Measuring the oscillator strength of intercombination lines of helium-like V ions in a laser-produced-plasma

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Abstract

We present results of measurements of the oscillator strength of intercombination lines of He-like Vanadium ions in high energy density (HED) laser-produced-plasmas and compare them with the simulations from commonly used codes and data from the NIST database. Whilst not yet sufficiently accurate to constrain different trusted atomic-physics models for the particular system studied, our results are in agreement with the available data within experimental error bars, yet differ from cruder approximations of the oscillator strength used in certain atomic-kinetics packages, suggesting that this general method could be further extended to be used as a measurement of the oscillator strength of additional atomic transitions under the extreme conditions that are achieved in HED experiments.

Keywords: oscillator strength, cylindrical plasmas, spectroscopy

1. Introduction

X-ray spectroscopy is a commonly used technique to diagnose the temperature [1, 2, 3, 4, 5, 6, 7, 8, 9] and density [2, 10, 11, 12, 13] of hot plasmas. In particular, ratios of intensities of different lines are often compared with

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calculated spectra to infer the conditions of the plasma. However, the results obtained from this comparison rely on the accuracy of the line strengths and transition rates used for the synthetic spectra, which depend on the fidelity of complicated atomic physics models.

Depending on the completeness of the model used and the approximations included, the calculated rates for a particular transition can vary considerably [14], which results in the wrong conditions being inferred from the experimental data. A particularly interesting example of the problems that can arise owing to the difference between calculations and experiments is that of the ratio between the $3C$ and $3D$ components of the fine structure of the $(2p^5\ 3d) \rightarrow (2p^6)$ transition in Fe XVII. Although these lines are commonly emitted from hot astrophysical bodies, they are poorly fitted by models, as calculations predict a larger ratio for the oscillator strength of these lines than what measurements have shown [15, 16]. As more precise measurements are obtained, the difference between the calculated and measured ratio of oscillator strengths persists, making this an ongoing problem in astrophysical spectroscopy.

Additionally, recent quantum electrodynamic (QED) calculations have shown that for a sufficiently high temperature of the plasma, the rate of radiative transitions induced by the thermal radiation field within the plasma can be of the same order of magnitude as the spontaneous radiative decay rate [17]. This is particularly important for high energy density (HED) science, as it might be a non-negligible effect at the extreme conditions that are generated in these cases.

Experimentally benchmarking the results from transition rate calculations with experimental data is non-trivial, as measuring these values in well characterised systems requires complicated and very specific experimental designs. Since the construction of the Electron Beam Ion Trap [18] (EBIT) machine in 1988, there has been significant progress in studying the atomic properties of highly charged ions [19, 20, 15]. Additionally, new techniques to measure the absolute value of oscillator strengths have recently been developed [21, 22]. Nevertheless, although the contribution from EBIT has been of great importance, the data are still scarce.

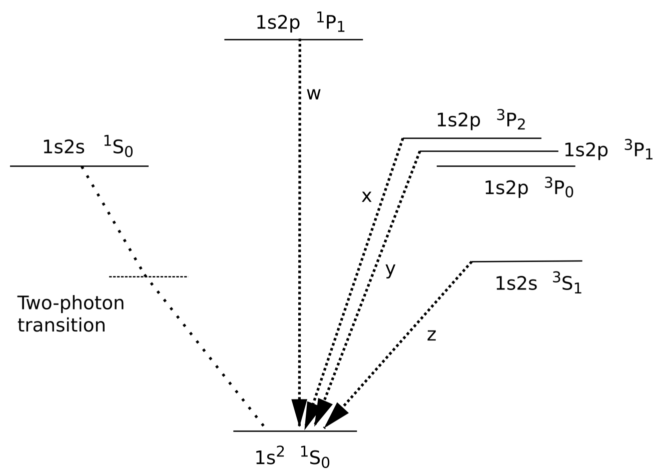


Figure 1: Configuration of the excited states of the Heα complex showing the four transitions involved. We focus in particular on the w and y lines, as the x and z lines are not present in HED plasmas in most cases.

In a recent publication, we showed that the ratio of intensities of an optically thick to an optically thin line can be used as a reliable diagnostic of the optical depth, and hence the ion density of HED cylindrical plasmas, when measured from two different directions of observation [23]. In particular, we focused on the resonance and intercombination components of the Heα complex ($1s2p \to 1s^2$), hereafter referred to as w and y lines (using Gabriel's notation [24]) and shown in Figure 1 together with the remaining components of the Heα complex. Experimental validation of this method was recently obtained [25] at the OMEGA laser facility [26]. It is in the above context that we show here that by using the same experimental set-up implemented in those experiments, it is possible to extend our method for measuring the optical depth of a given transition, into a measurement of its oscillator strength, albeit admittedly at present with quite limited accuracy.

The paper is structured as follows. First, the equations detailing how the oscillator strength can be obtained from the line ratios are detailed, with focus on the simplifications that arise from using the w and y lines. Secondly, the experimental set-up from the OMEGA experiments is briefly described, as it was discussed in depth in a previous publication [25]. Finally, the results obtained for the oscillator strength of the y line of vanadium are shown, and compared with those from commonly used atomic kinetics codes, as well as with the data from the National Institute of Standards and Technology (NIST). Finally we discuss how the experimental design could be extended to study different atomic transitions and reduce the uncertainties in the measurement.

2. Theory

Consider a spectrometer observing a perfectly cylindrical plasma. We make the common assumption that the detector is sufficiently far from the plasma so that all the rays reaching the detector are parallel. Additionally, the detector is assumed to see all of the plasma. These approximations hold for the OMEGA experiments here reported, given that the size of the targets is of the order of $\sim 100\,\mu\text{m}$, and the detectors are placed $\sim 30\,\text{cm}$ away from the center of the target chamber.

If the spectrometer has a face-on view of the target (that is, it is looking down the axis of the cylinder), the ratio between the spectral flux of two lines at line center, can be written as

$$\left.\frac{F_1}{F_2}\right|_{FO} = \frac{S_1}{S_2}\,\frac{1-e^{-\kappa_1 H}}{1-e^{-\kappa_2 H}}, \tag{1}$$

where S_i is the value of the source function of each line at line center, κ_i is the opacity of the transition at line center, and H is the thickness of the cylinder.

The side-on view (looking down the radial direction) is slightly more complicated to calculate explicitly, but can be approximated with good accuracy as

$$\left.\frac{F_1}{F_2}\right|_{SO} = \frac{S_1}{S_2}\,\frac{1-e^{-1.45\kappa_1 R}}{1-e^{-1.45\kappa_2 R}}, \tag{2}$$

where R is the radius of the cylinder and the factor 1.45 accounts for the fact that not all the rays travel the same path along the radial direction. In the optically thin limit, this factor becomes $\pi/2$, but when optical depth considerations are taken into account, using this approximation reduces numerical errors [23].

These expressions can be further simplified if one of the lines considered is optically thick, for example, by taking the aforementioned w and y components of the Heα complex. For elements with $Z \sim 20 - 30$ the opacity of the w lines is ~ 20 times greater than that of the y line. It is therefore possible to design experiments that render the w line completely optically thick, while keeping the optical depth of the y line below a few units. In that case, it is possible to approximate, $(1 - e^{-\kappa_w H}) \sim (1 - e^{-1.45\kappa_w R}) \sim 1$.

By taking lines 1 and 2 as w and y respectively, equations 1 and 2 take the following form

$$\begin{aligned} \left.\frac{F_w}{F_y}\right|_{FO} &= \frac{S_w}{S_y} \; \frac{1}{1-\exp(-\kappa_y H)} \\ \left.\frac{F_w}{F_y}\right|_{SO} &= \frac{S_w}{S_y} \; \frac{1}{1-\exp(-1.45\kappa_y R)}, \end{aligned} \tag{3}$$

and dividing the expression for face-on view by its equivalent for side-on view, one obtains

$$\frac{F_w/F_y|_{FO}}{F_w/F_y|_{SO}} \sim \frac{1 - \exp\left(-1.45\kappa_y R\right)}{1 - \exp\left(-\kappa_y H\right)}. \tag{4}$$

Equation 4 relates magnitudes that are directly observable in experiments (the flux of two spectral lines from two different directions of emission and the thickness and radius of a cylindrical plasma) with an intrinsic atomic property (the opacity at the experimental conditions). Therefore, by measuring the observables, it is possible to obtain the exact value of κ_y, hereafter denoted as just κ.

Furthermore, the opacity of a given spectral line at line center is given (in SI units) by

$$\kappa = \frac{1}{4\pi\varepsilon_0} \cdot \frac{\pi e^2}{m_e c} n_i F f \phi_0, \tag{5}$$

where n_i is the ion density of the plasma, F is the fraction of ions in the ground state of the transition (in this case the He-like ground state), f is the oscillator strength and ϕ_0 is the value at line center of the normalized line profile function. Therefore, if the temperature and density of the plasma are known, the opacity of a line is entirely determined by F and f.

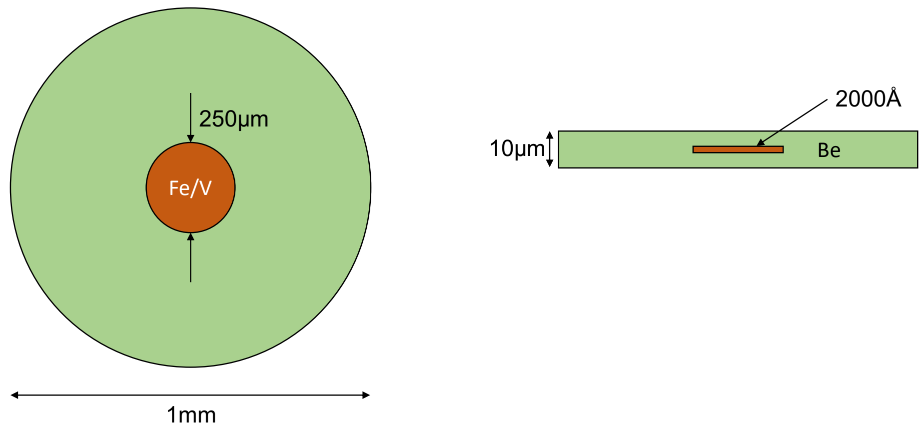


Figure 2: Schematic drawing of the targets used in the experiment. View from the top (left) and side (right). The green disk corresponds to the Be tamper, whereas the brown region represents the Fe/V dot. The thickness of the dot has been exaggerated for clarity.

This is simplified once again by considering HED plasmas where, at the usual conditions, the fraction of ions in the He-like ground state is relatively simple to estimate, and most calculations agree within $\sim 5-10\%$. Therefore, by combining equations 4 and 5, one can calculate the oscillator strength of the y transition from the w/y ratios measured from two different views of a plasma cylinder, provided that the dimensions of the cylinder, as well as its temperature and density, are known.

3. Experimental set-up

All the quantities referred to above were measured in recent experiments conducted at the OMEGA Laser facility [26], at the Laboratory for Laser Energetics (LLE) in the University of Rochester. The targets were disks 250 μm in diameter and 2000 Å thick, made of a mixture of Iron and Vanadium (volumetrically equal). These dots were buried in a Be tamper disk 1 mm in diameter and 10 μm thick, with 5 μm of tamper on either side of the target disk. The larger radius of the tamper was designed to provide radial pressure to the target and keep it cylindrical during the expansion [27]. A schematic drawing of the targets is shown in figure 2.

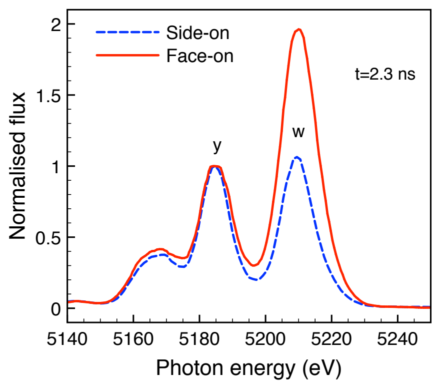
36 beams irradiated the targets, 18 of them impinging on each face of the Be tamper with a total of $3 \times 10^{14}\,\mathrm{Wcm}^{-2}$ of 3ω light on each side of the target. A 3 ns square pulse was used, with a total energy of 10 kJ.

Time-resolved X-ray images of the expanding cylinders were recorded using two X-Ray Pinhole Camera (XRPINH), whereas the K-shell spectral emission was measured with two Multi-Purpose Spectrometer (MSPEC). The detectors were fielded such that in every shot one XRPINH and one MSPEC were looking face-on to the plasma, and the other XRPINH and MSPEC had a side-on view. By adjusting the timing of all four diagnostics, using this configuration we could measure the face-on and side-on spectra from the target with the MSPECs at the same time that the thickness and radius of the cylinder were measured with the XRPINHs.

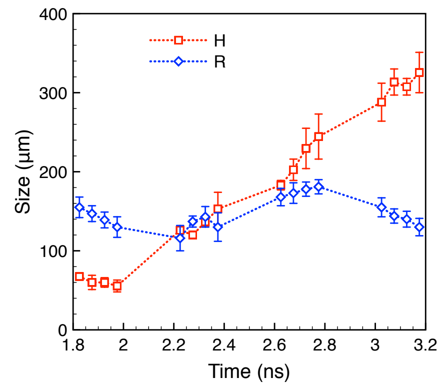
The density of the plasma at each time was calculated from the measurements of the immediate thickness and radius of the cylinder, by imposing a conservation of particles condition, given that the initial dimensions of the target are known. The temperature was obtained from the K-shell spectral measurements. More details on the experimental set-up are given in Pérez-Callejo *et al.* [25], where these experiments were first reported.

4. Results

We focus on the spectral emission from the V, given that the Be tamper had some Fe contamination that is blended with the Fe spectrum from the target. In figure 3a we show an example of the face-on and side-on spectral emission from the Heα complex of vanadium. The spectra are normalised to the peak of the y line, and it can be seen that the w/y ratios are noticeably different between both views. In the experimental temperature and density conditions ($T_e \sim 1-2\,\mathrm{keV}$, $n_i \sim 10^{19}\,\mathrm{cm}^{-3}$) the main broadening mechanism affecting the shape of the Heα lines is the Doppler effect, with the contribution from Stark broadening being almost negligible. Therefore, the lines have a Gaussian profile with a Full Width



(a)



(b)

Figure 3: (3a) Example of the V Heα emission detected by the face-on and side-on spectrometers normalised to the peak of the y line. The w/y ratios are noticeably different between both views. The weaker peak at $\sim 5165\,\text{eV}$ corresponds to the emission from Li-like satellites blended with the Heα complex. These spectra were taken 2.3 ns into the laser pulse. (3b) Evolution of the plasma thickness (H) and radius (R). Note that the radius stays constant to a 20% owing to the effect of the Be tamper, and the expansion happens mostly in the axial direction.

at Half Maximum (FWHM) of the order of $2-3\,\text{eV}$. Although in the figure this is masked by the instrument response (the spectrometer had a resolution of $12\,\text{eV}$), the line ratios are conserved after the instrumental broadening. We are using eV in this section to discuss line widths, as it is the most commonly used unit in HED spectroscopy, but the reader is advised to note that in equation 5, the normalized line profile ϕ_0 is given in frequency units, as SI units were being used.

Additionally, in figure 3b, we show the evolution of the thickness H and radius R of the cylinder during the laser pulse. Using these values and equation 5, it is possible, as discussed above, to obtain the values of the opacity of the y line at line center as a function of the temperature and density of the plasma.

The obtained values for the opacity of the y line at line center are shown in figure 4 as a function of the temperature and density of the plasma. The width of the uncertainty region in the data comes from the uncertainty in the

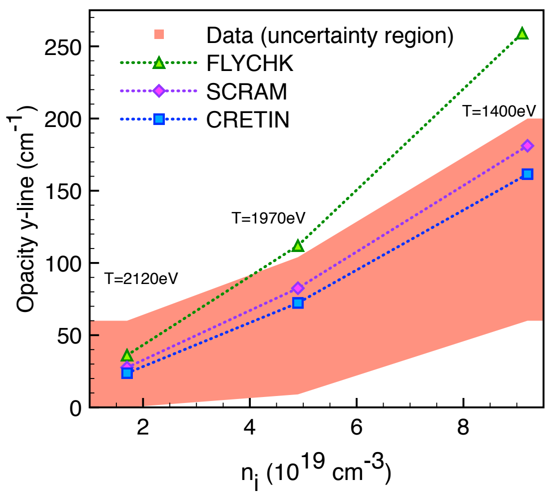


Figure 4: Value of the opacity of the y line at line centre as calculated from the experimental line ratios compared with the results from three different codes. The differences between codes are up to a $\sim$ 50%. The red shaded region corresponds to a 1-sigma level of uncertainty in the data arising from the uncertainty in the measurement of the plasma dimensions.

measured thickness and radius of the cylinder, and represents a 1-sigma level. We also show for comparison the results from three different spectral codes that are commonly used among the HED community, Cretin [28], SCRAM [29] and FLYCHK [30]. Although Cretin and SCRAM produce results that lie well within the uncertainty region of the data, the values from FLYCHK are much larger (up to $\sim$ 50%). However, it is important to note that whilst in SCRAM and Cretin the atomic data are generated previously using the Flexible Atomic Code (FAC) [31] and are stored in an external file, in the online code FLYCHK, the atomic data are generated automatically using simplified approximations when the code is run (indeed it is this approach that allows FLYCHK to easily simulate such a wide range of elements with limited computational resources, and in such a manner that it can easily be used by a non-specialist). In particular the oscillator strength of the y line is calculated in FLYCHK following the Z-expansion work by Drake and Dalgarno[32, 33]. That is to say the discrepancy between the experimental data and the FLYCHK predictions has no bearing on the validity of the best oscillator strengths *per se*, but does illustrate potential pitfalls that can exist when making over-simplified approximations.

The fraction of ions in the He-like ground state F, was calculated for each point in Figure 4 using the three atomic kinetics codes shown, at the corresponding temperature and density conditions. At each point, all three codes obtain similar values of F, between 0.85 and 0.9, with differences between the codes of less than 5%. As mentioned above, one advantage of using the He-like radiation is that the fraction of He-like ions is high and stable over a relatively wide range of temperatures owing to its high ionisation potential compared with the ionisation stages preceeding it, which explains why all the codes agree, and there is little uncertainty associated with this parameter. Using Equation 5 and these values for F, it is possible to translate the measured opacity values into values of the oscillator strength of the y line. These are shown in figure 5, where each of the data points corresponds to a different set of temperature and density (specified in Figure 4), as the target expands. Time is indicated with respect to the start of the laser pulse. The uncertainty bars in this plot, which correspond to a 1-sigma level, arise from the uncertainty in the measured thickness and radius, as well as from the small differences in the values of F calculated by the three codes of consideration. Similarly to figure 4, the results from Cretin (dotted green line), SCRAM (dashed-dashed-dotted blue line) and FLYHCK (dashed red line), as well as from the NIST database (dashed-dotted orange line), are shown for comparison.

It can be seen that the size of the uncertainty bars increases as a function of time. This is owing to the fact that as the targets expand, their thickness and radius become comparable and small errors in the measurement of their size translate to larger errors in the opacity. Additionally, their shape starts to differ from a perfect cylinder, and the equations presented in section 2 lose their validity. For this reason, we consider the value obtained for the first timestep in Figure 5, when the targets are most cylindrical. In this case, the obtained oscillator strength agree with the calculations in Cretin and SCRAM as well as the value from the NIST database, showing the validity of this method.

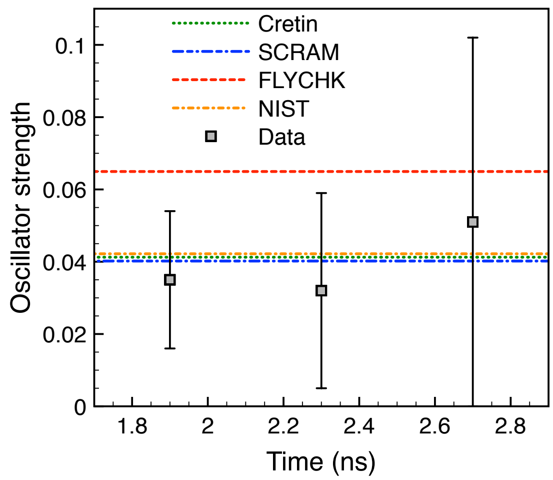


Figure 5: Value of the oscillator strength of the y line at line centre as calculated from the experimental line ratios compared with the results from three different codes and the NIST database. Each of the data points corresponds to a timestep in the experiment. The error bars, which correspond to a 1-sigma level, increase as a function of time owing to the plasma losing its cylindrical geometry.

It is interesting to note that, although the oscillator strength values in Cretin and Scram are within a 3% of each other, their opacity predictions differ by a $\sim 10-15\%$. This difference arises from two main factors. As mentioned above, the fraction of ions in the He-like ground state calculated by Cretin and SCRAM differ by $\sim 5\%$, and additionally, the lineshapes calculated by each code have slightly different widths owing to their different treatment of line broadening. These differences in the line profile are translated to the opacity via the ϕ_0 factor in Equation 5. The accumulated effect of these small differences causes the predicted opacity to disagree from code to code, although their oscillator strengths are similar.

5. Conclusions and discussion

We have presented a method to measure the oscillator strength of the intercombination line of the Heα complex using HED cylindrical plasmas. The first experimental results for vanadium plasmas agree with predictions from commonly used atomic physics codes, as well as with the values in the NIST database. Although the uncertainty bars in this first measurement are still sufficiently large such that it does not allow for discrimination between different calculations based on the FAC [31], the accuracy is sufficient to discriminate between these models and the predictions of FLYCHK which rely on simplifying approximations for atomic data generation. It is worth noting that this experimental setup was not specifically designed for an oscillator strength measurement, but for a study of geometrical effects. As such, the plasma was intended to expand, which is the main source of error in this case. This expansion could be reduced by burying the cylindrical target in a larger foam tamper, as proposed by Mancini *et al.* [34]. Additionally, a more careful consideration of the geometry of the dot and the tamper material to control the radial pressure, can prevent the radial expansion, which would ensure a better geometry, and potentially a greater accuracy for this type of measurements.

It is important to note that, while in this case we have measured the oscillator strength of the y component of the Heα complex, there is in principle no limitation in the method as to which lines can be studied, as long as one of them is optically thick and the other is not. This method can be easily extended to different components of the K-shell spectrum of HED plasmas, such as the Heβ, Li-like or H-like emission. This work shows how a simple experimental set-up can be used to obtain good estimates of the oscillator strength of some atomic transitions in HED conditions, potentially helping to benchmark the results from atomic physics codes, as well as QED predictions of the change in transition rates as a function of the temperature of the plasma.

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