SATELLITE LINE SPECTRA FROM LASER-PRODUCED PLASMAS

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Received 1973 October 22; revised 1974 February 11

ABSTRACT

We have obtained X-ray spectra of high-temperature plasmas produced by the 100 GW glass laser at the Naval Research Laboratory. In this paper, we discuss the satellite lines of hydrogen-like and helium-like ions, observed in the 2–12 Å region for elements ranging from sodium through titanium. The satellite lines are due to transitions of the type, \( 1s^n l - 2p^l n \), \( n = 2, 3 \); and \( 1s^2 l - 2s^2 l 3p \). Physical conditions in the plasma are discussed in terms of relative line-intensity ratios and line profiles.

Subject headings: plasmas — spectra, laboratory — spectra, X-ray

I. INTRODUCTION

In the last few years there has been considerable interest in the spectra of hydrogen-like and helium-like ions, and associated satellite lines which are due to transitions from doubly excited configurations. Resonance lines and satellite lines of elements ranging from carbon through nickel fall between ~1.6 and ~40 Å, and these lines from cosmically abundant elements are important features in the spectra of solar flares in the X-ray region. The satellite lines that we discuss are due to three types of transitions. The satellites of hydrogen-like ions near \( \lambda a \) arise from transitions of the type, \( 1s n l - 2p n l \), \( n = 2, 3 \). The satellite lines of helium-like ions are due to transitions of the type, \( 1s^2 n l - 1s 2p n l \), \( n = 2, 3 \); and \( 1s^2 2l - 1s 2l 3p \). Some of these transitions were first reported by Edlén and Tyrén (1939).

Recently, Gabriel (1972) has shown that the ratios of the satellite lines to the resonance lines of the helium-like ions may be used to (a) determine the electron temperature of the plasma, and (b) determine the departure of the plasma from ionization equilibrium. Thus, the satellite lines are an important diagnostic tool for determining physical conditions in high-temperature, highly ionized plasmas in both astrophysical and laboratory plasmas.

The solar-flare observations of satellite lines are summarized in Walker and Rugge (1971), Neupert (1971), Doschek (1972), and Grineva et al. (1973). Good reviews of the literature concerning laboratory observations of satellite lines may be found in Gabriel and Jordan (1969) and Walker and Rugge (1971). Recent laboratory observations have been reported by Peacock, Hobby, and Galanti (1973).

In this paper, we present satellite spectra of most of the elements from sodium through titanium, obtained from laser-produced plasmas. The relative line intensities and line profiles are discussed in terms of physical conditions in the laser plasmas, and are compared with expectations based on Gabriel’s (1972) development of the theory. Some of our measured intensities are apparently not in agreement with Gabriel’s results.

II. THE EXPERIMENT

The present spectra were obtained from plasmas produced by focusing a high-powered (100 GW) glass laser pulse (\( \lambda = 1.06 \mu m \)) onto solid targets containing the particular elements considered. The pulse duration was 0.9 ns, and the energy on target ranged from ~20 to ~60 joules. McMahon and Emmett (1971) have described the early development of this laser system. A description of the present system is given by McMahon and Barr (1973).

The laser beam was focused by means of a f1.9 lens onto the targets, which were enclosed in vacuum. The size of a well-focused spot was less than 75 μ. The resulting plasmas, produced by conversion of laser energy into thermal energy of the target material, were about 250 μ in diameter. The plasma had lifetimes of the order of nanoseconds.

To obtain some of the satellite spectra discussed in this paper, a prepulse was delivered onto the target to produce partial ionization of the plasma before the arrival of the main pulse. This was accomplished by diverting a few joules of the main pulse along a shorter path length to the target. The time difference between...
The satellite lines of the hydrogen-like ion are also produced by inner-shell excitation of the lithium-like ion, because the upper levels are metastable to autoionization. Thus, the dielectronically produced satellites may be used to determine the electron temperature, and the satellites produced by inner-shell excitation may be used to determine the departure from ionization equilibrium.

Goldsmith (1969) has shown that most of the satellite lines of the hydrogen-like ion are also produced by dielectronic recombination. Clearly, a similar theory should apply to the formation of these lines.

### III. DATA AND DISCUSSION

The satellite lines are diagnostically important because these lines are produced by two different atomic processes. Gabriel and Jordan (1969) have shown that most of the lithium-like satellites are produced primarily by dielectronic recombination of the helium-like ion. Therefore, the intensities of these satellites are proportional to the rate coefficient for dielectronic recombination and the fractional abundance of the helium-like ion. Ratios of the intensity of the lithium-like satellites to the intensity of the helium-like resonance line are therefore independent of the fractional abundance of the helium-like ion. However, these ratios are temperature dependent, because the resonance line is produced by electron impact excitation, which has a temperature dependence different from that of dielectronic recombination. On the other hand, some of the lithium-like satellites are primarily produced by inner-shell excitation of the lithium-like ion, because the upper levels are metastable to autoionization. (Dielectronic recombination is the inverse process of autoionization.) Thus, the dielectronically produced satellites may be used to determine the electron temperature, and the satellites produced by inner-shell excitation may be used to determine the departure from ionization equilibrium.

Goldsmith (1969) has shown that most of the satellite lines of the hydrogen-like ion are also produced by dielectronic recombination. Clearly, a similar theory should apply to the formation of these lines.

### TABLE 1

<table>
<thead>
<tr>
<th>Key*</th>
<th>Transition</th>
<th>Na X</th>
<th>Mg XI</th>
<th>Al XII</th>
<th>Si XIII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Å)</td>
<td></td>
<td>(Å)</td>
<td>(Å)</td>
<td>(Å)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(cm⁻¹)</td>
<td>(cm⁻¹)</td>
<td>(cm⁻¹)</td>
</tr>
<tr>
<td>1.</td>
<td>1s²2p ¹P - 2p² ¹D</td>
<td>10.195</td>
<td>9.811,000</td>
<td>8.550</td>
<td>11.696,000</td>
</tr>
<tr>
<td>2.</td>
<td>1s²2p ³P - 2p⁵ ³P</td>
<td>10.170</td>
<td>9.833,000</td>
<td>8.529</td>
<td>11.725,000</td>
</tr>
<tr>
<td>3.</td>
<td>1s²2p² ³P - 2p⁵ ³P</td>
<td>10.157</td>
<td>9.845,000</td>
<td>8.521</td>
<td>11.736,000</td>
</tr>
<tr>
<td>4.</td>
<td>1s²2p² ³P - 2p² ³P</td>
<td>10.119</td>
<td>9.882,000</td>
<td>8.493</td>
<td>11.774,000</td>
</tr>
<tr>
<td>5.</td>
<td>1s²2p² ³P - 2p⁵ ³P</td>
<td>10.060</td>
<td>9.940,000</td>
<td>8.445</td>
<td>11.841,000</td>
</tr>
<tr>
<td>6.</td>
<td>1s²2p² ³P - 2p² ³P</td>
<td>10.029</td>
<td>9.971,000</td>
<td>8.425</td>
<td>11.869,000</td>
</tr>
<tr>
<td>7.</td>
<td>1s²2p² ³P - 2p² ³P</td>
<td>10.023</td>
<td>9.977,000</td>
<td>8.419</td>
<td>11.878,000</td>
</tr>
</tbody>
</table>

* See fig. 1.
† Blend.

### a) Satellites of the Hydrogen-like Resonance Lines

The satellite lines of the hydrogen-like lines have not been as extensively investigated as the lithium-like satellites of the helium-like lines. Walker and Rugge (1971) have summarized the data known up to the present work, and have determined electron temperatures in solar active regions using satellite spectra of magnesium.

We have obtained satellite spectra for the hydrogen-like ions of sodium, magnesium, aluminum, and silicon. The wavelengths of lines and multiplets we have observed are given in table 1, along with respective energies and classifications. The experimental wavelengths were obtained by choosing appropriate lines due to transitions from singly excited hydrogen-like and helium-like ions as wavelength standards. The identifications of the satellite lines were made by comparing our experimental results with extrapolations of satellite lines previously observed in the elements lighter than sodium, e.g., Feldman and Cohen (1969) and Feldman et al. (1974). To classify the lines, we relied on previously reported data for F viii (Feldman et al. 1974). The F viii satellite lines were classified by comparison with ab initio HX calculations done by one of us (R. D. C.). The HX computer programs include relativistic effects, intermediate coupling, and configuration interaction, and are described in greater detail elsewhere (Cowan 1967, 1968). Excellent agreement was found between the experimental and ab initio wavelengths for F viii. The tentative identifications of the blends due to 1s³l₂-2p³l were based entirely on the theoretical calculations for F viii, and the similar wavelength correspondence of these features in the heavier ions.

Figure 1 shows the helium-like satellites of sodium, magnesium, and aluminum. The numbers over the lines are keyed to the numbers in table 1. We defer a discussion of the relative intensities and widths of these lines to §§ IIIc and d.

### b) Satellites of the Helium-like Principal Series

The satellite lines of the helium-like ions are due to three main types of transition arrays: 1s²2l-1s²2l3p;
Fig. 1.—Satellite lines of the $1s^2 S_{1s} - 2p^2 P_{1/2,3/2}$ La lines. The numbers refer to the transitions in table 1. Note the fine-structure splitting of the $La$ aluminum line.

$1s^2 nl - 1s^2 p^m$, $n > 2$; and $1s^2 2l - 1s^2 2l$. The first type of transitions, i.e., $1s^2 2l - 1s^2 3l$, have been observed by us for the ions magnesium, aluminum, silicon, and sulfur. They fall on the long-wavelength side of the $1s^1 S_{1s} - 1s^3 P_1$ helium-like line. We have identified these lines by relying exclusively on the ab initio calculations performed by one of us (R. D. C.), and the results are given in table 2. The experimental wavelengths were again derived by choosing appropriate lines due to transitions from singly excited states of hydrogen-like and helium-like ions as wavelength standards. Some of the data are shown in figure 2, keyed to the letters in table 2. Our results, coupled with the theoretical calculations, confirm the identifications of these transitions in spectra of solar flares (Neupert 1971; Doschek and Meekins 1973) and in spectra of solar active regions (Walker and Rugge 1971).

The satellites of the second type of transitions fall very close to, and mostly on the long-wavelength side of the resonance line of the helium-like ion. The different possible multiplets are badly blended, and for large $n$, they merge with the resonance line. We were only able to resolve clearly the emission of the blended $n = 3$ multiplets. We have observed such transitions for the ions from sodium through titanium, excluding argon, phosphorus, and scandium. The identifications have been made using the theoretical calculations of Summers (1973), and the results are given in table 3. These blended multiplets may be seen in figures 3 and 4, and are indicated by the number, 1, above the transition. Transitions of this type have been observed by Parkinson (1972) in solar-active-region spectra of neon and magnesium. Experimental wavelengths were obtained in a manner to be described below.

The most extensively analyzed satellites are those of the third type of transition, $1s^2 2l - 1s^2 2l$. Gabriel (1972) has calculated wavelengths for all the lines of this array for selected elements from carbon through copper. These wavelengths were adjusted by comparison with experimental results for some of the lighter ions such as oxygen.

### Table 2

**Satellite Lines of the $1s^2 1S_{1s} - 1s^3 P_1$ Helium-Like Line**

<table>
<thead>
<tr>
<th>Key*</th>
<th>Transition</th>
<th>Mg x</th>
<th>Al xi</th>
<th>Si xii</th>
<th>S xiv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\lambda$ (Å)</td>
<td>$\sigma$ (cm$^{-1}$)</td>
<td>$\lambda$ (Å)</td>
<td>$\sigma$ (cm$^{-1}$)</td>
</tr>
<tr>
<td>1</td>
<td>$1s^2 2p^2-1s^2 2p(P) P_{3/2} + S_{1/2}$</td>
<td>8.092</td>
<td>12,358,000</td>
<td>6.824</td>
<td>14,654,000</td>
</tr>
<tr>
<td>2</td>
<td>$1s^2 2p^2-1s^2 2p(P) P_{3/2} + D_{3/2}$</td>
<td>8.071</td>
<td>12,390,000</td>
<td>6.805</td>
<td>14,695,000</td>
</tr>
<tr>
<td>3</td>
<td>$1s^2 2p^2-1s^2 2p(P) P_{3/2} + S_{1/2}$</td>
<td>8.057</td>
<td>12,412,000</td>
<td>6.792</td>
<td>14,723,000</td>
</tr>
<tr>
<td>4</td>
<td>$1s^2 2p^2-1s^2 2p(P) P_{3/2} + D_{3/2}$</td>
<td>8.037</td>
<td>12,442,000</td>
<td>6.780</td>
<td>14,749,000</td>
</tr>
<tr>
<td>5</td>
<td>$1s^2 2s^2 2ls-1s^2 2s_{3/2} P_{3/2}$</td>
<td>7.998</td>
<td>12,503,000</td>
<td>6.748</td>
<td>14,819,000</td>
</tr>
<tr>
<td>6</td>
<td>$1s^2 1S_{1s}-1s^3 P_1$</td>
<td>7.850</td>
<td>12,738,000</td>
<td>6.636</td>
<td>15,072,000</td>
</tr>
</tbody>
</table>

* See fig. 2.
† Wavelengths obtained from Ermolaev and Jones (1973).
We experienced a difficult problem in obtaining good experimental wavelengths for some of our spectra of these lines. The problem arose because, due to the experimental arrangement, only the helium-like resonance line (1s^2 1S_0 -1s2p 1P_1), the helium-like intercombination line (1s^2 1S_0 -1s2p 3P_2), and the 1s^22P_1 -1s2p2P_1 satellite lines, were recorded in most of the spectra. However, the intercombination line is blended with satellite lines that are of comparable intensity, and therefore only one helium-like line, i.e., the resonance line, could be chosen as a known wavelength standard for calibrating the films. Furthermore, many of the satellite lines predicted by Gabriel are badly blended in the spectra. Thus, it is difficult to give meaningful experimental wavelengths for these features even assuming that accurate wavelength calibrations could be obtained.

We therefore decided to obtain wavelengths for these particular types of transitions in the following way. From our earlier work on fluorine (Feldman et al. 1974) and from the recently obtained high-resolution solar-flare iron spectrum obtained by Grineva et al. (1973), it can be seen that Gabriel's wavelengths for the 1s^22p 2P_3/2 -1s2p 2D_5/2 and 1s^22p 2P_1/2 -1s2p 2D_3/2 satellite lines are accurate enough to be chosen as wavelength standards. These lines appear relatively unblended in our spectra, and we have visually identified the lines by comparing their relative positions with the resonance and blended intercombination lines of the helium-like ions. This allows us to use

### Table 3

<table>
<thead>
<tr>
<th>Ion</th>
<th>λ (Å)</th>
<th>θ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na IX</td>
<td>11.029</td>
<td>9,067,000</td>
</tr>
<tr>
<td>Mg X</td>
<td>9.190</td>
<td>10,881,000</td>
</tr>
<tr>
<td>Al XI</td>
<td>7.773</td>
<td>12,865,000</td>
</tr>
<tr>
<td>Si XII</td>
<td>6.661</td>
<td>15,013,000</td>
</tr>
<tr>
<td>S XIV</td>
<td>5.049</td>
<td>19,806,000</td>
</tr>
<tr>
<td>Cl XV</td>
<td>4.452</td>
<td>22,462,000</td>
</tr>
<tr>
<td>K XVII</td>
<td>3.537</td>
<td>28,272,000</td>
</tr>
<tr>
<td>Ca XVIII</td>
<td>3.181</td>
<td>31,437,000</td>
</tr>
<tr>
<td>Ti XX</td>
<td>2.614f</td>
<td>...</td>
</tr>
</tbody>
</table>

* The features are indicated by the number, 1, in figs. 3 and 4.

† This multiplet is too badly blended in titanium to give a meaningful wavelength.
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Fig. 4.—Satellite lines of the $1s^23s_2-1s2p^2P_{\text{3}1/2}$ resonance line of the helium-like ions. The number, 1, refers to the transitions in table 3, and the letters indicate the transitions in table 4.

either of the unblended satellite lines and the helium-like resonance lines as wavelength standards to calibrate the spectra. In the heavier ions such as calcium, the satellite lines merge close enough to the intercombination line so that the intercombination line may be chosen as a standard. This alternative approach for the heavier ions gave results that agreed within 0.001 Å (the experimental accuracy) with results based on the satellite-line standard.

Because of the severe blending of some of the satellite lines, we do not give a table with experimental wavelengths. Rather, the data are shown in figures 3 and 4 as microdensitometer tracings corrected for the film response. In table 4 we have listed Gabriel's theoretical wavelengths for the most intense of the expected satellite lines, and have indicated the positions of these lines with letters and tick marks in the figures. For ease in comparison with Gabriel's results, we have chosen the same key letters used by Gabriel (1972).

c) Discussion of Intensities

We confine our discussion of intensities to the lithium-like $1s^22p-1s2p^2P_{\text{3}3/2}$ type transitions, and the helium-like satellites, $1s2p^22P_{\text{3}1/2}-1s2p^22S_{\text{1}1/2}$. Autoionization rates for the other types of transitions are not yet available.

From inspection of figures 3 and 4, the following differences in the spectra of the $1s2p^22L_{\text{1}1/2}-1s2p^22S_{\text{1}1/2}$ type transitions can be seen in proceeding from sodium through titanium:

1) The intensity of the intercombination line $y$, blended with the satellite lines $m$, $n$, $s$, and $t$, increases with increasing atomic number $Z$ relative to the intensity of the resonance line, $w$.

2) The intensity ratio of satellite lines $q$ and $r$ to satellite lines $k$ and $j$ decreases in proceeding from sodium through titanium. This effect is especially clear if data for elements lighter than sodium are examined, e.g., fluorine; see Feldman et al. (1974).

3) The intensity of the blended emission near lines $a$ and $d$ increases relative to the intensities of lines $k$ and $j$ for the heavier ions. This effect is made especially clear by comparing the data for chlorine and calcium. In fact, the intensity of lines $a$ and $d$ rivals the intensity of lines $k$ and $j$ in titanium.

4) In addition to these differences in line intensities, note that the predicted position of line $y$ in the lighter

<table>
<thead>
<tr>
<th>Table 4: Computed Wavelengths*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key</strong></td>
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<tr>
<td>a...</td>
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<tr>
<td>d...</td>
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<tr>
<td>m...</td>
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<tr>
<td>n...</td>
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<tr>
<td>q...</td>
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<tr>
<td>r...</td>
</tr>
<tr>
<td>t...</td>
</tr>
<tr>
<td>w...</td>
</tr>
<tr>
<td>y...</td>
</tr>
</tbody>
</table>

* In angstroms, Gabriel 1972.
† See figs. 3 and 4.
‡ Interpolated or extrapolated wavelengths from Gabriel (1972). Accuracy is ~ ±0.002 Å.
§ Wavelengths obtained from Ermolaev and Jones (1973).
ions—sodium, magnesium, and aluminum—does not coincide with the peak of emission in the vicinity of this line.

5) Also, the predicted position of lines \( a \) and \( d \) for some of the elements such as chlorine does not appear to coincide with the peak of emission in the vicinity of these lines.

The above differences between heavy- and light-ion spectra can be easily accounted for in a qualitative manner with the possible exception of items (2) and (5). Consider first item (2). According to Gabriel's (1972) relative line intensities, lines \( q \) and \( r \) should be somewhat less than, but comparable in intensity with lines \( k \) and \( j \), at least for elements with \( Z \lesssim 16 \), regardless of the state of ionization equilibrium. In the case of sulfur, for example, the minimum value of the theoretical ratio is 0.79, which would occur in the event that the plasma is in a state of extreme transient ionization. However, although lines \( q \) and \( r \) are blended with \( a \) and \( d \) in our data, it is clear that the experimental intensity ratio is no greater than \(~1/4\). Furthermore, in the case of extreme transient ionization, the intensity ratio of lines \( a \) and \( d \) to \( j \) and \( k \) should be \(~3\) for sulfur. Again the experimental ratio is \(~1/4\).

It is suspected (Bhalla, Pollard, and Hein 1973) that Gabriel's autoionization rates, which were derived from Propin's (1960, 1961, 1964) results, may be too large by an as yet undetermined amount. This may lead to some of the anomalies in relative line intensities. Perhaps an additional complication may arise from the high densities of these plasmas, which could lead to considerable optical depth in some of the lines. If resonance scattering were important for some of the satellite lines, their intensities could be substantially reduced because of the probability of autoionization upon absorption. It seems clear that the forbidden line of the helium-like ion, i.e., \( 1s^21S_0-1s2s^3S_1 \), which falls near lines \( k \) and \( j \), cannot be contributing to the intensities near \( k \) and \( j \), because this line will be quenched by electron impact excitation to \( 1s2p^2P_1 \), or by ionization from \( 1s2s^2S_1 \). Even if this assumption is incorrect, the forbidden line could only contribute to satellite line \( j \), and not to line \( k \), in the heavier ions such as calcium.

We also note that the helium-like satellites appear to show the same type of intensity behavior, as can be seen from the data in figure 1. Multiplet 3 is expected to be comparable in intensity to the \( 1s2p^1P_1-2p^21D_2 \) line (line 1).

We have no good explanation for item (5). The emission is so severely blended in the region of lines \( a \) and \( d \) that it is not possible to interpret the apparent line displacement. In this connection it should also be noted that there is some error in positioning the lines on the densitometer tracings due to errors in estimating the wavelengths of the lines used as standards. Our relative wavelength errors are believed to be \(~0.001\) Å for sodium, and correspondingly less for heavier ions.

The other differences among the spectra are more easily accounted for. The increase of the blended intercombination to resonance line ratio (item 1) can be accounted for by: (1) an increase in the absolute intensity of line \( y \) due to an increasing decay rate \( A(1^1S_0-2^3P_3) \) with increasing \( Z \), i.e., for small \( Z \), the \( 2^3P_1 \) level may be partially quenched by ionization (Griem 1973); (2) an increase in intensity of the satellite lines, \( m, n, s, \) and \( t \) relative to the resonance line as \( Z \) increases. Gabriel (1972) shows that the satellite intensities relative to the resonance-line intensity scale as \( Z^4 \) for autoionization rates large compared with radiative rates; and (3) a decrease in the peak intensity of the helium-like resonance line due to multiple scattering.

The increase of \( a \) and \( d \) relative to lines \( k \) and \( j \) for the heavier ions (item 3) is indicative of an increasing abundance of the lithium-like ion relative to the helium-like ion as \( Z \) increases, and is qualitatively expected from Gabriel's theory. The strong intensity of this line indicates that the laser plasmas are in a state of transient ionization.

The deviation of line \( y \) from the peak of the emission near this line (item 4), which is observed in the lighter ions of sodium and magnesium in particular, has three possible explanations. First, the satellite lines \( m, n, s, \) and \( t \) are of comparable intensity to the intercombination line. The emission in the region of line \( y \) is broadened toward short wavelengths, an effect that is shown clearly in the silicon data. However, in the spectra of F viii (Feldman et al. 1974), the intercombination line is the strongest line in the blend. Similarly, for the heavy ions such as calcium, the intercombination line \( y \) falls at the peak of the emission feature.

A second possible explanation for the apparent displacement of line \( y \) in the spectra of the lighter ions is that the intercombination line is emitted primarily in the outer regions of the plasma, where the electron density is lower. In the dense central portion of the plasma, the \( 2^3P_1 \) level may be quenched by ionization collisions (Griem 1973). In this case, assuming that the resonance and satellite lines are emitted in the denser regions, the apparent wavelength of the intercombination line would be shifted toward the resonance line by an amount which is in fact consistent with the observed displacements for the lighter ions. The effect would not be noticeable for higher-Z ions because the \( 2^3P_1 \rightarrow 1^1S_0 \) decay rate increases rapidly with \( Z \).

A third possible explanation for the deviation of line \( y \) from the emission peak is suggested by the recent work, of Peacock et al. (1973). They have found that in their laser plasmas, the emission from the satellite lines comes from a small region near the surface of the target. Emission from the helium-like ions comes from a more extended region. In this case, our use of the helium-like resonance line and the satellite line \( j \) as wavelength standards would be misleading and would lead to the effect observed in the position of line \( y \).

In view of the anomalous intensities observed in our spectra, and in view of the possibility of substantial optical depth in the resonance lines, we cannot give a reliable electron temperature based on satellite-to-resonance-line intensities. In fact, if the laser plasmas are in extreme transient ionization, i.e., where the
process of dielectronic recombination is negligible compared with inner-shell excitation, the satellite-line to resonance-line ratios give no information on electron temperature, but can only give the lithium-like to helium-like ion ratio.

As mentioned, the helium-like satellite lines also appear to show the same anomalous intensities as the lithium-like ions. One interesting question, however, is the mechanism of formation of the 1s2p 3P-2p 3P multiplet (lines 2 in fig. 1), which is analogous to lines a and d in figures 3 and 4, and which is metastable to autoionization. We suggest that this line is formed by electron-impact excitation of the excited triplet states of the helium-like ions, i.e.,

$$1s2p \, ^3P + e \rightarrow 2p \, ^3P + e' .$$

If optical depth effects are neglected, the intensity $I_s$ (photons s$^{-1}$ sr$^{-1}$) of the 1s2p 3P-2p 3P multiplet would then be

$$I_s = \frac{V}{4\pi} N_s N(1s2p \, ^3P) C(1s2p \, ^3P \rightarrow 2p \, ^3P),$$

(1)

where $N(1s2p \, ^3P)$ is the population of the 1s2p 3P levels, $V$ is the plasma volume in which the satellite line is emitted, $N_s$ is the electron density, and $C$ is the excitation coefficient (cm$^3$ s$^{-1}$). Assuming that the helium-like intercombination line is emitted from the same volume, $V$, the intensity ratio $R$ of the satellite line to the intercombination line would be

$$R = \frac{3N_s C(1s2p \, ^3P \rightarrow 2p \, ^3P)}{A(1s2p \, ^3P \rightarrow 1s^2 \, ^1S_0^0)},$$

(2)

where the factor 3 accounts for the fact that $N(1s2p \, ^3P)$ represents the total population of the 1s2p 3P levels, while the intercombination line is due only to the decay rate, $A$, from 1s2p 3P, at the high densities in laser plasmas.

Equation (2) may be applied to our data for fluorine (Feldman et al., 1974). For the fluorine plasma we obtained an electron temperature $T_e \gtrsim 4 \times 10^6$ K, from resonance line ratios. For $T_e = 4 \times 10^6$ K, equation (2) gives $N_s = 6 \times 10^{10}$ cm$^{-3}$, using the Gaunt factor approximation in evaluating $C$ (van Regemorter 1962), and the oscillator strengths calculated by one of us (R. D. C.). We previously obtained a density of $5 \times 10^{19}$ cm$^{-3}$ using the Stark broadening of higher members of the Lyman series of F IX, and the principal series of F VIII, which is consistent with the density derived here from the satellite- to intercombination-line ratio.

**d) Line Profiles**

As mentioned, the data shown in figures 1-4 have been corrected for the nonlinear photographic effect by application of the H and D response curves of the film. It is therefore possible to measure half-widths of lines, since the intensity ordinate of the figures is a true intensity, and not a density. In figure 2, the full width at half-maximum (FWHM) of the 1s2p 3P-2p 3P line (2) for aluminum is 6.7 mÅ. If we assume an ion temperature of $\sim 10 \times 10^6$ K, which is consistent with electron temperatures derived from resonance-line ratios assuming coronal equilibrium (Klein et al. 1973), then, from the FWHM, the source size is 260 μ. This result, which is consistent with pinhole photographs (Holzrichter et al. 1973), assumes Gaussian distributions for the Doppler line shape and for the intensity distribution over the cross-section of the plasma viewed by the crystal.

The widths of other satellite lines, and also the principal series lines of the hydrogen-like and helium-like ions, are all consistent with ion temperatures between $\sim 10 \times 10^6$ K and $\sim 20 \times 10^6$ K, and source sizes between ~200 and 300 μ. There may also be some broadening due to resonance absorption.

**IV. CONCLUSIONS**

We have observed and classified satellite lines to the principal series lines of hydrogen-like and helium-like ions for elements ranging from sodium through titanium. Comparisons of the data with a recent theoretical development by Gabriel (1972) indicate a discrepancy between theory and experiment in certain relative line intensities. These differences may only be apparent, i.e., perhaps due to optical depth in some of the satellite lines.

According to Gabriel's theory, the strength of the satellite lines $a$ and $d$ to lines $k$ and $j$ indicate that the laser plasmas are in a state of transient ionization. In plasmas of elements such as calcium and titanium, the satellite intensities rival the intensities of the helium-like resonance line.

From a line profile of aluminum the source size is 260 μ, assuming an ion temperature of $10 \times 10^6$ K. Half-widths of other lines are consistent with similar ion temperatures and source sizes. In the lighter-ion spectra, apparent shifts in wavelength may be due to spatial emission properties of the plasma.

These laboratory experiments should form the basis for a reliable spectroscopic diagnostic tool that can be applied to solar-flare plasmas, and perhaps other intriguing astrophysical plasmas. Further laboratory observations of satellite lines, and more detailed calculations of autoionization rates, should resolve the apparent discrepancies between experiment and the theory of formation of these lines. The theory can also be extended to the helium-like satellites, and to the lithium-like satellites of the 1s 1S0-1s2p 3P line of the helium-like ions. The theory has the advantage, from the experimental standpoint, that all the relevant spectral lines are close in wavelength, which mitigates calibration problems.

We thank Dr. John Stamper, Dr. John McMahon and in particular Orville Barr for their generous assistance, and T. deRieux and L. Scott for operating the laser. We also thank Drs. R. C. Elton, T. N. Lie, Hans Griem, and M. Blaha for helpful conversations.
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