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EUV Spectra from Xe^{10+} Ions Measured from LHD

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Abstract

We have observed EUV spectra from Xenon ions in Large Helical Device (LHD) in the wavelength range of 10 – 17 nm using a high resolution spectrometer. We compare the spectra with theoretical calculations and identify the spectral lines near 13 nm for the $4d^8 - 4d^7 5p$ transitions of Xe^{10+}. The observed intensity ratios for prominent lines show the plasma conditions for different shots.

Keywords:

EUV spectrum, Xenon ion, low temperature plasma, atomic data, atomic code

1. Introduction

Extreme-ultraviolet (EUV) light sources from compact plasmas are now intensively studied for the next generation of lithography. The emission from multi-charged Xe ions has strong peaks near 11 and 13 nm and the emission near 13 nm is attributed to transitions in Xe^{10+}. Better knowledge of this emission is important for EUV sources and for optimization of a 13.5 nm EUV source.

Recently EUV spectra from Xenon ions in LHD have been measured in the wavelength range 10 – 17 nm. We analyze the spectral lines near 13 nm. We compare the spectra with theoretical calculations and identify the spectral lines from Xe^{10+} ions.

We can make a bench mark test of computer codes using the observed spectral lines. This is important because the theory has not been extensively tested for such high-Z low charge ions.

We will study plasma conditions which give the best EUV emission and will make a collisional radiative model for high-Z many-electron ions.

2. Experimental measurement

Xe gas was puffed into LHD plasma in NIFS and the EUV spectra from Xe ions were measured every 1 sec. The electron temperature at the center of LHD is about 3 keV while the periphery is about 10 – 30 eV. Generally Xe emission is weak in the beginning of the plasma and strong during or after radiation collapse. A 2 m grazing incidence multichannel spectrometer SOXMOS [1] with 600 grooves/mm grating was used for measurement. The measured line-width (FWHM) is $\delta\lambda = 0.023$ nm for the 13.2830 nm Fe XXIII line.

We used the spectra before Xe gas puffing for wavelength calibration. Spectra with and without Xe gas puffing are shown in Fig. 1. Iron Fe XXIII 13.283, Fe XXI 12.873, Fe XXII 13.577, C VI 13.49, Cr XXI 14.987 nm lines were used as references. We also made a wavelength calibration using the theoretical formula given in Ref. [1] with parameters of the incident and diffraction angles, the central wavelength. However this calibration curve does not reproduce the observed reference lines. Therefore we used a calibration by least square fit to several measured reference lines which are shown in Fig. 1.

After wavelength calibration, we compare the observed spectra for different shots plotted on the same wavelength scale. In Fig. 2, we show the observed spectra measured from two different shots in the wavelength scale together with the spectrum without Xe gas. The strong peaks numbered 1, 2, . . . are considered to be lines from Xe ions, based on the comparison to spectra obtained without Xe gas puff, except line no.4 which

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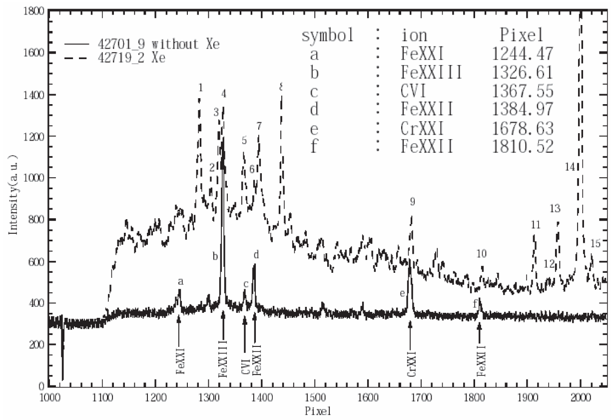

Fig. 1 The observed spectra with xeon (dotted line) and without xenon (solid line).

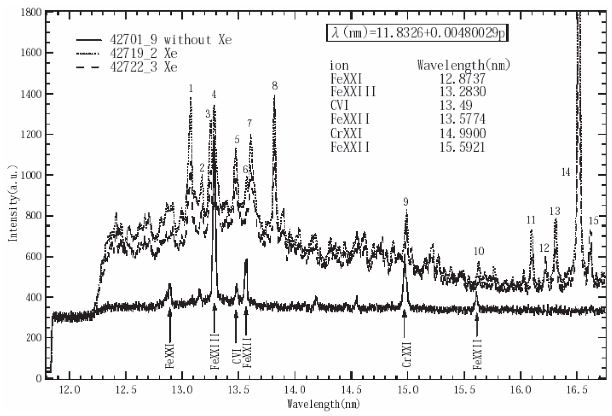

Fig. 2 The observed spectra with xenon ions and without xenon in the wavelength scale.

appears to be blended with a Fe XXIII line.

3. Theoretical calculations

Since the electron configuration for Xe^{10+} is complicated, we cannot find accurate theoretical atomic data. Recently Churilov *et al.* [2, 3] in NIST measured Xe^{10+} spectra and gave a list of prominent lines. Sasaki reports spectra calculated by a collisional radiative model based on atomic data from the Hullac code [4] .

We calculated atomic data with three different atomic codes; MCDF (Multiconfiguration Dirac-Fock) by Y. Ki. Kim [5] and by Fritzche [6], Cowan (Multiconfiguration Hartee-Fock) code [7] in relativistic mode and the Hullac code [8]. The results are compared each other. The schematic energy level diagram calculated by Hullac code for Xe^{10+} is shown Fig. 3. The isolated levels under $4d^75f$ below 100 eV appear when the levels $4d^8$, $4d^74f^1$, $4d^75s^1$, $4d^75p^1$, $4d^75d^1$, $4d^75f^1$ and $4p^54d^9$ are taken into account as input data for Hullac code. They do not appear when only $4d^8$ and $4d^75f^1$ are considered as input data. The dotted line indicates the ionization potential 229.02 ± 0.20(eV) [3].

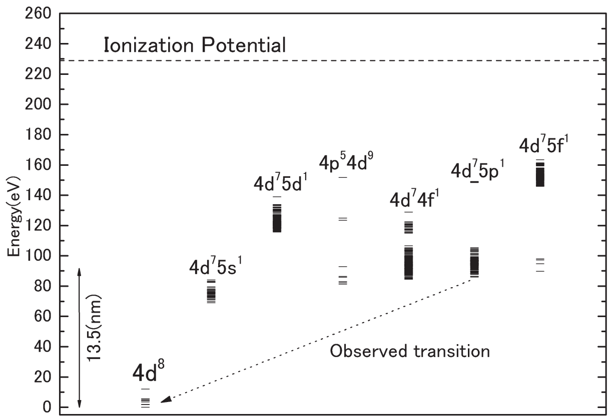

Fig. 3 Schematic energy level diagram for Xe^{10+} calcluted by Hullac [8].

For a many electron system like Xe^{10+} ions, configuration interaction by electron correlation is important. Configurations taken into account in our calculations are $4s^24p^64d^8$ (lower state) and $4s^24p^64d^75p^1$ (upper state) for MCDF code [5], $4s^24p^64d^8$, $4s^24p^44d^{10}$ (lower state) and $4s^24p^64d^75p^1$, $4s^24p^64d^74f^1$, $4s^24p^54d^9$ (upper state) for Cowan code and $4s^24p^64d^8$, $4s^24p^64d^74f^1$, $4s^24p^64d^75s^1$, $4s^24p^64d^75p^1$, $4s^24p^64d^75d^1$, $4s^24p^64d^75f^1$ for Hullac code. The Fritsche's MCDF code [6] includes more than 100 configurations.

We obtain many lines from the results of theoretical codes. Both wavelengths and transition probabilities Ar can be compared. We also compared our measured spectra with Churilov [2,3].

Since it is difficult to compare the atomic data in detail for each line, we made a convoluted spectra with a Gaussian profile assuming the integrated line intensity is equal to theoretical value gA_r (s^{-1}) where g is the statistical weight of the upper level i and A_r is the transition probability from the upper level i to the lower level j. The MCDF calculations include 421 lines and

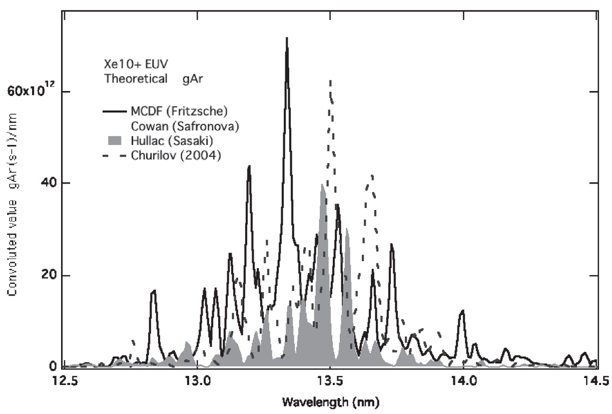

Fig. 4 Theoretical convoluted spectra for Xe^{10+} ions by MCDF [6], Cowan [7], Hullac [8] code and Ref. [3].

589 lines respectively for the codes of reference [5] and [6]. The Cowan code calculation includes 195 lines.

As seen in Fig. 4, the total convoluted spectra look similar and the strong peaks coincide with each other. However the detailed structure are quite different.

4. Comparison of observed spectra with theoretical calculations and identifications

We also compared the observed spectra with theoretical convoluted spectra based on the data by MCDF and Cowan codes as well as Churilov *et al.* [3]. The agreements are not very good. However we can identify the strong lines with an error of 0.01 nm (0.1 A). The comparison of observed spectra with theoretical calculations near 13 nm is shown in Fig. 5. We also compare our observed spectra with the data by Churilov *et al.* [3] in Fig. 6.

The observed lines (number 1 and 8) at 13.071 and 13.820 nm are always strong but the theoretical value of gA_r is not large. The lines with the large theoretical gA_r values are not always strong in measured spectra. One of the reasons is that the observed lines are emitted by excitation by electron impact or recombination. In order to analyze the intensities we need to make a collisional radiative model which includes all these processes. Another reason is the difference in theoretical atomic data. We have identified the strong observed Xe^{10+} lines. Some of the strong lines are identified with the transitions between singlets although the ground state is the triplet $4p^6 4d^8\ ^3F_4$. This suggests the lines are emitted through cascade or recombination. Recombination emission is also supported by the fact that the emission is strong later phase of the plasma.

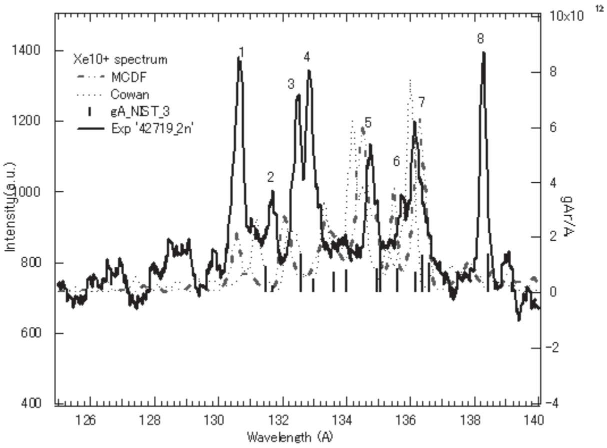

Fig. 5 The observed spectrum (solid line) and the theoretical spectra by MCDF (dot-dashed line) and Cowan code (dashed line).

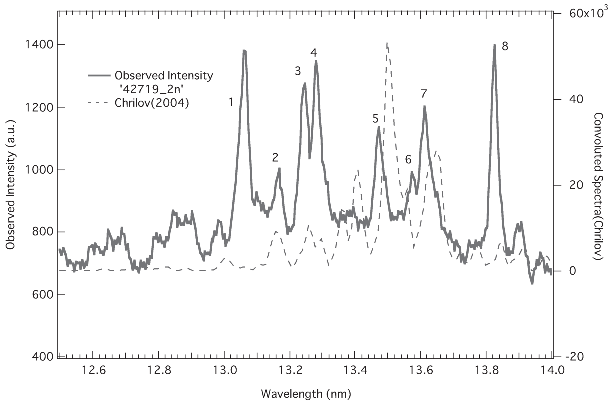

Fig. 6 The observed spectra (solid line) and the spectra by Churilov *et al.* [3] (dotted line).

The comparison of observed lines with the use of the list of lines by Ref. [3] is shown in Table 1. The value of $\Delta\lambda$ in Table1 indicate the wavelength difference between our observed line and Churilov *et al.* [3]. We did not list the data by the MCDF and the Hullac codes, because *LS* coupling scheme is not easy to make correspondence for each level with *jj* coupling scheme.

5. The contribution of highly charged ions

Since the temperature in the center of the plasma is about 2 – 3 keV, highly ionized Xe ions (more than 10+) are expected. We have to confirm that the observed lines are emitted from Xe^{10+} in low temperature plasma. Previously highly ionized Xe ion spectra were measured in TFR Tokamak plasma [9] and W7-AS plasmas [10]. They identified the lines from Xe^{19+} – Xe^{25+} ions. We want to know which ions are the source of the observed lines. In order to know the intensity of the lines produced in plasma, we have estimated the effective emission rate coefficients using Mewe's empirical formula [11] for the lines Xe^{10+} 4d – 5p and Xe^{26+} 4d – 4f transitions both of which emit lines near 13 nm. The effective excitation rate coefficients for two lines are shown in Fig. 7. The rate coefficients for the line of Xe^{26+} is smaller than that of Xe^{10+} by two orders of magnitude.

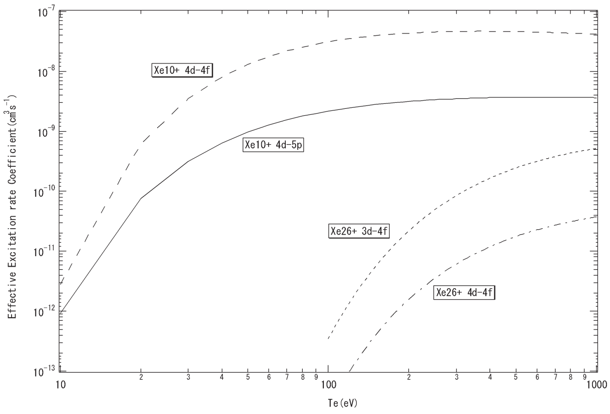

Fig. 7 The effective excitation rate coefficients for Xe^{10+} (4d – 5p) and Xe^{26+} (4d - 4f) lines.

Table 1 Comparison of observed lines (Fig. 2) with the lines listed in Churilov (2004).

	42719_2	42722_3	Churilov[3]	lower level			upper level			
number	wavelength(nm)	wavelength(nm)	wavelength(nm)	configuration	Term	J	configuration	Term	J	⊿λ (nm)
1	13.0712	13.0712	13.0679	$4p^64d^8$	3F	2	$4p^64d^75p^1$	-	1	0.0033
2	13.1768	13.1768	13.1515	$4p^64d^8$	1G	4	$4p^64d^75p^1$	-	3	0.0253
3	13.2536	13.2536	13.2573	$4p^64d^8$	1G	4	$4p^64d^75p^1$	-	3	0.0037
4	13.2872	13.2920	13.2983	$4p^64d^8$	3P	1	$4p^64d^75p^1$	-	2	0.0111, 0.0063
5	13.4744	13.4744	13.5072	$4p^64d^8$	3F	4	$4p^64d^75p^1$	-	5	0.0328
6	13.5704	13.5800	13.5614	$4p^64d^8$	3F	4	$4p^64d^75p^1$	-	4	0.009, 0.0186
7	13.6088	13.6088	13.6213	$4p^64d^8$	3F	3	$4p^64d^75p^1$	-	3	0.0125
8	13.8200	13.8200	13.8459	$4p^64d^8$	1G	4	$4p^64d^75p^1$	-	4	0.0259

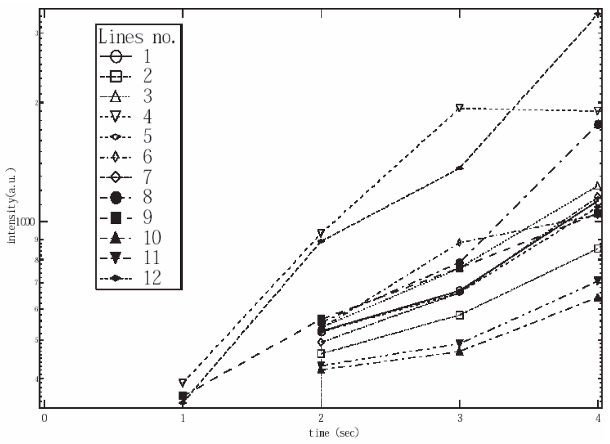

Fig. 8 Time evolution of the lines near 13 nm for shot #42801.

Therefore the density of Xe^{26+} ions should be larger than those of Xe^{10+} by two orders of magnitude if we assume the same electron densities.

In order to know the contribution of highly charged ions we studied the time behavior of line intensities for the shot (#42801) where four spectra are obtained during 4 sec. The plasma collapse at 3.6 sec for this shot and the temperature begins to decrease at 3 sec. Therefore the temperature at 4 sec is considered lower than at the previous time. We plotted the time behavior of the line intensities in Fig. 8. As is seen in Fig. 8, almost all the line intensities increase except no.4 which is considered to be a line from Fe XXIII. This is evidence that most of the lines are emitted from low charge ions like Xe^{10+}. However we can not exclude the possibility of lines of highly charged ions. We are investigating this question. The strongest line No. 14 in Figs. 1 and 2 might be the resonance line of Xe^{24+} ions.

6. Summary

EUV Xe ion spectra from LHD near 13 nm are measured. Theoretical calculations for Xe^{10+} were performed and compared with observed spectra. Several strong lines are identified, although the agreements are not good for some lines. LHD spectra can give a bench - mark test of theoretical data for wavelengths of Xe ions. We are making a model for intensities of high Z ions with many electrons. For different shots, the intensity ratios of several strong lines are different. The different intensity ratios suggest different conditions in plasmas. We can study the optimal condition for Xe ion emissions from the intensity ratios. Strong emission is measured during radiation collapse or after radiation collapse. We will study this difference in the future with a collisional radiative model. We also would like to study the continuum emission near 13 nm observed in the spectra which might be produced by free- free, free-bound and two photon emissions.

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