Identification of new Ti XXI and Ti XIX transitions emitted by laser-produced plasmas

J. C. Moreno, S. Goldsmith,* and H. R. Griem

Laboratory for Plasma and Fusion Energy Studies, University of Maryland, College Park, Maryland 20742

Leonard Cohen

Laboratory for Solar Physics, Goddard Space Flight Center, Greenbelt, Maryland 20771

M. C. Richardson

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623-1299

Received July 27, 1987; accepted September 1, 1987

New spectral emission lines of Ti XXI and Ti XIX have been observed and classified from a laser-produced plasma. The wavelength region for these lines is from 12 to 15 Å.

This study of the spectra of highly ionized titanium emitted from laser-produced plasmas (LPP) is part of a larger project devoted to the study of thermal transport of 351-nm laser-energy flux through spherical parylene-layer targets.[1] The transport of the impinging laser radiative energy into the target from the plasma region that reached critical density and hence reflects the laser influx is accomplished by electron conduction. Such studies of electron thermal conductivity have usually been performed using composite targets coated on the outer surface with two different material layers. The process of heat transport is studied in the first layer; the second layer serves to register the penetration of the laser energy by emitting its characteristic radiation, which corresponds usually to highly ionized atoms.[2] In the present experiment, the outer layer was made of parylene, and the substrate was titanium. The spectra emitted by the highly ionized titanium plasma contained the new transitions reported here. The new transitions in heliumlike and berylliumlike titanium are of the type $2l$–$3l'$ and $2l$–$4l'$, where the first number is the principal quantum number and l and l' are the azimuthal quantum numbers. Such transitions are of interest for the development of x-ray lasers, as population inversion can be obtained in highly ionized LPP by preferential population of higher levels.[3] Furthermore, the spectra of highly ionized plasmas are very important as tools for plasma diagnostics (for example, see Ref. 4). In the present case,[1] the relative intensity of spectral lines corresponding to the same ion or emitted by different ions was used to derive the laser-radiative-energy penetration. The study of line intensity ratios was the basis for the determination of electron temperature in the titanium plasma and thus was a measure of energy penetration.

The titanium plasma used in our study was produced with the Omega laser system at the Laboratory for Laser Energetics (LLE) at the University of Rochester. The laser system comprises 24 Nd:glass laser beams frequency tripled to a wavelength of 351 nm. Typical incident intensities used in this investigation were 4×10^{14} W/cm^2, with a pulse length of 600 psec. To improve the uniformity of target irradiation, the laser light was focused at eight times the spherical target radius behind the target. The spherical targets consisted of glass microballoons, 400 μm in diameter and approximately 10 μm in wall thickness (Fig. 1). These microballoons were coated with a thin (2-μm) layer of Ti to provide signature-line emission for the thermal-transport study. A final overcoat (0–11 μm) of parylene was deposited on the targets. Using targets with different external coating thicknesses was an essential part of the thermal-transport study but also facilitated the spectroscopic study of highly ionized titanium by providing a novel method for ionization differentiation.

The target element spectra were recorded by a 3-m grazing-incidence spectrograph[5] using Kodak 101-05 photographic plates. The grating had 1200 lines/mm and a blaze angle of 2° 35′. At an angle of incidence of 88°, the blaze wavelength is close to 60 Å. However, as the spectrograph was loaded with only one 25.6-cm plate, the upper limit of the observed wavelength was 58 Å. The radiation from the plasma was focused onto the entrance slit of the spectrograph with a cylindrical concave mirror positioned at a grazing angle of incidence to the incoming radiation, and the mirror could be adjusted to focus the light. Each spectral plate was obtained with a single laser shot. The positions of the lines on the plates were measured to within 1 μm using a Grant comparator. Wavelength calibration was made relative to C V, C VI, O VII, and O VIII resonance lines[6] and previously measured lines of Ti ions[7] (see also reference list of Ref. 8). The source of the oxygen lines is in the titanium, probably in the form of titanium oxide, and not in the microballoon glass as no silicon lines were observed. Some of the strong Ti XX and Ti XIX lines were measured at second or even third order and were useful in establishing improved reference lines in the 10–20-Å region. The estimated accuracy of the listed wavelength should be better than 0.005 Å

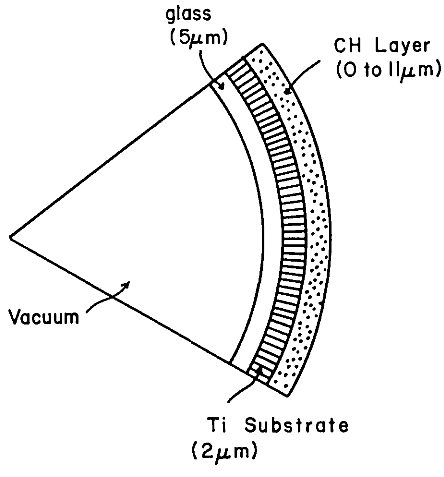

Fig. 1. A LLE typical spherical target used for these measurements.

for well-resolved strong lines and about 0.01 Å for the weaker ones.

As was mentioned, to differentiate between lines of different titanium ions, the effect that the external parylene layers had on the intensity of the various lines was utilized. Increasing the thickness of the parylene limited the penetration of the heat front and led to the lowering of the highest degree of ionization observed in the titanium spectra. Thus, the lines of heliumlike Ti XXI were observed only with the target, which had no parylene overcoat. On the plate obtained using a target with a 3-μm outer layer of parylene, the Ti XXI disappeared while the intensity of both the Ti XX and Ti XIX lines was markedly increased relative to that of the previous one. The plate corresponding to a target with 5 μm of parylene coating showed again rich spectra of Ti XX and Ti XIX with approximately the same relative intensity as on the previous plate, but possibly having a lower absolute intensity. Rich spectra of Ti XIII to Ti XVIII were observed with overcoat layers of 5 and 7 μm; the results of this study will be published later. Interestingly, two resonance lines of Ti XIII, neonlike titanium, were observed at 26 Å. With an external-layer thickness of 11 μm, no lines of titanium or oxygen ions were observed at all. Radiation transfer in the carbon plasma should not influence the intensity of the titanium lines below 20 Å as the carbon plasma is transparent in this region. We believe that the intensity variation between the various spectroscopic plates is caused not only by a decrease in the plasma electron temperature, which results from the increase in the parylene thickness, but also by a reduction in the total number of Ti ions. Thus, we suggest that with a decrease in the energy transfer the fraction of solid titanium becoming a plasma diminishes. Figure 2 presents three titanium spectra in the region from 12 to 16 Å, demonstrating the effect of the parylene coating on the excitation of the ionic spectral lines.

The classifications of the identified new lines of Ti XXI and Ti XIX are listed in Table 1. The accuracy of the lines in the table is estimated to be ±0.01 Å with the exception of the two Ti XXI lines at 14.5 and 14.6 Å whose wavelength uncertainty should be less then ±0.005 Å. The observed transitions in the heliumlike Ti XXI ion correspond to transitions of type $2s$–$3p$ and $2p$–$3d$. Recently some of these transitions were observed in Si XIII (Ref. 12; the silicon plasma was also produced by the Omega system at LLE), but the present work pushes the observation to a higher-ionization state. Theoretical wavelengths for these transitions were derived from the energy levels and transitions calculated by Drake[9] and Sampson et al.[10] Good agreement is found between the two sets of calculations. All the Ti XXI calculated lines are presented in Table 1, though experimentally not all were observed. The lines of the $2p$–$3d$ transitions are the strongest, those of $2s$–$3p$ are very weak, and the $2p$–$3s$ transitions are absent. This intensity pattern duplicates the one observed in Si XIII by Feldman et al.[12] and is characteristic of the laser-produced plasma. Each of the lines at 14.197 and 14.510 Å is a blend of two or three transitions. The 14.197-Å line corresponds most probably to the transition $1s2s\ {}^3S_1$–$1s3p\ {}^3P_0$, which is theoretically the stronger.

Wavelengths and oscillator strengths of the transitions $2s^2$–$2s4p$, $2s2p$–$2s4s$, $2s2p$–$2s4d$, $2p^2$–$2p4s$, and $2p^2$–$2p4d$ were calculated using the relativistic Hartree–Fock programs of Cowan.[11] Configuration interactions between the relevant upper or lower levels were included. Two programs are used. The first calculates *ab initio* values of the Slater energy parameters, and the second calculates wavelengths and oscillator strengths from scaled energy parameters. In Table 1 we list the calculated wavelengths of only the intense transitions, i.e., those with gf values larger than 0.1, where g is the statistical weight of the lower level and f is the oscilla-

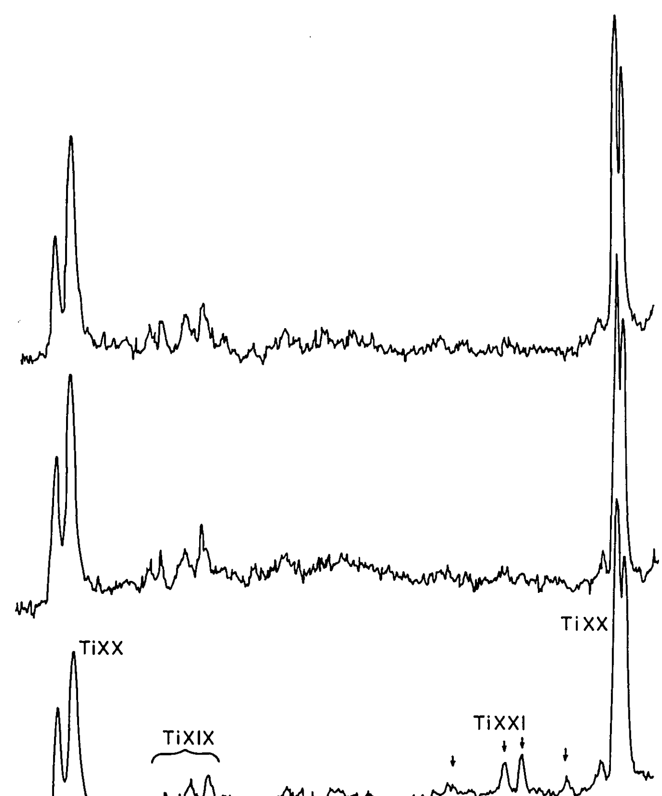

Fig. 2. Three titanium spectra with different coatings of parylene. From bottom to top the spectra have 0, 3, and 5 μm of CH, respectively.

Table 1. New Classified Lines of Ti XXI and Ti XIX (Wavelengths in Angstroms)

Ion	Transition	Calculated	Measured	Intensity[a]
XXI	$1s2s\,^3S_1$–$1s3p\,^3P_2$	14.163[b]	14.165	2
XXI	$1s2s\,^3S_1$–$1s3p\,^3P_1$	14.197[b]	14.197	1
XXI	$1s2s\,^3S_1$–$1s3p\,^3P_0$	14.203[b]		
XXI	$1s2p\,^3P_0$–$1s3d\,^3D_1$	14.496[b]		
XXI	$1s2p\,^3P_1$–$1s3d\,^3D_1$	14.518[b]		
XXI	$1s2p\,^3P_1$–$1s3d\,^3D_2$	14.519[b]	14.510	8
		14.505[c]		
XXI	$1s2s\,^1S_0$–$1s3p\,^1P_1$	14.520[b]		
XXI	$1s2p\,^3P_2$–$1s3d\,^3D_3$	14.622[b]	14.619	10
XXI	$1s2p\,^3P_2$–$1s3d\,^3D_1$	14.635[b]		
XXI	$1s2p\,^3P_2$–$1s3d\,^3D_2$	14.636[b]		
XXI	$1s2p\,^3P_0$–$1s3s\,^3S_1$	14.712[b]		
XXI	$1s2p\,^3P_1$–$1s3s\,^3S_1$	14.735[b]		
XXI	$1s2p\,^3P_2$–$1s3s\,^3S_1$	14.856[b]		
XXI	$1s2p\,^1P_1$–$1s3d\,^1D_2$	14.897[b]	14.885	8
		14.870[c]		
XXI	$1s2p\,^1P_1$–$1s3s\,^1S_0$	15.018[b]		
XIX	$2s2p\,^3P_2$–$2p4p\,^3P_2$	11.946[d]		
XIX	$2s2p\,^3P_2$–$2p4p\,^3D_3$	11.951	11.958[e]	
XIX	$2s2p\,^3P_1$–$2p4p\,^3D_2$	11.966		
XIX	$2s^2\,^1S_0$–$2s4p\,^1P_1$	12.004	12.010	5
XIX	$2s2p\,^1P_1$–$2p4p\,^1D_2$	12.239		
XIX	$2s2p\,^3P_0$–$2s4d\,^3D_1$	12.390	12.379	1
XIX	$2s2p\,^3P_1$–$2s4d\,^3D_2$	12.414	12.410	10
XIX	$2s2p\,^3P_2$–$2s4d\,^3D_3$	12.479	12.480	15
XIX	$2p^2\,^3P_1$–$2p4d\,^3P_1$	12.571		
XIX	$2p^2\,^3P_1$–$2p4d\,^1D_2$	12.589	12.592	1
XIX	$2p^2\,^3P_0$–$2p4d\,^3D_1$	12.616		
XIX	$2p^2\,^3P_2$–$2p4d\,^3P_2$	12.617	12.622	20
XIX	$2p^2\,^3P_2$–$2p4d\,^3D_3$	12.625		
XIX	$2p^2\,^3P_1$–$2p4d\,^3P_2$	12.672	12.688	1
XIX	$2p^2\,^3P_2$–$2p4d\,^3F_3$	12.719		
XIX	$2p^2\,^1D_2$–$2p4d\,^1F_3$	12.724	12.726	20
XIX	$2p^2\,^1S_0$–$2p4d\,^1P_1$	12.979		

[a] Visual estimate of intensity on plate. The Ti XX line at 12.516 Å is taken as 100.
[b] Ref. 9.
[c] Ref. 10.
[d] All Ti XIX lines are calculated by a relativistic Hartree–Fock program (Ref. 11).
[e] Blended line with Ti XX.

tor strength. Both the wavelengths and intensity patterns of the identified lines agree with their calculated values. A more detailed model of the plasma parameters is needed for making a significant comparison between the observed and calculated intensity pattern. Two Ti XIX lines, calculated to have wavelengths of 11.946 and 11.951 Å and large gf values, could not be observed because they are blended with a very strong Ti XX line. The same $n = 2$ to $n = 4$ transitions have already been studied in V XX by Bromage *et al.*[13] in a laser-produced plasma. The intensity patterns of V XX and Ti XIX spectra are also consistent.

ACKNOWLEDGMENTS

We thank Dr. W. E. Behring for the use of the spectrograph and the laser operation staff and target fabrication group at the Laboratory for Laser Energetics for their outstanding support. Special thanks are due to V. Kaufman, National Bureau of Standards, for his help in calculating the relativistic Hartree–Fock spectrum of Ti XIX. We also thank W. C. Martin for providing us with a copy of G. W. F. Drake's calculation of the Ti XXI lines. This research was supported by the U.S. Department of Energy under contract No. DE-AS08-86DP10554.

* On sabbatical from School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel.

REFERENCES

1. J. C. Moreno, H. R. Griem, S. Goldsmith, A. Krumbein, R. Epstein, P. Jaanimagi, M. C. Richardson, and B. Yaakobi, "Thermal transport studies of 351 nm laser-produced plasmas using XUV spectroscopy," J. Appl. Phys. (to be published).
2. B. Yaakobi, O. Barnouin, J. Delettrez, L. M. Goldman, R. Marjoribanks, R. L. McCrory, M. C. Richardson, and J. M. Soures, "Thermal transport measurements in six-beam, ultraviolet irradiation of spherical targets," J. Appl. Phys. **57,** 4354 (1985).
3. S. Suckewer, C. H. Skinner, H. Milchberg, C. Keane, and D. Voorhees, "Amplification of stimulated soft x-ray emission in a confined plasma column," Phys. Rev. Lett. **55,** 1753 (1985).
4. S. Goldsmith, J. F. Seely, U. Feldman, W. E. Behring, and L. Cohen, "Electron temperature and average density in spherical laser-produced plasmas: ultraviolet plasma spectroscopy," J. Appl. Phys. **58,** 4011 (1985).
5. W. E. Behring, R. J. Ugiansky, and U. Feldman, "High resolution rocket EUV solar spectrograph," Appl. Opt. **12,** 528 (1973).
6. R. L. Kelly, *Atomic and Ionic Spectrum Lines below 2000 Å—H through Ar,* U.S. Department of Energy Rep. ORNL-5922 (U.S. Department of Energy, Oak Ridge, Tenn., 1982).
7. K. Mori, W. Wiese, T. Shirai, Y. Nakai, K. Ozawa, and T. Kato, "Spectral data and Grotrian diagrams for highly ionized titanium Ti V–Ti XXII," At. Data Nucl. Data Tables **34,** 79 (1986).
8. J. Sugar and C. Corliss, "Atomic energy levels of the elements: potassium through nickel," J. Phys. Chem. Ref. Data **14,** Suppl. 2, 1 (1985).
9. G. W. F. Drake, *Calculated Transition Frequencies for Helium-like Ions,* University of Windsor Reprint, (University of Windsor, Windsor, Ontario, Canada).
10. D. H. Sampson, S. J. Goett, and R. Clark, "Electron-impact collision strengths for excitation of He-like ions from levels with $n = 1$ and 2 to singly excited levels with higher $n \leq 5$," At. Data Nucl. Data Tables **29,** 467 (1983).
11. R. D. Cowan, "Theoretical calculation of atomic spectra using digital computers," J. Opt. Soc. Am. **58,** 808 (1968).
12. U. Feldman, J. O. Ekberg, C. M. Brown, J. F. Seely, and M. C. Richardson, "$2l$–$3l'$ and $2l$–$4l'$ transitions in heliumlike and hydrogenlike silicon," J. Opt. Soc. Am. B **4,** 103 (1987).
13. G. E. Bromage, R. D. Cowan, B. C. Fawcett, and A. Ridgeley, "Classification of Be I-like and B I-like iron and vanadium spectra from laser-produced plasmas," J. Opt. Soc. Am. **68,** 48 (1978).