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Study of $n = 2$, $\Delta n = 0$ transition of Be-, B-, C-, N- and O-like sequence in the beam–foil spectrum of titanium*

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The foil-excited the spectrum of highly stripped titanium ions between 12–40 nm has been studied. Titanium ions of 80 and 120 MeV were provided by the HI-13 tandem accelerator at the China Institute of Atomic Energy. GIM-957 XUV-VUV monochromator was refocused to get highly-resolved spectra. Our experimental results and the published spectral data of laser-produced plasma show agreement in nearly all cases within ±0.03 nm. The spectra contained some weak or strong lines previously unclassified. These spectral lines mainly belong to $2s2p^2$ for TiXVIII, $2p^3$ for TiXVIII, $2s2p^3$ for TiXVII, $2p^64p$ for Ti XII and $2p^63d$ for Ti XII transitions.

Keywords: spectra, highly-ionized ion, beam–foil technique
PACC: 3220J, 3450H, 3220n

1. Introduction

The spectrum 12 nm $\leq \lambda \leq$ 40 nm of foil- excited titanium has been observed recently. In the past, most of the published works on the spectrum of titanium have been carried out at beam energies below 30 MeV by using ordinary Van de Graff accelerators, cyclotrons, and tandem Van de Graff accelerators, and most of published works on the spectrum of titanium at high ionization stages have been on EUV spectrum by using laser-produced plasma. The purpose of this work is to give a comprehensive survey of the spectrum of titanium at high ionization stages in the wavelength range 12–40 nm using the beam–foil method, and the spectra of highly ionized titanium obtained in this paper have better resolution at higher energy. Spectral studies using different methods are of interest for diagnostics of low-density, high-temperature plasmas such as are generated in magnetic confinement machines for nuclear fusion.

2. Experimental procedure

A general description of the experimental set-up has been given in Ref.[1,2], while some details of the light-collecting system are given here. The experiment was performed at the HI-13 tandem accelerator at the China Institute of Atomic Energy (CIAE). The heavy-ion accelerator, with a maximum terminal voltage of 15 MV (routinely running at 2–14 MV), is equipped with several kinds of ion sources. In this experiment, multiply charged Ti ions were accelerated to 80 and 120MeV respectively, and directed through a 25 μg/cm^2 carbon foil. The radiation emitted by the foil-excited ion was analysed with a 2.2 meter grazing incidence GIM-957 XUV-VUV monochromator equipped with a 600 lines/mm grating. The angle of incidence was 88.5°. The spectrometer viewed the beam at 90°, and its entrance slit was placed close to the ion beam with 6 mm diameter, i.e., 7.5 mm from the centre of the beam. Using a 20 μm entrance slit, the full width at half maximum of the spectral lines was about 0.04 nm, yielding a wavelength uncertainty of less than 0.005 nm for the majority of the identified lines. During the experiment, beam currents ranging from 0.4 to 0.5 μA were used. During the microcomputer-controlled scan, the channeltron de-

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tector moved along the Rowland circle with increment of the chordal distance of 0.1 mm, and the light intensity at each point was normalized to a fixed amount of beam charge collected in a Faraday cup. In order to separate the electrons emitted by the foil from the Faraday cup itself, a suppressor ring with a potential of 300 V was placed in front of the Faraday cup.

3. Results and discussions

In the experiment, the accelerating process ensured a high degree of beam purity, and in the recorded spectra we never observed lines that might be ascribed to the excitation of the carbon of the foil, the observed lines were attributed solely to the incident ions. The identification of the lines in this work was very simple due to the previous excellent experimental results and the unique charge state calculation made possible by Nikolaev and Dimitriev.[3] Wavelength determination was based on the wavenumber of the transitions with net charge $\xi = N + 1$ along the isoelectronic sequence and comparison with spectral data of laser-produced plasma. Additional support of the identification is given by observing the intensity variation of the lines as a function of beam energy. Figure 1 shows part of a spectrum in the experiment at 80 and 120 MeV. The majority of the identified transitions are given in Tables 1–5 together with the results of laser-produced spectra. Comparison of these data with those of laser-produced plasmas shows agreement in nearly all cases within ±0.03 nm. The reference wavelengths were obtained from Refs.[4–6], where the wavelength uncertainty was given as ± 0.05 nm. The uncertainty of our measured wavelengths is ±0.04 to ± 0.2 nm, most of the increase being due to the wavelength determination of overlapping or weak lines. In our experiment, most of the lines observed could be identified from the available tabulations[4−7] as belonging to the spectra of TiXIX, TiXVIII, TiXVII), Ti XVI and TiXV.

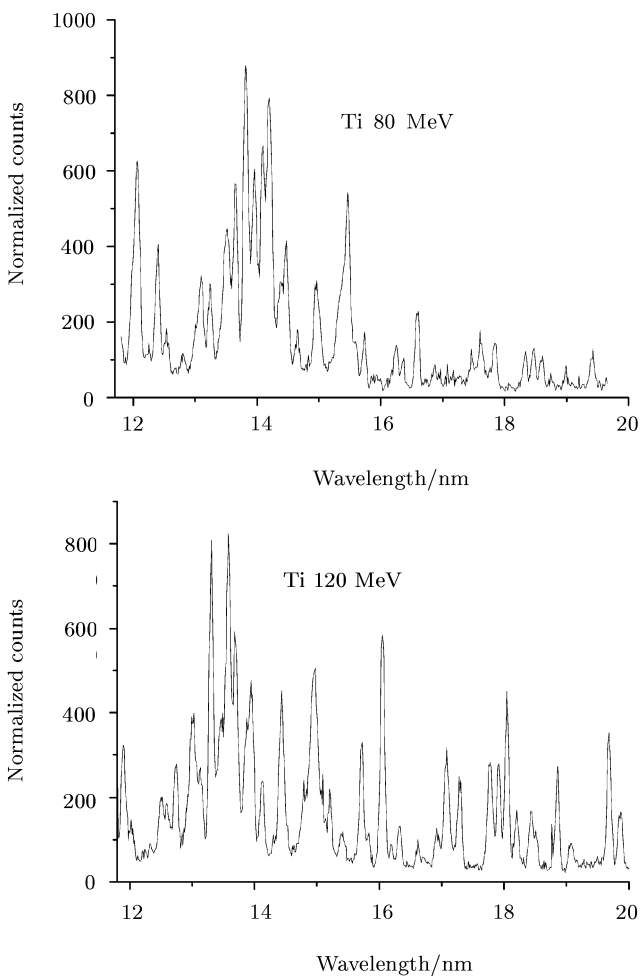


Fig.1. Beam-foil spectrum of titanium in 12–40 nm.

3.1. Be-like sequence

The transitions belonging to $2p^2$ configurations have been identified for Be-like sequence. The classification was based on the comparison with results of laser-produced spectra. The results are given in Table 1.

Table 1. Be I-like titanium

Transition	Wavelength/nm	
	This experiment	Laser experiment[7]
$2s2p\ ^3P_2$–$2p^2\ ^1D_2$	17.524	17.533
$2s2p\ ^3P_0$–$2p^2\ ^3P_1$	19.361	19.354
$2s2p\ ^1P_1$–$2p^2\ ^1S_0$	19.438	19.437
$2s2p\ ^3P_1$–$2p^2\ ^3P_1$	19.957	19.989
$2s2p\ ^3P_2$–$2p^2\ ^3P_2$	20.612	20.610
$2s2p\ ^3P_1$–$2p^2\ ^3P_0$	21.216	21.222

3.2. B-like sequence

Numerous transitions belonging to $2s2p^2$ and $2p^3$ have been identified for B-like sequence. Our wavelength measurements together with observation of laser experiments and theoretical results are given in Table 2.

Table 2. BI-like titanium

Transition	Wavelength/nm		
	This experiment	Laser experiment[6,7]	Theory[8]
$2s^22p\ ^2P_{1/2}$–$2s2p^2\ ^2P_{3/2}$	13.386	13.3852	13.3858
$2s2p^2\ ^4P_{3/2}$–$2p^3\ ^2D_{3/2}$	13.406		13.4068
$2s^22p\ ^2P_{1/2}$–$2s2p\ ^2P_{1/2}$	13.628	13.6280	
$2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2P_{3/2}$	14.470	14.4759	14.4755
$2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2P_{1/2}$	14.749	14.7607	14.7596
$2s2p^2\ ^2D_{5/2}$–$2p^3\ ^2P_{3/2}$	15.017	15.015	
$2s2p^2\ ^4P_{3/2}$–$2p^3\ ^4S_{3/2}$	15.902		15.8982
$2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2S_{1/2}$	16.175		16.1978
$2s2p^2\ ^4P_{5/2}$–$2p^3\ ^4S_{3/2}$	16.622	16.6225	16.6225
$2s^22p\ ^2P_{1/2}$ –$2s2p^2\ ^2D_{3/2}$	17.987	17.9902	17.9895
$2s2p^2\ ^2D_{3/2}$–$2p^3\ ^2D_{5/2}$	18.776	18.755	18.7552
$2s2p^2\ ^2D_{5/2}$–$2p^3\ ^2D_{5/2}$	18.962	18.966	18.9642
$2s2p^2\ ^2D_{3/2}$–$2p^3\ ^2D_{3/2}$	19.125	19.123	19.1210
$2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2D_{5/2}$	19.782	19.7838	19.8187
$2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2D_{3/2}$	20.015		20.0145
$2s2p^2\ ^2P_{3/2}$–$2p^3\ ^2P_{3/2}$	20.810	20.807	20.8083
$2s2p^2\ ^3P_{1/2}$–$2p^3\ ^2P_{1/2}$	21.039	21.051	21.0497
$2s2p^2\ ^3P_{1/2}$–$2p^3\ ^2P_{3/2}$	20.237		20.2481
$2s2p^2\ ^2P_{3/2}$–$2p^3\ ^2P_{1/2}$	21.652		21.6558

3.3. C-like sequence

Spectra of CI-like titanium were previously observed from laser produced-plasmas, some of the lines were found in the solar spectrum. In Table 3 we give some identification results.

Table 3. CI-like titanium

Transition	Wavelength/nm	
	This experiment	Laser experiment [6,7]
$2s^22p^2\ ^3P_2$–$2s2p^3\ ^3S_1$	12.777	12.7782
$2s\ 2p^3\ ^3D_1$–$2p^4\ ^3P_1$	13.551	136.393
$2s^22p^2\ ^1D_2$–$2s2p^3\ ^1D_2$	14.193	14.1948
$2s^22p^2\ ^3P_0$–$2s2p^3\ ^3P_1$	14.688	14.6856
$2s^22p^2\ ^1S_0$–$2s2p^3\ ^1P_1$	14.967	
$2s^22p^2\ ^3P_1$–$2s2p^3\ ^3P_2$	15.228	15.2174
$2s^22p^2\ ^3P_1$–$2s2p^3\ ^3P_1$	15.326	15.3554
$2s^22p^2\ ^3P_1$–$2s2p^3\ ^3P_0$	15.426	15.4133
$2s2p^3\ ^3P_1$–$2p^4\ ^3P_0$	15.668	15.657
$2s^22p^2\ ^3P_2$–$2s2p^3\ ^3P_2$	15.853	15.846
$2s2p^3\ ^3P^\circ_{\ 1}$ –$2p^4\ ^3P_2$	17.002	
$2s2p^3\ ^3P_2$ –$2p^4\ ^3P_2$	17.127	17.109
$2s^22p^2\ ^3P_0$ –$2s2p^3\ ^3D_1$	17.235	17.2380
$2s^22p^2\ ^3P_2$ –$2s2p^3\ ^3P_1$	18.155	
$2s^22p^2\ ^3P_1$–$2s2p^3\ ^3D_2$	18.207	18.2072
$2s^22p^2{}^1D_2$ – $2s2p^3\ ^3P_2$	18.309	
$2s^22p^3\ ^1D_2$–$2p^4\ ^1D_2$	18.657	18.686
$2s^22p^2\ ^3P_2$–$2s2p^3\ ^3D_2$	21.528	

3.4. NI-like sequence

Lines of N-like titanium are given in Table 4. The identification are based on the observation of laser produced spectra of titanium[6,7] and NIST data.

Table 4. NI-like titanium

Transition	Wavelength/nm	
	This experiment	Laser experiment[5]
$2s2p^4\ ^2D_{3/2}$– $2p^5\ ^2P_{1/2}$	12.907	12.9075
$2s^22p^3\ ^2P_{3/2}$–$2s2p^4\ ^2P_{3/2}$	13.200	13.2022
$2s^22p^3\ ^2P_{3/2}$–$2s2p^4\ ^2S_{1/2}$	13.879	13.8760
$2s^22p^3\ ^2D_{3/2}$–$2s2p^4\ ^2D_{3/2}$	14.344	14.3459
$2s^22p^3\ ^4S_{3/2}$–$2s2p^4\ ^2P_{1/2}$	15.757	15.7812
$2s^22p^3\ ^4S_{3/2}$–$2s2p^4\ ^4P_{3/2}$	16.092	16.1168
$2s^22p^3\ ^2P_{1/2}$–$2s2p^4\ ^2D_{3/2}$	16.264	16.2503
$2s2p^4\ ^2P_{3/2}$–$2p^5\ ^2P_{1/2}$	16.345	16.3410
$2s^22p^3\ ^2P_{3/2}$–$2s2p^4\ ^2D_{5/2}$	16.720	16.7242
$2s2p^4\ ^2S_{1/2}$–$2p^5\ ^2P_{3/2}\}$		16.7297
$2s2p^4\ ^2P_{3/2}$–$2p^5\ ^2P_{3/2}$	17.825	17.8240

3.5. O- and Na-like sequence

Table 5 gives some of the spectral lines of O- and Na-like titanium in this experiment and the observation of Sugar *et al.*[6]

Table 5. O I and Na-like titanium

Transition	Wavelength/nm	
	This experiment	published data[4]
$2s^22p^4\ ^3P_2$–$2s2p^5\ ^3P_1$	13.461	13.457
$2s^22p^4\ ^3P_1$–$2s2p^5\ ^3P_0$	13.834	13.833
$2s^22p^4\ ^3P_2$–$2s2p^5\ ^3P_2$	14.028	14.034
$2s^22p^4\ ^3P_1$–$2s2p^5\ ^3P_1$	14.207	14.209
$2s^22p^4\ ^3P_0$–$2s2p^5\ ^3P_1$	14.280	14.272
$2s^22p^4\ ^3P_1$–$2s2p^5\ ^3P_2$	14.848	14.854
$2s^22p^4\ ^1S_0$– $2s2p^5\ ^1P_1$	13.119	13.112
$2p^63d\ ^2D_{3/2}$–$2p^64p\ ^2P_{3/2}$	13.970	
$2p^63s\ ^2S_{1/2}$–$2p^63d\ ^2D_{5/2}$	19.878	

From the above tables we can see that our experimental results show good agreement with the results of laser produced spectra of titanium in all cases. There are eleven lines that have not been found in the previously published experimental work for Ti XII–Ti XIX spectra between 12nm and 40 nm. The eleven lines of 13.406, 15.902, 16.175, 20.015, 20.237, 21.652, 14.967, 17.002, 18.155, 18.309 and 21.528 nm in Tables 1–4 are identified as $2s2p^2\ ^4P_{3/2}$–$2p^3\ ^2D_{3/2}$ of Ti XVIII, $2s2p^2\ ^4P_{3/2}$–$2p^3\ ^4S_{3/2}$ of Ti XVIII, $2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2S_{1/2}$ of Ti XVIII, $2s^22p\ ^2P_{3/2}$–$2s2p^2\ ^2D_{3/2}$ of XVIII, $2s2p^2\ ^3P_{1/2}$–$2p^3\ ^2P_{3/2}$XVIII, $2s2p^2\ ^2P_{3/2}$–$2p^3\ ^2P_{1/2}$XVIII; $2s^22p^2\ ^1S_0$–$2s2p^3\ ^1P_1$ of Ti XVII, $2s2p^3\ ^3P_1$ –$2p^4\ ^3P_2$ of Ti XVII, $2s^22p^2\ ^3P_2$ –$2s2p^3\ ^3P_1$ of Ti XVII and $2s^2\ 2p^2\ ^1D_2$ – $2s2p^3\ ^3P_2$ $2s^22p^2\ ^3P_2$–$2s2p^3\ ^3D_2$ transitions, respectively, transitions of Ti XVIII show reasonably good agreement with theoretical calculation.[8] The two lines of 13.970 and 19.878 nm Na-like titanium found in this work are listed in Table 5, and identified as $2p^63d\ ^2D_{3/2}$ – $2p^64p\ ^2P_{3/2}$ of Ti XII and $2p^63s\ ^2S_{1/2}$ – $2p^63d\ ^2D_{5/2}$ of Ti XII transitions. These thirteen lines are not found in published works and are new lines detected and accurately measured in the present work.

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