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Line identifications and radiative-branching ratios of magnetic dipole lines in Si-like Ni, Cu, Zn, Ge, and Se

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Magnetic dipole transitions within the ground-state configuration of Si-like Ni, Cu, Zn, Ge, and Se have been observed. Seven lines have been newly identified. Observations are made on the Texas Experimental Tokamak by laser-ablation injection of each of these elements into the plasma. The radiative-branching-ratio technique, utilizing lines originating from the same upper level, $3p^2\,{}^1D_2$, is used for the radiometric calibration of a 1-m normal-incidence spectrometer. This calibration is in good agreement with the absolute radiometric calibration obtained by using an argon miniarc.

I. INTRODUCTION

Magnetic dipole ($M1$) transitions within the levels of the ground-state configurations of high-Z ions provide valuable data about high-temperature plasmas. They have been used for the measurements of ion temperature,[1] impurity density,[2] absolute excitation rates,[3] plasma rotation, and impurity transport[4,5] in tokamaks. Also, suitable line pairs of $M1$ lines originating from the same upper level can be used for *in situ* calibration of spectrometers,[6] especially in the vacuum ultraviolet spectral region. In this paper, we describe the identification of several $M1$ lines in the Si isoelectronic sequence. We also describe the radiometric calibration of a 1-m normal-incidence spectrometer (1-m NI), using these $M1$ line pairs, and compare this to the radiometric calibration using a standard argon miniarc source.

II. LINE IDENTIFICATIONS

The experiment is conducted on the Texas Experimental Tokamak (TEXT). The peak electron temperature and the electron density of the hydrogen plasma are 725 eV and 2.5×10^{15} cm^{-3}, respectively. The laser-ablation technique is used to inject the elements nickel, copper, zinc, germanium, and selenium. A detailed description of the injection method and the procedure for line identifications can be found in our earlier papers.[7,8] We utilized three spectrometers for our line identifications: a 2.2-m grazing-incidence instrument, a 1-m NI spectrometer, and a 1-m Czerny Turner spectrometer (1-m CT). The setup is described in Ref. 7. In the present work the 1-m CT is used as a two-channel instrument. It is equipped with two exit ports with a mirror arrangement to direct the output beam to the port of choice. One exit port is equipped with an exit slit and a photomultiplier to use the instrument as a spectrometer. An optical multichannel analyzer (OMA) is set up at the focal plane of the other exit port. Besides these three instruments, a vacuum normal-incidence time-resolving spectrometer (NITS) with a multichannel detector is also used for line identifications. A complete description of the instrument can be found in Ref. 9. The wavelength calibration of the spectrometers is carried out as described in Ref. 7. The 1-m CT with the OMA is calibrated with Hg I lines at 4347.5 and 4358.34 Å from a low-pressure mercury lamp. These lines are scanned across the face of the OMA to determine their relative pixel numbers from one end to the other. The change in dispersion with respect to the pixel number is determined from the pixel separation for these two lines. The maximum change in dispersion noticed was 0.005 Å/pixel.

Our line identifications for the various transitions from the ions of Si isoelectronic sequence are listed in column 4 of Table I. Identifications are carried out with the aid of predicted values published in Ref. 10. Wavelengths below 2000 Å are identified by the 1-m NI. The two vacuum ultraviolet (vuv) lines of selenium are also observed on the NITS. Wavelengths above 2000 Å are observed with the 1-m CT. The ${}^3P_2$-${}^1D_2$ transitions in Ni XV and Cu XVI, and the ${}^3P_1$-${}^3P_2$ transition in Se XXI are observed on the OMA detector as well as on the photomultiplier detector. The uncertainty in our wavelength measurements is ±0.5 Å. This is arrived at from the instrumental linewidth and the fit to the observed line profile, as discussed in Ref. 7. The calculated wavelengths for these transitions are taken from Ref. 10 and are listed in column 3 of Table I.

Two of the listed lines are reported in the literature[11-13] and those wavelength identifications are given in column 5. Our observed wavelength for the Ni XV ion agrees with the solar observation.[11] According to the literature, ${}^3P_1$-${}^3P_2$ line identification in Se XXI is uncertain. Denne *et al.*[12] identified this line earlier at 4396.5 Å on the Princeton Large Torus (PLT) tokamak. However, Burrell *et al.*[13] subsequently reported that they could not

TABLE I. Magnetic dipole lines in the Si isoelectronic sequence. Values above 2000 Å are in air. (The uncertainty in the measured values is ±0.5 Å.)

Ion	Transition	Calculated wavelength[a] (Å)	Observed wavelength (Å) This work	Observed wavelength (Å) Other work
Ni XV	$3p^2\ {}^1D_2$-${}^3P_1$	2085.5	2085.0	2085.51[b]
	${}^1D_2$-${}^3P_2$	2818.01	2816.4	
Cu XVI	${}^1D_2$-${}^3P_2$	2555	2544.7	
Ge XIX	${}^1D_2$-${}^3P_1$	1343	1341.2	
	${}^1D_2$-${}^3P_2$	1816	1809.9	
Se XXI	${}^1D_2$-${}^3P_1$	1070	1069.2	
	${}^1D_2$-${}^3P_2$	1416	1414.2	
	${}^3P_2$-${}^3P_1$	4397.7	4395.4 4424.1[d]	4396.5[c]

[a] Reference 10.

[b] Reference 11.

[c] Reference 12.

[d] Reference 13.

locate this line at 4396.5 Å and they identified a line at 4424.1 Å to be this line. They made their observations on the Doublet-III tokamak. In order to resolve this discrepancy, we scanned both wavelength regions using both the OMA and the photomultiplier modes of operation on the 1-m CT. We could unambiguously locate a line with Se XXI time history at 4395.4 Å±0.5 Å. This wavelength is closer, but 1.1 Å below, to the value of Denne *et al.* We could not locate a Se XXI line at the wavelength of Burrell *et al.* Our value is also closer to the predicted value, shown in Table I.

III. RADIOMETRIC CALIBRATIONS

There are two $M1$ lines from the same upper level ${}^1D_2$ in each of the Si-like ions. These line pairs form very good radiative branches for calibrating the sensitivity of a spectrometer at a specific wavelength with respect to the other branch where a calibration exists. The advantage of using the $M1$ lines is that their transition probabilities are theoretically calculable to a high accuracy.

In a recent publication, Chung *et al.*[14] reported the effect of quenching of the radiative transition probability. They observed a density dependence for the intensity branching ratio of C IV lines, 5801–5812 and 312 Å, which share a common upper level, generated in a laser-produced plasma. They observed the effect only to happen at densities above 10^{17} cm^{-3} for these lines. They analyzed and discounted the possibility of self-absorption. Such a quenching effect is unlikely for low-electron-density plasmas considered here. However, any such effect should cancel out in our case because the transition probability ratio for the line pairs under consideration is close to unity.

According to the branching-ratio method,[6] the relative sensitivity of the spectrometer is given by

$$\frac{\alpha_1}{\alpha_2}=\frac{\lambda_1 A_2 S_1}{\lambda_2 A_1 S_2}\ , \tag{1}$$

where λ_1 and λ_2 are the wavelengths of the lines, S_1 and S_2 are the measured signals (in mV), A_1 and A_2 are the calculated transition probabilities, and α_1 and α_2 are the sensitivities of the spectrometer at λ_1 and λ_2. In the present work, intensities are measured by using the 1-m NI. The sensitivity ratios obtained by using Eq. (1) are listed in Table II. The wavelengths of the lines and the calculated transition probabilities[10] are also given in Table II. The maximum error in signal ratios is estimated to be ±10%, mainly from the shot-to-shot variations in the signals. The wavelength coverage extends from 2816 to 1069 Å as we go from Ni XV to Se XXI along the isoelectronic sequence. The good wavelength overlap between the branches of neighboring ions allows one to extend the calibration from the ultraviolet region to vacuum-ultraviolet region in a stepladder fashion.

The calibration obtained by the branching-ratio method is compared to a standard source calibration. The standard source is an argon miniarc source calibrated at the National Institute of Standards and Technology (NIST). The uncertainty in this calibration is estimated

TABLE II. Branching-ratio calibration of the 1-m normal-incidence monochromator.

Ion	λ (Å)	Transition probabilities[a] (sec^{-1})	Relative sensitivity α_1/α_2
Ni XV	λ_1 2085.0	A_1 194	0.99
	λ_2 2816.4	A_2 205	
Cu XVI	λ_1 1871.3	A_1 332	0.9
	λ_2 2544.3	A_2 328	
Zn XVII	λ_1 1674.2	A_1 556	0.85
	λ_2 2284.6	A_2 526	
Ge XIX	λ_1 1341.2	A_1 1480	0.47
	λ_2 1810.4	A_2 1310	
Se XXI	λ_1 1069.2	A_1 3650	0.34
	λ_2 1414.2	A_2 3130	

[a] Reference 10.

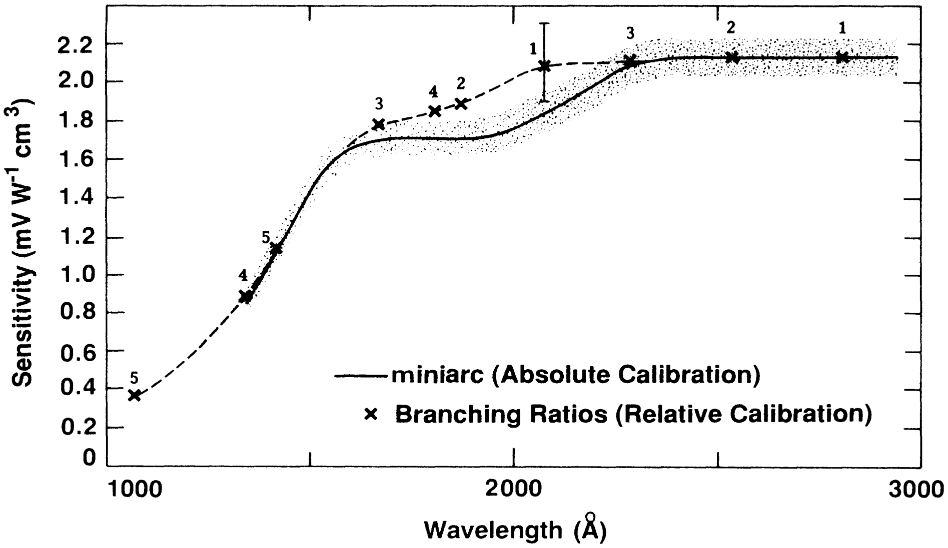

FIG. 1. Calibration of the sensitivity of the 1-m normal-incidence spectrometer (1-m NI).

to be ±5%. It is operated at 1 atm of argon pressure and calibrated as an irradiance standard with a magnesium fluoride window. It is mounted 15 cm away from the entrance slit of the 1-m NI and its light does not overfill the grating. The solid line in Fig. 1 shows the absolute radiometric calibration of the sensitivity of the instrument. The shaded area represents its ±5% uncertainty. The numbered points on the graph are plotted by using the measured sensitivity ratios given in Table II. The value for the longer-wavelength point of each branch is obtained by interpolating between the calibration values for the two lines in the previous branch. The absolute sensitivity value from the miniarc calibration at 2816 Å is used to plot the longest-wavelength point of Ni XV branching ratio as a first step of the ladder. The miniarc standard source calibration is only available from higher wavelength down to 1300 Å because of its magnesium fluoride window cutoff. The dashed curve which overlaps the solid line, for the most part, is the branching-ratio calibration. The agreement is very good considering the uncertainty of ±10% in the experimental branching ratios and the ±5% uncertainty in the miniarc transfer standard.[15] The rapid fall in the sensitivity of the instrument towards shorter wavelengths is the result of the absorption of magnesium fluoride coating on the aluminum grating.[16] In principle, this stepladder approach can be continued to extend the calibration into the soft-x-ray wavelength region by using the *M*1 line pairs along the isoelectronic sequence. Also, the advantage in this method is that the calibration could be done *in situ* on the tokamak.

IV. SUMMARY

Seven new *M*1 lines of Si-like Ni, Cu, Zn, Ge, and Se ions are identified on the TEXT. A previous discrepancy in the identification of the $^3P_1$-$^3P_2$ transition in Se XXI is resolved. Our measured wavelength for the line is 4395.4 Å. The intensities of *M*1 lines are used to radiometrically calibrate *in situ* a 1-m normal-incidence spectrometer. This calibration is compared with the absolute calibration obtained by using an argon miniarc transfer standard source. The agreement is within the experimental uncertainty of ±15%.

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