# JOSA COMMUNICATIONS

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# $2l$–$3l'$ and $2l$–$4l'$ transitions in heliumlike and hydrogenlike silicon

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Wavelengths are reported for the $n = 2$–$n = 3$ and $n = 2$–$n = 4$ transitions of Si XIII and Si XIV, as observed in a laser-heated plasma. The wavelength range of the observations is 24–40 Å.

Silicon transitions belonging to Balmer series in the He I and H I isoelectronic sequences are of interest in a number of disciplines. Population inversions in heliumlike or hydrogenlike ions are among the most promising schemes for the generation of x-ray lasers.[1,2] Recent theoretical calculations and laboratory demonstrations have shown that significant gain can be achieved in transitions of the type $2l$–$nl'$.[3–5] An important application for x-ray lasers will be in microscopy of biological substances. Such microscopy will have to employ radiation with wavelengths shorter than the $K$ edge of carbon ($\lambda < 42$ Å). An x-ray laser based on the above-mentioned transitions of Si XIII and Si XIV will have the desired wavelength.

Energy levels determined by using the $2l$–$nl'$ transitions in high-$Z$ ions are of interest in evaluating theoretical atomic calculations. Although measurements for the $2l$–$2l'$ transitions in hydrogenlike and heliumlike species exist for fairly high-$Z$ ions,[6,7] measurements of $2l$–$nl'$ transitions with $n > 2$ are available only for neon and lower-$Z$ ions.[8,9] In this research, we present measurements of $2l$–$3l'$ and $2l$–$4l'$ transitions in Si XIII and Si XIV.

The silicon plasma was produced by the OMEGA laser[10] at the University of Rochester's Laboratory for Laser Energetics. Uncoated glass microballoons were spherically irradiated by 24 beams of frequency-tripled (351-nm) laser radiation. Each laser beam carried about 60 J of energy in a 450-psec pulse. The focused intensity on the target surface ranged from $2 \times 10^{14}$ to $1 \times 10^{15}$ W/cm$^2$. The spectra were recorded by a 3-m grazing-incidence spectrograph[11] using Kodak 101-05 photographic plates. The grating had 1200 lines/mm and a blaze angle of 2° 35′. For a 88-deg angle of incidence, the blaze wavelength is about 60 Å. Light from the plasma was focused astigmatically onto the entrance slit of the spectrograph by a gold-coated cylindrical mirror positioned 70 cm in front of the slit and 130 cm from the plasma. A single laser shot was sufficient to produce the observed silicon and oxygen spectra. In two of the exposures, we obtained spectra from the glass microballoons alone, whereas in the remainder the glass-microballoon spectra were superimposed upon other spectra for calibration. Wavelength determinations were possible since the O VII, O VIII, Si X, Si XI, and Si XII lines are well known[12] and the Si XIV lines (H I-like) could be calculated accurately from theoretical energy levels.[13]

Figure 1 is a section of the glass-microballoon spectrum that includes lines of highly ionized silicon and oxygen, together with some of the spectral identifications. The wavelengths were calculated by fitting a fourth-order polynomial to known wavelengths[12] of Si XI, Si XII, Si XIV and O VII, O VIII. As the lines originate in a very hot plasma, they are quite broad, but the absolute accuracy is ±0.01 Å, and the separation of nearby lines is measured to an accuracy of ±0.005 Å.

In Si XIII we have observed lines belonging to four triplet systems: $1s2s$–$1s3p$, $1s2p$–$1s3d$, $1s2p$–$1s3s$, and $1s2p$–$1s4d$. Table 1 reports the calculated and measured wavelengths for the $1s2l$–$1s3l'$ and $1s2l$–$1s4l'$ transitions in Si XIII. Triplet transitions are stronger than the corresponding singlet transitions of the type reported here. The population of the metastable triplet $1s2l$ levels becomes large, and ions from these populations can be easily reexcited upward by collisions. The strongest observed Si XIII line is $1s2p\ {}^3P_2$–$1s3d\ {}^3D_3$, and the second strongest is a blend of the transitions $1s2p\ {}^3P_1$–$1s3d\ {}^3D_2$ and $1s2p\ {}^3P_0$–$1s3d\ {}^3D_1$. The 36.451-Å line is a blend of the three transitions of $1s2s\ {}^3S_1$–$1s3p\ {}^3P_J$. However, the branching ratio for $1s2s\ {}^3S_1$–$1s3p\ {}^3P_1$ is small, so its contribution to the observed line is probably minor. The faint line at 38.66 Å may be the $1s2p\ {}^3P_2$–$1s3s\ {}^3S_1$ transition. Two lines at 28.162 and 28.222 Å are the $1s2p\ {}^3P$–$1s4d\ {}^3D$ transitions. In the singlet system, only the $1s2p\ {}^1P_1$–$1s3d\ {}^1D_2$ is observed. The $1s3p\ {}^1P_1$ level decays primarily into the ground state $1s^2\ {}^1S_0$, and the $1s2p\ {}^1P_1$–$1s3s\ {}^3S_1$ was too weak to observe. The calculated wavelengths are based on a recent compilation of energy levels for silicon ions.[13]

We have observed four lines of Si XIV that are reported in

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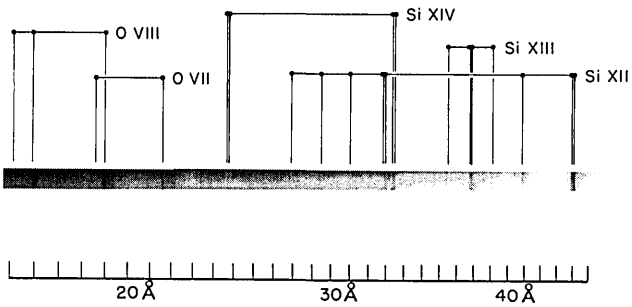


Fig. 1. Spectrum from laser-heated glass microballoon between 15 and 45 Å. Transitions of highly ionized silicon and oxygen are indicated on the figure.

**Table 1. Wavelengths for Si XIII Transitions (in angstroms)**

| Transition | Calculated[a] Wavelength | Measured Wavelength | Int. (Est.) |
|---|---|---|---|
| $1s2p\ ^1P_1$–$1s3s\ ^1S_0$ | 39.415 | – | |
| $1s2p\ ^1P_1$–$1s3d\ ^1D_2$ | 39.100 | 39.109 | 5 |
| $1s2p\ ^3P_2$–$1s3s\ ^3S_1$ | 38.639 | 38.66 ? | 1 |
| $^3P_1$– $^3S_1$ | 38.533 | – | |
| $^3P_0$– $^3S_1$ | 38.506 | – | |
| $1s2p\ ^3P_0$–$1s3d\ ^3D_1$ | 37.761 } | 37.784 | 9 |
| $^3P_1$– $^3D_2$ | 37.786 } | | |
| $^3P_2$– $^3D_3$ | 37.877 | 37.881 | 12 |
| $1s2s\ ^1S_0$–$1s3p\ ^1P_1$ | 37.812 | – | |
| $1s2s\ ^3S_1$–$1s3p\ ^3P_2$ | 36.433 } | | |
| $^3S_1$– $^3P_1$ | 36.461 } | 36.451 | 5 |
| $^3S_1$– $^3P_0$ | 36.469 } | | |
| $1s2s\ ^3S_1$–$1s4p\ ^3P_2$ | 27.341 | – | |
| $^3S_1$– $^3P_1$ | 27.348 | – | |
| $^3S_1$– $^3P_0$ | 27.350 | – | |
| $1s2p\ ^3P_0$–$1s4d\ ^3D_1$ | 28.163 } | 28.162 | 1 |
| $^3P_1$– $^3D_2$ | 28.177 } | | |
| $^3P_2$– $^3D_3$ | 28.221 | 28.222 | 1 |
| $1s2p\ ^1P_1$–$1s4d\ ^1D_2$ | 28.908 | – | |

[a] For details, see Ref. 13.

**Table 2. Wavelengths for Si XIV Transitions (in angstroms)**

| Transition | Calculated[a] Wavelength | Measured Wavelength | Int. (Est.) |
|---|---|---|---|
| $2s\ ^2S_{1/2}$–$3p\ ^2P_{1/2}$ | 33.355 | – | |
| $^2P_{3/2}$ | 33.308 } | 33.309 | 5 |
| $2p\ ^2P_{1/2}$–$3d\ ^2D_{3/2}$ | 33.302 } | | |
| $^2P_{3/2}$– $^2D_{5/2}$ | 33.444 | 33.443 | 8 |
| $2s\ ^2S_{1/2}$–$4p\ ^2P_{1/2}$ | 24.710 } | | |
| $^2P_{3/2}$ | 24.699 } | 24.703 | 2 |
| $2p\ ^2P_{1/2}$–$4d\ ^2D_{3/2}$ | 24.696 } | | |
| $^2P_{3/2}$– $^2D_{5/2}$ | 24.779 | 24.778 | 2 |

[a] For details, see Ref. 13.

Table 2. Two lines are $2l$–$3l'$-type transitions, and two are $2l$–$4l'$. The 33.443- and 24.778-Å lines are unblended, whereas the other two are blends. The intensity figures given in the tables are visual estimates of plate blackening.

As can be seen from the tables, the agreement between the measured and calculated wavelengths is rather good. In order to test the quantum electrodynamics effects involved in calculating the silicon energy levels observed here, it will be necessary to improve the wavelength determinations by at least a factor of 3.

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