Observation of Visible and Near-UV M1 Transitions from Highly Charged Kr, Mo and Xe Ions in LHD and its Prospect to Impurity Spectroscopy for D-T Burning Plasmas

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Magnetic dipole (M1) transitions from highly charged heavy impurities have been surveyed in visible and near-UV wavelength ranges longer than 2500 Å using a 1.33 m Czerny-Turner spectrometer in the Large Helical Device (LHD) for use in future visible impurity spectroscopy of D-T burning plasmas. The M1 transitions of KrXXII (Kr^{21+}: P-like) $3s^23p^3$ $^2D_{3/2}$-$^2D_{5/2}$ 3463.75 ± 0.05Å, KrXXIII (Kr^{22+}: Si-like) $3s^23p^2$ $^3P_1$-$^3P_2$ 3841.07 ± 0.03 Å, MoXXIX (Mo^{28+}: Si-like) $3s^23p^2$ $^3P_1$-$^3P_2$ 2842.10 ± 0.05 Å, XeXXXIII (Xe^{32+}: Ti-like) $3d^4$ $^5D_3$-$^5D_2$ 4139.01 ± 0.02 Å have been successfully observed using an external puff of Kr and Xe and an impurity pellet injection of Mo. As a result, the identification of the Ti-like XeXXXIII M1 transition, as observation for the first time in laboratory fusion plasmas, strongly suggests that the visible impurity spectroscopy of tungsten ions using Ti-like WLIII (W^{52+}: 3626Å) instead of the conventionally used EUV spectroscopy is possible in future D-T burning plasmas.

Keywords: plasma spectroscopy, highly charged ion, magnetic dipole transition, heavy impurity, krypton, molybdenum, xenon, tungsten, burning plasma

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Impurity spectroscopy has usually been performed in VUV and EUV ranges below 1000 Å in fusion plasma research measuring allowed (electric dipole: E1) transitions of highly charged impurity ions. In D-T burning plasmas in the future the grating and CCD detector of the VUV (or EUV) spectrometer could possibly be damaged by the high neutron flux. Moreover, the tritium contamination of the spectrometer is also a serious problem in terms of safety in addition to having a negative effect on the detector. In contrast, visible spectroscopy employing optical fibers allows the easy separation of the spectrometer from the burning fusion device, providing a large advantage to reduce effects of the neutron flux and the tritium contamination in the burning plasma spectroscopy.

Magnetic dipole (M1) transitions emitted among ns^2np^k (k = 1-5) ground states have been recently observed in laboratory fusion plasmas [1]. The importance of the M1 transition is that the spectral lines are emitted mainly in the visible range. However, wavelengths of the M1 transitions fall again below 2500 Å when the nuclear number of the element, Z, is greater than 40 (see Fig. 1). Fifteen years ago, Feldman, Indelicato and Sugar found that the M1 transitions of $3d^4$ $^5D_3$-$^5D_2$ from Ti-like ions of $60 \leq Z \leq 92$ are emitted in the visible range [2], as shown in Fig. 1. Since then, Ti-like M1 transitions have been studied in theoretical and experimental works. Especially, experimental works have been extensively performed in electron beam ion trap (EBIT) devices [3–21]. On the other hand, heavy elements such as molybdenum and tungsten are candidates for plasma facing materials in ITER. If the impurity diagnostics of such heavy impurities is made possible using visible spectroscopy, the essential difficulty related to the impurity diagnostics in the burn-

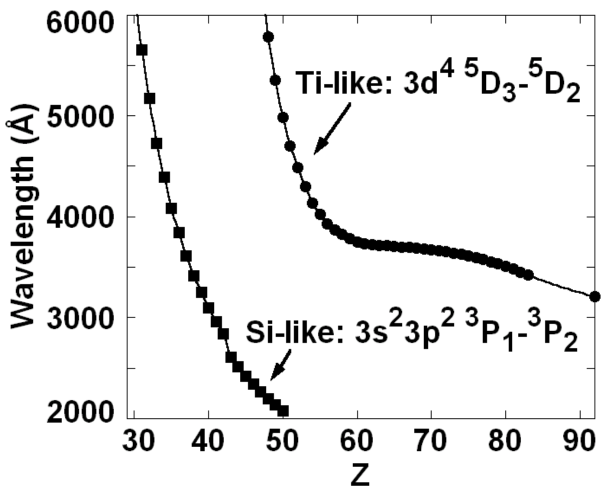

Fig. 1 Z dependence of wavelengths for Si-like [1, 36] and Ti-like [2, 19, 20] M1 transitions.

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ing plasma can also be solved. Visible M1 transitions from argon have been studied and the wavelengths and the physical processes of the M1 transition have been analyzed in details in the Large Helical Device (LHD) [22–24]. The M1 transitions from highly charged heavy impurity ions of Kr, Mo, Xe and W have also been surveyed in the visible and near-UV ranges above 2500 Å. In this paper, results of the survey are reported along with a line analysis and the measured M1 transitions are listed with precisely determined wavelengths.

In the present study, the Kr and Xe are externally puffed at the beginning of LHD NBI discharges. When the rare gas is puffed during the discharges, the particle supply becomes inefficient due to the screening effect of the ergodic layer. Typical plasma parameters of the discharges are the electron temperature of $T_e \sim$ 1-2 keV and the electron density of $n_e \sim 2\text{-}5 \times 10^{19}\,\mathrm{m}^{-3}$. The magnetic field strength in the present experiment is 3 T at the magnetic axis. The Mo and W are injected using an impurity pellet injection method. The carbon pellet including a thin wire (0.1-0.2 mm in diameter and 0.5 mm in length) instead of pure metallic pellets is injected into the LHD discharges to avoid the plasma thermal collapse. [25, 26]. The M1 transition is observed using a 1.33 m Czerny-Turner-type spectrometer with a 1800 grooves/mm grating and a back-illuminated charge-coupled device (CCD) detector [27]. The reciprocal liner dispersion of this spectrometer is 3.85 Å/mm. The visible emission is collected by a focusing lens and is transmitted through optical fibers with a core diameter of 100 µm. The fibers are installed and arranged on the window of the diagnostic port. The other ends of the fibers are coupled on the entrance slit of the visible spectrometer. The size of the CCD exposure area is $13.3 \times 13.3\,\mathrm{mm}^2$ ($13 \times 13\,\mu\mathrm{m}^2$/pixel) and the total number of channels is 1024×1024. The CCD is operated at −20°C to reduce the thermal noise to a negligible level.

Figure 2 shows the spectrum of the M1 transition of KrXXII (Kr^{21+}: P-like) $3s^23p^3\ ^2D_{3/2}\text{-}^2D_{5/2}$ 3463.75 ± 0.05 Å. The KrXXII line has a wider Doppler broadening as compared with other lines in low-ionized charge states, because impurity ions in higher ionization stages exist in the higher temperature region of the plasma. If the intensity of the M1 transition is sufficient, the existence of the M1 transition in the spectrum can be easily noticed. The wavelength of the M1 transition is carefully determined by interpolation between well-known lines of BII 3451.3030 Å and ArIII 3480.55 Å. Boron is brought into LHD with boronization for wall conditioning. Since in the present study Kr gas is puffed in low-density Ar discharges, visible Ar lines are bright. It is seen that emission lines from low-ionized ions are splitted by the Zeeman effect. There exists an unknown line at 3466 Å. This line has also the Doppler broadening as the KrXXII M1 transition. Therefore, the unknown line is also estimated to be the M1 transition.

The measured M1 transitions are listed in Table 1 with the wavelength determined in the present study. The error value of wavelength is determined only by the Doppler shift of plasmas, which is estimated from the line shift distribution measured using several discharges, since the statistical error in the present experiment is much less than 0.02 Å. Experimental results from EBIT are presented for comparison. The accuracy of the wavelength obtained here is much better than the result from EBIT. The difference in the brightness of the M1 transition between the LHD plasma and EBIT is the main reason why the determined wavelength accuracy is so different, because the error in wavelengths is essentially determined by statistical error as a function of the signal counts when the measured line is analyzed with line fitting. The M1 transitions from LHD plasmas are really much brighter than those from EBIT. The difference is estimated to be on the order of 10^3-10^5. Theoretically predicted wavelengths are also listed in Table 1. However, the calculated values are much different from the measured values. At present it is very difficult to theoretically calculate the wavelengths of heavy elements because of the complicated atomic system.

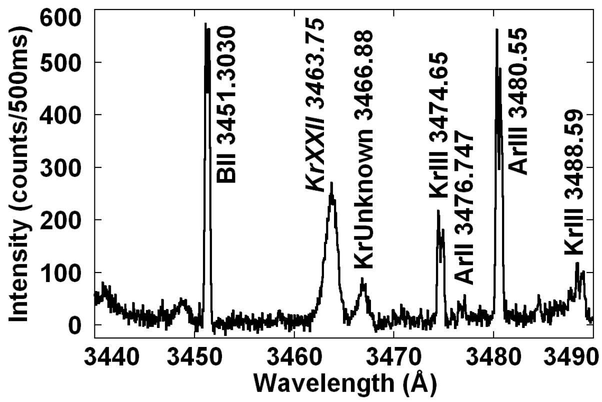

Fig. 2 Spectrum with KrXXII M1 transition. Italic fonts indicate the Kr M1 lines.

KrXXIII (Kr^{22+}: Si-like) $3s^23p^2\ ^3P_1\text{-}^3P_2$ 3841.07 ± 0.03 Å is observed under the same experimental condition as the KrXXII line, as shown in Fig. 3. Here, HI 3835.384 Å and ArII 3850.581 Å are useful reference lines for the wavelength determination. The wavelength of the KrXXIII M1 transition has been widely examined in several experimental works from EBIT (see Table 1). Only one of them has been obtained from TEXT tokamak [32]. Through the use of an elaborate fitting procedure, the highly precise measurement of the KrXXIII line reported from EBIT has a value of 3841.146 ± 0.002 Å [35].

A spectrum of MoXXIX (Mo^{28+}: Si-like) $3s^23p^2\ ^3P_1\text{-}^3P_2$ 2842.10 ± 0.05 Å in the same isoelectronic sequence as the KrXXII line is shown in Fig. 4. The vertical scale in the figure is adjusted to the MoII lines for the sake of clarity. The MoXXIX wavelength is determined based on the multiple MoII lines. Carbon lines are recorded in Fig. 4. Car-

Table 1 M1 transitions of heavy impurity elements observed in the present study and determined wavelengths. Comparison is made for former experimental works and calculated results.

Spectra	Transitions	Observed (Å)			Calculated (Å)	
		This work	Others		Others	
KrXXII	$3s^23p^3$	3463.75±0.05	3464.7±0.6	[28]	3446±30	[1]
(Kr^{21+})	$^2D_{3/2}$-$^2D_{5/2}$		3464	[8]	3438±2	[30]
E_i=990 eV			3466.6±0.2	[29]		
KrXXIII	$3s^23p^2$	3841.07±0.03	3840.9±0.3	[1,31,32]	3663.4999	[36]
(Kr^{22+})	$^3P_1$-$^3P_2$		3840.8±2	[3]	3832±40	[1]
E_i=935 eV			3842.6	[11]	3845	[34]
			3841.4±0.2	[33]	3837.0±6.5	[35]
			3840.5±0.9	[14]		
			3841.1±0.2	[29]		
			3843±2	[34]		
			3841.146±0.002	[35]		
MoXXIX	$3s^23p^2$	2842.10±0.05	2841.1±0.2	[1,31]	2712.1511	[36]
(Mo^{28+})	$^3P_1$-$^3P_2$		2840±2	[8]	2834±40	[1]
E_i=1590 eV						
XeXXXIII	$3d^4$ $^5D_3$-$^5D_2$	4139.01±0.02	4139.4±2.0	[3]	3952.5	[2]
(Xe^{32+})			4130±0.2	[10]	4130	[4]
E_i=1920 eV			4138.7	[11]	4079.3	[6]
			4138.8±0.7	[14]	4036.59	[10]
			4139±2	[34]	4052	[11,34]
					4155.3	[14]
					4156.44	[15]
					4125.9	[18]
					4138.3	[19]
WLIII	$3d^4$ $^5D_3$-$^5D_2$	-	3626±2	[13]	3546.1	[2]
(W^{52+})			3626.7±0.5	[14]	3524	[4]
E_i=4927 eV			3627.13±0.10	[12,20]	3601.5	[9]
					3624.7	[14]
					3625.68	[15]
					3606.8	[18]
					3627.2	[19]

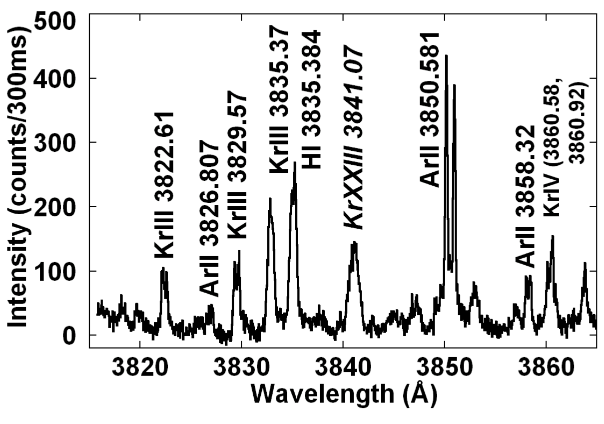

Fig. 3 Spectrum with KrXXIII M1 transition. Italic fonts indicate the Kr M1 line.

bon is a uniquely abundant impurity in LHD and originates mainly in the carbon divertor plates. The MoXXIX line is measured for the first time in PLT tokamak [1]. Other experimental works are performed in EBIT [8].

A spectrum of XeXXXIII (Xe^{32+}: Ti-like) $3d^4$ $^5D_3$-$^5D_2$ 4139.01 ± 0.02 Å is traced in Fig. 5. The Ti-like XeXXXIII measured in LHD is obtained for the first time in laboratory fusion plasmas, whereas several experimental results have been reported using EBITs (see Table 1). High ionization energy is required to produce the Xe^{32+} ions in plasmas in addition to producing a stable discharge without MHD instability. The LHD discharge is very favorable for the study of highly ionized heavy elements. The wavelength of the XeXXXIII determined here is in close agreement with the calculated result of 4138.3 Å. The Hatree-Fock approach including relativistic corrections has been used with semi-empirical adjustments considering the ex-

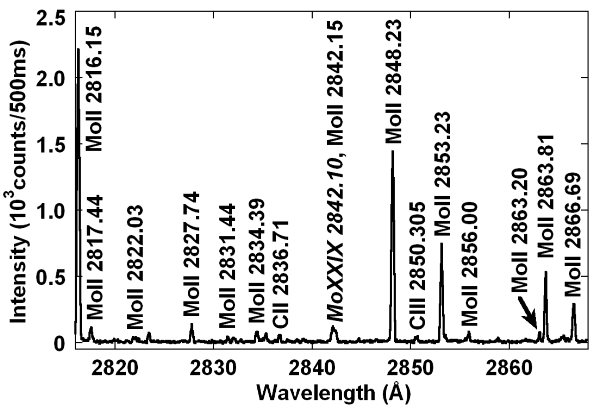

Fig. 4 Spectrum with MoXXIX M1 transition. Italic fonts indicate the Mo M1 line.

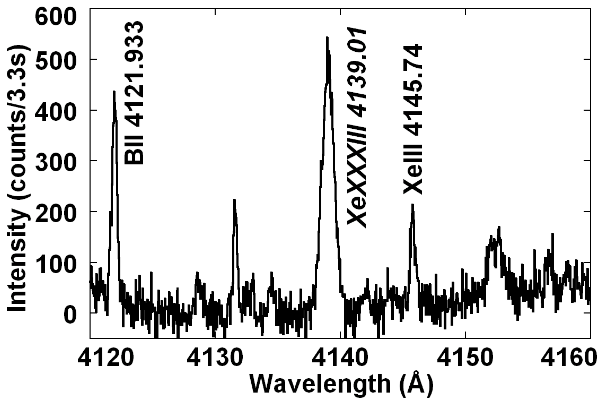

Fig. 5 Spectrum with XeXXXIII M1 transition. Italic fonts indicate the Xe M1 line.

perimental results [19] (see Table 1). Finally, Ti-like WLIII (W^{52+}) M1 transition was attempted to observe by injecting a tungsten-included impurity pellet in LHD. However, it was difficult to measure it, because the amount of W^{52+} was small in LHD discharges. The ionization energy of W^{52+} is 4927 eV and high-electron temperature above 5 keV is necessary for observation of W^{52+}.

In summary, M1 transitions of KrXXII (Kr^{21+}: P-like) $3s^23p^3\ ^2D_{3/2}$-$^2D_{5/2}$ 3463.75 ± 0.05 Å, KrXXIII (Kr^{22+}: Si-like) $3s^23p^2\ ^3P_1$-$^3P_2$ 3841.07 ± 0.03 Å, MoXXIX (Mo^{28+}: Si-like) $3s^23p^2\ ^3P_1$-$^3P_2$ 2842.10 ± 0.05 Å, XeXXXIII (Xe^{32+}: Ti-like) $3d^4\ ^5D_3$-$^5D_2$ 4139.01 ± 0.02 Å have been observed with high accuracy in LHD. These observed M1 lines will be useful to visible impurity spectroscopy in D-T burning plasmas in the future.

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