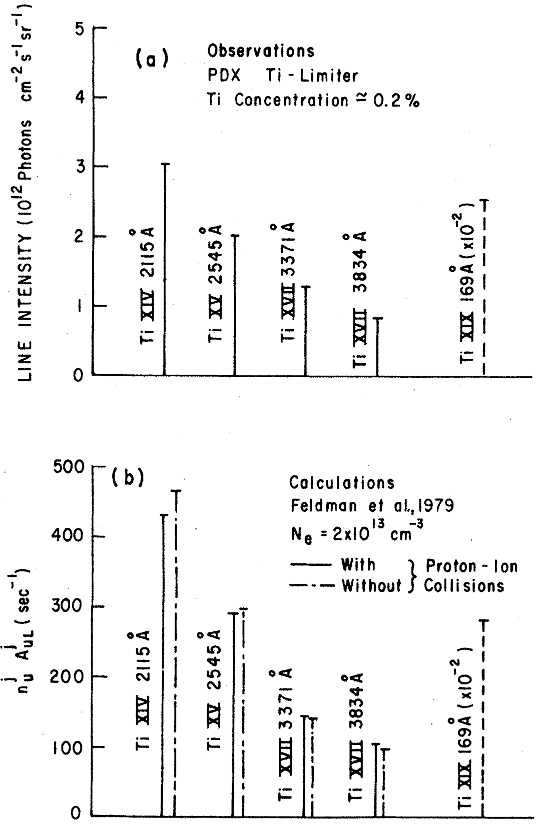

FIG. 3. (a) Measured absolute intensities at the time of their maxima of various titanium lines in a PDX discharge (electron density $N_e \approx 1.3 \times 10^{13}$ cm^{-3}). (b) Calculated emissivity *per ion* of the same lines, at electron temperature and density close to experimental conditions.

the calculation were 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 is 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 (more precisely, of the number of ions along the line of sight).

In view of the potential uncertainties in the various rate coefficients, the similarity of the calculated relative intensities with the measurements is remarkable, and there are reasons to believe that the actual correlation may be still closer. During the quasisteady phase of a tokamak discharge (which includes the 120–200-msec interval of the present measurements) the shapes of the radial distributions of electron temperature and density do not change appreciably, even though their magnitudes may change slowly. Consequently the radial distribution (i.e., the distribution along the line of sight) of the emissivity of each titanium ion at the time of its peak emission is also practically the same, being determined mostly by the electron temperature profile. Furthermore the total titanium density in the emitting region is approximately proportional to the density of the particular state of ionization and hence to each of the measured peaks.

The actual time behavior of the titanium concentration is not independently known in the present case. However, on the basis of studies of iron and oxygen concentrations (determined from spatially resolved resonance-line intensities) in similar discharges of other tokamaks,[19,20] we expect that in this quasisteady phase of the discharge the relative titanium concentration remains a constant fraction of the plasma (electron) density. The latter was slowly rising in the 120–200 msec interval (from about 1.2×10^{13} cm^{-3} to 1.4×10^{13} cm^{-3}), and if we were to assume that the relative titanium concentration indeed remained constant, then the *relative* pattern of the calculated and measured intensities would virtually coincide. We infer from this observation that there are no substantial errors or omissions in the rate coefficients used in the calculations[17] of the line emissivities. (Alternatively one could state that the calculations imply a constant titanium concentration.) The value of this concentration that would match the absolute scales of Figs. 3(a) and 3(b) is about $2 \times 10^{-3} N_e$, corresponding to a near central titanium density of about 2.6×10^{10} cm^{-3} at 200 msec. (The emission occurs over an equivalent path length of about 20 cm, over which the electron density is nearly constant. The line-average Ti XIX density is then about 8.4×10^{9} cm^{-3}, the rest being due to adjacent states, mostly Ti XVIII and XX, deduced partly from ionization calculations and partly from observed line intensities of these states.)

Finally we note that the predicted 1776-Å line of Ti XVIII and most of the intercombination lines should have readily measurable 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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