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THE Cu I AND Zn I-LIKE SPECTRA OF Pr, Eu, Gd, Dy AND Yb EMITTED BY A
TOKAMAK PLASMA IN THE 50-200 Å RANGE

W.L. HODGE⁽¹⁾, M. FINKENTHAL⁽²⁾, H.W. MOOS, S. LIPPMANN,
L.K. HUANG, A. BAR-SHALOM⁽³⁾ and M. KLAPISCH*

Department of Physics and Astronomy, The Johns Hopkins
University, Baltimore, MD 21218, U.S.A.

*Racah Institute of Physics, The Hebrew University,
IL-91904 Jerusalem, Israel

Abstract

Spectra of rare earth elements, praseodymium, europium, gadolinium, dysprosium and ytterbium ($Z=59$ to $Z=70$) have been recorded from a high temperature ($T=1-1.4$ keV) - low density ($n_e=10^{13}\text{cm}^{-3}$) tokamak plasma, in the 50-200 Å range. The absolute brightnesses of the lines originating in $4-4$ transitions of Cu I and Zn I-like ions of the above mentioned elements have been measured by means of a photometrically calibrated grazing incidence spectrometer. Newly identified Cu I-like, $4s^2S_{1/2}-4p^2P_{1/2}$ transitions in Pr^{3+} , Eu^{3+} , Gd^{3+} , Dy^{3+} and Yb^{3+} , and intercombination transitions $4s^2^1S_0-4s4p^3P_1$ in the Zn I-like ions of the mentioned elements are presented. The identifications are based on interpolation of previous experimental results, ab initio energy level computations using the RELAC code and are substantiated by the time histories of individual spectral lines. The experimental line intensities of the Cu I and Zn I-like ions are compared with those predicted by a collisional-radiative model under the conditions of the tokamak plasma.

The present work was motivated by the potential use of Cu I and Zn I-like lines of the rare earth ions as electron density diagnostics of high temperature plasmas. Many of the lines of interest have been previously identified by Reader and Luther (1981) and Doschek *et al.* (1987) for the copper isoelectronic sequence. In the Zn I-like sequence, the $4s^2^1S_0-4s4p^3P_1$ lines have been identified for the elements of interest by Reader and Luther (1980) and Acquista and Reader (1984). Recently, Hinnov *et al.* (1987), have measured intercombination lines of rare earth ions, isoelectronic with Zn I. However, one of the elements we were interested in, europium, has not been investigated by Reader and Luther (1981). We measured and identified in the spectra emitted by the TEXT tokamak plasma, lines emitted by $4s-4p$, $4p-4d$ and $4d-4f$ transitions of Eu^{3+} . Also, the $4s^2S_{1/2}-4p^2P_{1/2}$ transitions in Pr^{3+} , Eu^{3+} , Gd^{3+} , Dy^{3+} and Yb^{3+} are identified for the first time in the present work. Zn I-like, Gd^{3+} , Dy^{3+} and Yb^{3+} intercombination lines emitted within $4s^2^1S_0-4s4p^3P_1$ transitions have been identified.

Ab initio energy level computations using the relativistic parametric potential code RELAC (Klapisch *et al.* 1979) have been used to predict the wavelengths of the Cu I-like and the Zn I-like lines. Also predicted wavelengths of the forbidden (M1) lines $^3P_2\rightarrow^3P_1$ within the $4s4p^3P$ multiplet and magnetic quadrupole (M2) lines originating from the $4s^2^1S_0-4s4p^3P_2$ transition are included in the present work. The line intensities of the CuI-like, Eu^{3+} and Zn I-like lines, emitted in the tokamak spectra have been compared with predictions of a collisional radiative model. (The model is discussed in a recent paper of the authors (Finkenthal *et al.* 1987).

The rare earth elements have been introduced in the TEXT tokamak (at Fusion Research Center, Austin) by the laser blow-off technique (D.R. Terry *et al.* 1983). The experimental conditions are similar to those described by Finkenthal *et al.* (1986).

The spectra, in the 50-200 Å range, were recorded by a grazing incidence time-resolving spectrograph, GRITS (Hodge, Stratton and Moos 1984).

(1) Present address : High Energy Laser Associates, Piedmont, CA 94611, U.S.A.

(2) Permanent address : Racah Institute of Physics, The Hebrew University, IL-91904 Jerusalem, Israel

(3) Permanent address : Nuclear Research Center of Negev, Beer-Sheva, Israel

Figure 1 shows the spectra of europium, gadolinium and dysprosium between 54 and 106 Å. All the spectra show a similar pattern: a band at the shorter wavelength side and a relatively narrow region containing a few bright lines. These bands have been analyzed in a previous work (Finkenthal *et al.* 1986) and shown to originate in $4d^{K-4f}$ and $4p^6 4d^{K-4p^5 4d^{K+1}}$ transitions of ions isoelectronic with Pd I to Rb I. The line spectrum, at the longer wavelength side is dominated by the resonance transitions in the Cu I and Zn I-like ions.

Table 1 presents the identification of the Eu^{3+} lines. Besides the ab initio calculations, interpolated values from the work of Reader and Luther (1981) were used to predict the wavelengths. The identification was quite straightforward for the strong lines presented in the table.

Table 2 presents the newly identified $4s^2 S_{1/2} - 4p^2 P_{1/2}$ transitions in Pr^{3+} , Eu^{3+} , Gd^{3+} , Dy^{3+} and Yb^{3+} ions. If the populations of the two levels $^2P_{1/2}$ and $^2P_{3/2}$ would be at Boltzmann equilibrium, the lines under discussion would be an order of magnitude weaker than those originating from the $4s^2 S_{1/2} - 4p^2 P_{3/2}$ transitions. However, at the relatively low tokamak densities the relative brightness ratios are quite different as indicated in the table for three different ions, Pr^{3+} , Eu^{3+} and Yb^{3+} . The lines being well separated, we assume an accuracy of 0.15 Å in the wavelength measurements. In order to confirm the identification, time histories of the lines under discussion have been compared with those already known emitted by the same ions.

The Zn I-like "intercombination" lines emitted within the $4s^2 ^1S_0 - 4s4p^3 P_1$ transition become stronger as Z increases since the 3P_1 level becomes strongly mixed with the 1P_1 (therefore the transition rates to the ground 1S_0 become higher). Table 3 presents the computed wavelengths of the intercombination, magnetic dipole and magnetic quadrupole lines. In the present work we only present the identification of the intercombination lines; a work in progress is discussing the line intensities of singlet, intercombination and forbidden lines. The $4s^2 ^1P_1 - 4s4p^3 P_1$ lines have been identified, as in the Cu I-like case, by comparison with ab initio interpolated values and comparison of the time histories of the candidate lines with those of the known $4s^2 ^1S_0 - 4s4p^3 P_1$ transitions.

Fig. 1. The Eu, Gd and Dy spectra emitted by the TEXT tokamak in the 50-100 Å range.

Table 1: Experimental and ab initio computed wavelengths of $4-4$ transitions in Eu^{3+} .

Transition	$\lambda(\text{Å})$		$B(\text{ph/cm}^2 \text{ sec sr})$ ($\times 10^{14}$)	B (predicted)
	predicted	measured		
$4s^2 S_{1/2} - 4p^2 P_{3/2}$	107.57	107.7	7.4	100
$4s^2 S_{1/2} - 4p^2 P_{1/2}$	171.03	171.6	4	59
$4p^2 P_{1/2} - 4d^2 D_{3/2}$	78.66	77.9		5
$4p^2 P_{3/2} - 4d^2 D_{5/2}$	100.2	100.0	1	8
$4p^2 P_{3/2} - 4d^2 D_{3/2}$	107.95	?		0.4
$4d^2 D_{3/2} - 4f^2 F_{5/2}$	94.10	?		0.8
$4d^2 D_{5/2} - 4f^2 F_{7/2}$	99.47	bl		1.15

$$n_e = 10^{13} \text{ cm}^{-3}; T_e = 1000 \text{ eV}$$

Table 2: The $4s\ 2S_{1/2}-4p\ 2P_{1/2}$ transitions in Pr^{30+} , Eu^{34+} , Gd^{35+} , Dy^{37+} and Yb^{42+} ions.

Ion	λ^* pred	λ meas
	Å	Å
Pr^{30+}	194.55 (RELAC)	195.7
Eu^{34+}	171.6	171.6
Gd^{35+}	166.5	166.8
Dy^{37+}	156.48 (RELAC)	157.0
Yb^{41+}	140.5 (139.96, RELAC)	140.95

*predicted by Reader and Luther, 1981, or computed ab initio by RELAC.

Table 3: Experimental and predicted wavelengths (RELAC) of allowed and forbidden Zn I-like lines of Pr^{29+} , Eu^{33+} , Gd^{34+} , Dy^{36+} and Yb^{40+}

Ion	Transition		
	$4s^2\ 1S_0-4s4p\ 3P_1$	$4s^2\ 1S_0-4s4p\ 3P_2$	$4s4p\ 3P_2 \rightarrow 3P_1$
	predicted	predicted	predicted
Pr^{29+}	208.5	146.35	491.1
Eu^{33+}	181.9	117.7	333.7
Gd^{34+}	176.1	111.6	304.6
Dy^{36+}	165.44	100.4	255.2
Yb^{40+}	147.2	81.5	182.7

All the predictions are ab initio RELAC computations.

References

- Acquista N. and Reader J. 1984 *J.Opt.Soc.Am.B* 649.
 Doschek G.A., Feldman U., Brown C.M., Seely G.F., Ekberg J.O., Behring W.E. and Richardson M.C., submitted to *J.Opt.Soc.Am.B*, 1987.
 Finkenthal M., Lippmann A.S., Huang L.K., Yu T.L., Stratton B.C., Moos, H.W., Klapish M., Mandelbaum P., BarShalom A., Hodge W.L., Phillips P.E., Price T.R., Porter, J.C., Richards B. and Rowan W.L. 1986 *J.Appl.Phys.* 59 3644.
 Finkenthal M., Moos H.W., BarShalom A., Spector N., Ziegler A., Yarkoni E. 1987, to be submitted *J.Phys.B, At.Mol.Phys.*
 Hinnov E., Beiersdorfer P., Bell R., Steven J., Suckewer S., von Goeler S., Wonters A., Dietrich D., Gerassimenko M. and Silver E., 1987, *Phys.Rev.A* 35 4876.
 Hodge W.L., Stratton B.C. and Moos H.W. 1984 *Rev.Sci.Instr.* 55 116.
 Klapish M., Schwob J.L., Fraenkel B.S., Oreg J. 1979 *J.Opt.Soc.Am.* 67 148.
 Reader J. and Luther G. 1980 *Phys.Rev.Lett.* 45 609.
 Reader J. and Luther G. 1981 *Physica Scripta* 24 732.