EXPERIMENTAL MEASUREMENT OF DIELECTRONIC SATELLITES TO THE He-LIKE ALUMINIUM Is2-1s2p 1P1 RESONANCE LINE FROM LASER PRODUCED PLASMAS

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EXPERIMENTAL MEASUREMENT OF DIELECTRONIC SATELLITES TO THE He-LIKE ALUMINIUM $1s^2-1s2p\,^1P_1$ RESONANCE LINE FROM LASER PRODUCED PLASMAS


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Abstract:— We present here experimental observations of satellite structure to the $1s^2-1s2p$ resonance lines of He-like Aluminium emitted from short pulse (20psec), dense ($n_e<10^{23}/cm^3$) laser produced plasmas. A Johann type PET (002) crystal spectrometer with high resolving power was used to make accurate line intensity measurements, which have given estimates of the electron temperature and density for these plasma conditions. The results are compared with theoretical calculations.

1. INTRODUCTION
Satellite structure to the resonance lines of He-like ions has been observed in high temperature astrophysical and laboratory plasmas, and generally is a strong feature of the x-ray spectra emitted from laser produced plasmas, Peacock et al [1]. For the cases of astrophysical and magnetically-confined plasmas, reasonable success has been achieved in understanding the plasma conditions from the satellite line intensity ratios, see Dubau and Volonté [2], DeMichelis and Mattioli [3] for examples. However, laser plasmas are more difficult to diagnose accurately since they rapidly become non steady-state with shorter laser pulse durations $<100$psecs and have large temperature and density gradients. This also applies to the interpretation of H-like and He-like resonance lines, but the advantage of satellite line diagnostics is that they are affected less strongly by opacity since the lower state in the transition is not the ground state. Nonetheless, several authors, including Jacobs and Blaha [4], Lunney [5], have performed detailed calculations which show that as well as the electron temperature, electron density information can also be gained from the satellite line ratios when $n_e$ exceeds $10^{19}/cm^3$ for $Z=13$ (Al). These calculations are compared with the results achieved here.

Dielectronic satellites of the type $1s^2nl-1s2pn1$ and $1s^2nl-1s2sn1$, with $n>2$, in Lithium-like ions are the most prominent and mainly appear on the long wavelength side of the resonance line $1s^2\,^1S_0-1s2p\,^1P_1$ (w) and intercombination lines $1s^2\,^1S_0-1s2p\,^3P_{1,2}\,(x,y)$ of the He-like ion, as shown for Aluminium in Figure 1. (The metastable forbidden line $1s2s\,^3S_1\,(z)$ present in Tokamak spectra [6], which coincides with the $j,k,l$ satellites for Aluminium, is not observed in laser plasmas due to collisional de-excitation [7]). The lines are
The upper level of the satellite line can be populated by either dielectronic recombination through electron capture by the He-like ion or through direct inner-shell excitation of the Li-like ion. For a recombining plasma the former is usually the main excitation process though in conditions of rapid ionization the latter can also contribute. The line intensities of the He-like ion and their satellites are strongly dependent on the plasma conditions, particularly the state of ionization, and the excited-state population distributions can vary between the coronal and LTE limits.

2. EXPERIMENTAL CONDITIONS AND INSTRUMENTATION

The spectra recorded here were emitted from solid and buried layer planar Aluminium targets illuminated with a high irradiance ($10^{16}$ Watts/cm$^2$ of $\lambda=0.52\mu m$ green light) 20psec pulse, single beam of the RAL VULCAN glass laser. This is part of a current suprathermal electron transport study at densities approaching $n_e \sim 10^{23}$/cm$^3$. The aim of the experiment was to show that in addition to thermal electron conduction heating matter at close to solid densities, there is increased suprathermal electron pre-heating due to the nature of the very short pulselength of short wavelength light at high
intensity. Further details and preliminary results of the experiment are discussed elsewhere [9]. The buried layer targets, discs of 300μm diameter having an Al layer of 0.2μm thickness under a plastic ablator top coat of 0.1-1.0μm, were designed to minimise opacity broadening of the resonance lines. The laser beam was focused to a spot size of 50μm diameter and a typical shot had 7J on target.

Two crystal spectrometers, a filtered pinhole camera and an x-ray diode array were used to monitor the x-ray emission from the plasma. A flat PET (002) (2d=8.74Å) crystal spectrometer [10] with moderate resolving power (λ/Δλ=500) recorded (on Kodak DEF film) the He-like and H-like resonance lines of Aluminium, as well as the K-emission from the deeper Cl, K and Ca layers. This spectrometer provided electron density ne information from the Stark width of the 1s^2-1s3p ^1P_1 Al XII line using computer code calculations [11], and an estimate of the electron temperature Te from the slope of the Al XII recombination continuum. A Johann type PET (002) crystal spectrometer [12] with high resolving power (λ/Δλ=7000) observed the n=2 transitions of He-like and H-like Al ion in the waveband 7.0-7.9Å. The crystal radius of R=300mm was chosen to maximise the spectrometer throughput and to achieve the required bandpass the target was placed inside the Rowland circle, about 90mm from the crystal. A 2μm Mylar window coated with 85Å of Al was placed in front of the crystal to protect it from reflected laser light and target debris. A time integrated spectrum was recorded in a single laser shot on Kodak DEF 392 x-ray film, which was protected from scattered visible and UV light by a 2μm filter coated with 1000Å of Al.

![Figure 2](image_url)

**Fig 2** shows power law fit, as described in Section 3, to Al XII 1s^2-1s2p ^1P_1 resonance line. Experimental points are represented by solid circles and best fit, using parameters indicated, shown by a solid line. (Arrow indicates long wavelength cutoff for fit to resonance line). Continuous blend of n ≥ 3 satellites is also shown and contributes 31% to the total line emission. The film fog level is at zero intensity on graph which indicates that the background intensity at 0.06ph/μm^2 is due to x-ray continuum emission.
3. ANALYSIS

The film was developed as described by Henke et al [13], followed by removal of the back emulsion coating to increase the signal to noise ratio. This S/N improvement was essential for accurate fitting of the low intensity Lorentzian wing feature of the spectral lines. The images were densitometered with a Joyce-Loebl MkIII micro-densitometer with matched influx/efflux 0.1NA optics, then digitised onto computer. The film optical density was converted into x-ray photon density using an analytical function for the film response based on the tabulation of [13]. An absolute sensitivity curve for the spectrometer, including the crystal reflectivity, the filters and geometry, was

![Diagram](image-url)

Fig 3 (above) shows the Al XI n=2 satellites at 7.85-7.89\AA in more detail. The spectrum was emitted from a solid Al target. Experimental points, represented by solid circles, have been fitted for the q,r and j,k,l multiplets. (The l-line, occurring under the j-line, is weak). The intensity ratios $I(q,r)/I(j,k,l)$ and $I(a-d)/I(j,k,l)$ become density sensitive when $n_e > 10^{19}$ cm$^{-3}$, discussed further in Section 4. The satellite line widths are narrower than the $1s^2$-1s2p resonance line Fig 2, possibly due to a combination of weaker Stark broadening (the additional electron has a screening effect), less opacity broadening and the emission coming from different plasma regions.
calculated to convert the data to absolute x-ray emission. The spectrometer sensitivity varied by 8% over the waveband shown in Fig 1, mainly because of the increasing crystal reflectivity with wavelength.

A power law profile \( L(x) \), shown below, was used to fit the experimental points where the peak intensity \( A \), centroid position \( x_0 \), FWHM \( \omega \), power \( n \) and background continuum \( B \) were allowed to vary for each line. The line position \( x \) was then converted to wavelength \( \lambda \) using a dispersion equation for a Johann spectrometer [14], which took account of the Rowland circle geometry and the crystal parameters. (Accurate wavelength measurements of all lines shown in Fig 1 have been made and will be published shortly.)

Fig 2 demonstrates the excellent fit to the \( 1s^2-1s2p \) Al XII resonance line and reveals the contribution from the Li-like \( n \geq 3 \) satellite lines on the long wavelength side. The FWHM \( \omega \) is 6.60mA, where the instrumental width, limited by the crystal diffraction width, contributed -17% to this value. When compared to the expected Stark width \(-3.3\text{mA} \) [15] for \( n_e \) approaching \( 10^{23}/\text{cm}^3 \), this suggests that the line is partly broadened by opacity. This is confirmed to some extent by Fig 3 which shows that the satellite line widths are narrower, \(-4.5\text{mA} \). This, however, could also be explained by the satellites having weaker Stark broadening (the additional electron having a screening effect) or the emission coming from different plasma regions. Further study of Stark broadening of satellite lines is needed plus spatial and temporal resolution of the plasma emission.

4. SATELLITE INTENSITY INTERPRETATION

The following results present a preliminary comparison of the experimental satellite density-sensitive line intensity ratios with some theoretical code calculations [4,5]. Various authors have shown that some satellite lines become density sensitive once \( n_e \) exceeds \( 10^{19}/\text{cm}^3 \) (for \( Z=13 \)). In principle the satellite line ratios should show no density dependence but should vary with the ionisation balance and therefore the electron temperature \( T_e \). However, at high densities collisional transitions occur between the auto-ionizing levels and re-distribute the populations. The intensity of the \( j,k,l \) multiplet which is strong at low densities is largely unaffected by electron collisional transitions between the auto-ionizing levels but remains a function of temperature. From Figs 1 and 3, the \( j,k,l \) and \( q,r \) ratios to the \( 1s^2-1s2p \) resonance line give a \( T_e \) of 300eV and 260eV respectively using tabulations of [4]. The addition of these collisional processes enhances the \( a-d \) multiplet intensity which is considerably weaker at low densities. The data of Fig 3 for laser irradiance of a solid Al target, suggest from the ratio \( I(a-d,q,r)/I(j,k,l) \) that \( n_e=5\times10^{22} \) while Fig 4 suggests \( n_e=8\times10^{22}/\text{cm}^3 \) for the Al coated with a 0.5um ablater. (This latter result is confirmed by the \( 1s^2-1s3p \) Al XII Stark width which suggests \( n_e=7\times10^{22}/\text{cm}^3 \) [15].)
In summary, accurate profile measurements of x-ray emission lines have been made using a Johann type spectrometer with high resolving power which is independent of the plasma dimensions or its distance from the crystal. The improved data is also a result of the high instrumental throughput, giving good S/N ratios, and the use of data analysis techniques.

The experimental data shown here have shown some agreement between the plasma density measurement from the Stark width of the $1s^2-1s3p$ Al XII line and the $1s^2-1s2p$ Al XII satellite structure. Interpretation of the satellites is limited mainly by the theoretical model approximations and the time averaged x-ray emission. Further work is required in modelling these transient plasma conditions and obtaining $n_e$ information from the Stark widths of the satellite lines.

This experiment is to be repeated on the RAL SPRITE KrF laser [17] using 5J of UV light ($\lambda=0.25\mu m$) in a 10psec pulse. Time resolved spectra of the $1s^2-1s3p$ Al XII resonance line and the $1s^2-1s2p$ satellite structure using the high resolution Johann spectrometer will give more accurate information on the plasma density, particularly for the x-ray emission after the laser pulse has ended, and remove some uncertainty in the interpretation of time-integrated data.
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