Relative populations of excited levels within the ground configuration of Si-like Cu, Zn, Ge, and Se ions

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Populations of $3p^2\ ^1D_2, ^3P_1, ^3P_2$ levels in Si-like Cu, Zn, Ge, and Se ions have been deduced from the measurements of absolute intensities of magnetic dipole transitions within the $3s^23p^2$ ground configuration. Observations have been made in the Texas Experimental Tokamak (TEXT). The measured population ratios are compared with theoretical calculations based on the distorted-wave approximation for the electron collisions and a semiclassical approximation for the proton collisions. The observed deviation from the statistical distribution for the excited-level populations within the ground configuration along the silicon isoelectronic sequence is in agreement with theoretical prediction.

Absolute intensities of magnetic dipole transitions within the ground configuration of high-Z ions have been used recently to deduce their ionic abundances in laboratory high-temperature plasmas.[1] However, a statistical distribution had to be assumed for the level populations in the ground configuration. The justification for this assumption was that the electron and proton collisional rates dominate over the forbidden magnetic-dipole transition probabilities and establish statistical distribution among these levels. However, this assumption may not be valid for all the ions in an isoelectronic sequence. This is because the magnetic dipole transition rate increases much more rapidly with Z than the collisional rate. Therefore, for high-Z ions in an isoelectronic sequence, the upper levels of the ground configuration would have populations lower than expected from statistical distribution because of the significant contribution due to magnetic dipole radiative decay. The purpose of this paper is to present an experimental and theoretical study of the deviation from statistical distribution of level populations within the ground configuration of the silicon isoelectronic sequence in a high-temperature plasma.

The silicon isoelectronic sequence was chosen for the present study for the following two reasons: (1) population ratios of different levels in the ground configuration could be examined without having to determine the absolute ground-state population, and (2) ions in the silicon isoelectronic sequence were easily produced in the Texas Experimental Tokamak (TEXT) where the experiment was conducted.

The level structure in the Se XXI ground configuration and the magnetic dipole transitions observed in this ex-

TABLE I. Atomic data and experimental measurements.

Ion and ionization potential	TEXT $N_e=3.0\times10^{13}$ cm^{-3} T_e and T_i for each ion	Transition	Wavelength (Å)	Transition probability (s^{-1})	Measured intensity (W cm^{-2} sr^{-1})	Line of sight upper-state population NI (10^{10} cm^{-2})
Cu XVI	$T_e=600$ eV	$^1D_2$-$^3P_1$	1871.3	332	1.2×10^{-6}	4.2
520 eV	$T_i=400$ eV	$^1D_2$-$^3P_2$	2544.7	328	0.8×10^{-6}	3.9
		$^3P_1$-$^3P_0$	5375.8	107	0.97×10^{-7}	3.1
Zn XVII	$T_e=660$ eV	$^1D_2$-$^3P_1$	1674.2	556	5.5×10^{-6}	10.5
590 eV	$T_i=440$ eV	$^1D_2$-$^3P_2$	2284.6	526	3.9×10^{-6}	10.7
		$^3P_1$-$^3P_0$	4355	200	4.6×10^{-7}	6.3
Ge XIX	$T_e=720$ eV	$^1D_2$-$^3P_1$	1341.2	1480	7.5×10^{-6}	4.3
730 eV	$T_i=480$ eV	$^1D_2$-$^3P_2$	1809.9	1310	4.6×10^{-6}	4.0
		$^3P_1$-$^3P_0$	2933.7	639	1.2×10^{-6}	3.5
		$^3P_2$-$^3P_1$	5170.3	72.4	1.26×10^{-7}	5.7
Se XXI	$T_e=728$ eV	$^1D_2$-$^3P_1$	1069.2	3650	9.8×10^{-6}	1.8
880 eV	$T_i=485$ eV	$^1D_2$-$^3P_2$	1414.2	3130	6.4×10^{-6}	1.8
		$^3P_1$-$^3P_0$	2042	1850	2.7×10^{-6}	1.9
		$^3P_2$-$^3P_1$	4396.5	107	1.0×10^{-6}	2.6

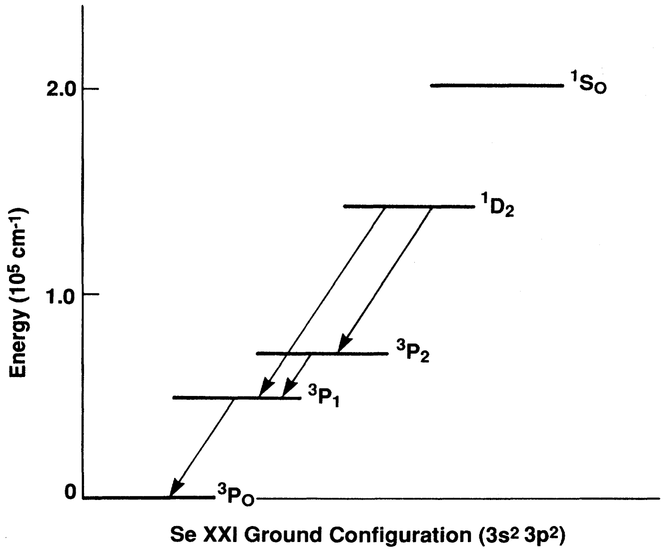

FIG 1. The energy-level structure in the Se XXI ground configuration and the observed magnetic dipole transitions.

periment are shown in Fig. 1. The population density along the line of sight in each excited state is deduced from the measurement of the absolute intensity of a spectral line originating from that level using the equation

$$Nl=\frac{4\pi I\lambda}{hcA}\ , \tag{1}$$

where N is the excited-state population density in cm^{-3}, l is the length of plasma emitting the radiation, I is the line intensity in W cm^{-2} sr^{-1}, λ is the wavelength, A is the transition probability, h is the Planck constant, and c is the velocity of light.

We injected the elements copper, zinc, germanium, and selenium into the hydrogen plasma by using the laser-ablation technique. Our experimental setup of spectrometers at TEXT has been described in an earlier publication.[1] We utilized a 1-m Czerny-Turner air-path spectrometer (CT) for wavelengths above 2500 Å and a 1-m normal-incidence spectrometer (NI) for wavelengths below 2500 Å to measure the spectral line intensities. The spatial locations of peak emission from the ions of interest were determined by the spatial scanning of resonance line emission from these ions utilizing the grazing-incidence time-resolving spectrograph (GRITS). The details about GRITS have been described in Ref. 2. The CT spectrometer was radiometrically calibrated using three different standard lamps: a tungsten strip lamp used as a radiance standard, a tungsten halogen lamp, and a deuterium arc lamp used as irradiance standards. The standard lamps were calibrated at the National Institute of Standards and Technology (NIST). The radiometric calibration of the NI spectrometer using a NIST-calibrated argon miniarc source and the branching-ratio technique has been described in Ref. 3. The solid angles subtended by the spectrometers were calculated from the measurements of the distances and

TABLE II. Experimental ratios of level populations and comparison to theoretical calculations.

Ion	$^1D_2$-to-$^3P_1$ population ratio: Experiment	Distorted-wave calculation a	Distorted-wave calculation b	Boltzmann distribution	$^1D_2$-to-$^3P_2$ population ratio: Experiment	Distorted-wave calculation a	Distorted-wave calculation b	Boltzmann distribution	$^3P_2$-$^3P_1$ population ratio: Experiment	Distorted-wave calculation a	Distorted-wave calculation b	Boltzmann distribution
Cu XVI	1.3	1.4	1.0	1.65		0.9	0.7	0.99		1.6	1.5	1.66
Zn XVII	1.7	1.4	1.0	1.65		0.9	0.7	0.99		1.6	1.5	1.66
Ge XIX	1.2	1.3	0.9	1.65	0.7	0.8	0.6	0.99	1.6	1.5	1.4	1.66
Se XXI	1.0	1.1	0.7	1.64	0.7	0.7	0.5	0.99	1.4	1.4	1.4	1.66

[a]Including proton collisions.
[b]Without including proton collisions.

the areas of precision apertures. The two instruments were cross-checked for their calibrations *in situ* by observing the intensity of the forbidden line of copper at 2544.7 Å using both instruments. The agreement was within the experimental uncertainty of $\pm 20\%$. The measured intensities of the forbidden transitions are given in column 6 of Table I. The upper-state populations along the spectrometer line of sight were deduced from the measured intensities using Eq. (1) and are given in column 7. The atomic data to evaluate Eq. (1) are taken from Ref. 4 and are also given in Table I.

The measurements of electron-density, electron-temperature, and ion-temperature spatial profiles of TEXT plasmas have been described in earlier publications.[1,5] The peak electron temperature, measured by Thomson scattering using a ruby laser, and the electron density, measured by using a microwave interferometer, were 725 eV and 2.5×10^{13} cm^{-3}, respectively. The peak ion temperature was 485 eV. The values of electron temperature and ion temperature corresponding to the spatial location of peak emission of each of the Si-like ions are given in column 2 of Table I. The uncertainty in the temperature measurements is estimated to be $\pm 10\%$.[1,5]

The theoretical calculations of level populations are done by solving steady-state rate equations for the Si-like ionic species. The measured plasma parameters of temperature and electron density given in Table I are used in setting up the theoretical model. Excitations within the ground configuration and to the $3s3p^3$ and $3p^4$ configurations are included in the theoretical model. Collisional and radiative rates are calculated in intermediate coupling. Calculations are done using a distorted-wave approximation for electron scattering. Configuration interactions and relativistic corrections are included in the calculations by using the SUPERSTRUCTURE program developed at the University College, London.[6] The wave functions are calculated using Thomas-Fermi potentials. Proton-induced collisions are included by using a semiclassical approach.[7]

In Table II the experimental ratios of excited-level populations within the ground configuration are compared with the theoretical calculations. Population ratios are considered for comparison because any systematic errors will cancel in the ratio. Using the electron temperature listed in Table I for each ion, the expected ratios for a Boltzmann distribution of level populations are given in Table II. These values are essentially constant along the isoelectronic sequence and are equal to the ratios of statistical weights because the Boltzmann factor is close to unity for our electron temperatures. The experimental population ratios for $^1D_2$ to $^3P_2$ and $^3P_2$ to $^3P_1$ of Cu XVI and Zn XVII are left blank because the forbidden line intensities from the $^3P_2$ level for these ions were very weak and could not be measured. The error in experimental ratios given in Table II for Cu XVI, Zn XVII, and Ge XIX are estimated to be $\pm 20\%$ because of the errors in measuring weak line intensities above the background and the uncertainty of cross calibration of spectrometers. However, the error in the experimental ratios for Se XXI is estimated to be only $\pm 10\%$ because of the improved signal-to-noise ratio as the lines are strong.

The population ratio of $^1D_2$ to $^3P_1$ in the distorted-wave calculation that included the effects of proton collisions is 14% below the constant Boltzmann value for Cu XVI and Zn XVII. It begins to deviate from this value for Ge XIX and falls 33% below the Boltzmann value for Se XXI. The uncertainty in distorted-wave calculations of population ratios is estimated to be $\pm 20\%$.[8] Therefore, the deviation from Boltzmann value for the population ratio of $^1D_2$ to $^3P_1$ in Ge XIX and Se XXI ions is statistically significant and is attributed to the increased contribution of magnetic dipole transition rate in the detailed balance for level populations.

The experimental ratios with $\pm 20\%$ uncertainty for Cu XVI, Zn XVII, and Ge XIX ions and $\pm 10\%$ uncertainty for the Se XXI ion are in agreement with theoretical calculations that included the effects of proton collisions, whereas the values for calculations without proton collisions are much lower than the experimental values as shown in Table II. This establishes the importance of proton collisions in populating the excited levels in the ground configuration. The statistically significant agreement between theoretical and the experimental ratio of $^1D_2$ to $^3P_1$ level populations for Se XXI confirms the predicted effect of the magnetic dipole transition rate in establishing the steady-state populations in the Se XXI ground configuration. Table II also indicates that the population ratios of lower-lying levels ($^3P_2$ to $^3P_1$) are closer to the Boltzmann values in Si-like ions.

In summary, the measured population ratios of the levels in ground configuration of Si-like ions showed good agreement with distorted-wave calculations that included the effects of proton collisions. The deviation from Boltzmann distribution becomes significant for the $^1D_2$ level in Se XXI for TEXT tokamak plasma conditions.

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