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Plasmas generated by irradiating targets with ~ 20 kJ of laser energy are routinely created in inertial confinement fusion research. X-ray spectroscopy provides one of the few methods for diagnosing the electron temperature and electron density. For example, electron densities approaching 10^{24} cm^{-3} have been diagnosed by spectral linewidths. However, the accuracy of the spectroscopic diagnostics depends the population kinetics, the radiative transfer, and the line shape calculations. Analysis for the complex line transitions has recently been improved and accelerated by the use of a database where detailed calculations can be accessed rapidly and interactively. Examples of data from Xe and Ar doped targets demonstrate the current analytic methods. First we will illustrate complications that arise from the presence of a multitude of underlying spectral lines. Then, we will consider the Ar He-like $1s^2$ ($^1S_0$) - 1s3p ($^1P_0$) transition where ion dynamic effects may affect the profile. Here, the plasma conditions are such that the static ion microfield approximation is no longer valid; therefore in addition to the width, the details of the line shape can be used to provide additional information. We will compare the data to simulations and discuss the possible pitfalls involved in demonstrating the effect of ion dynamics on lineshapes.

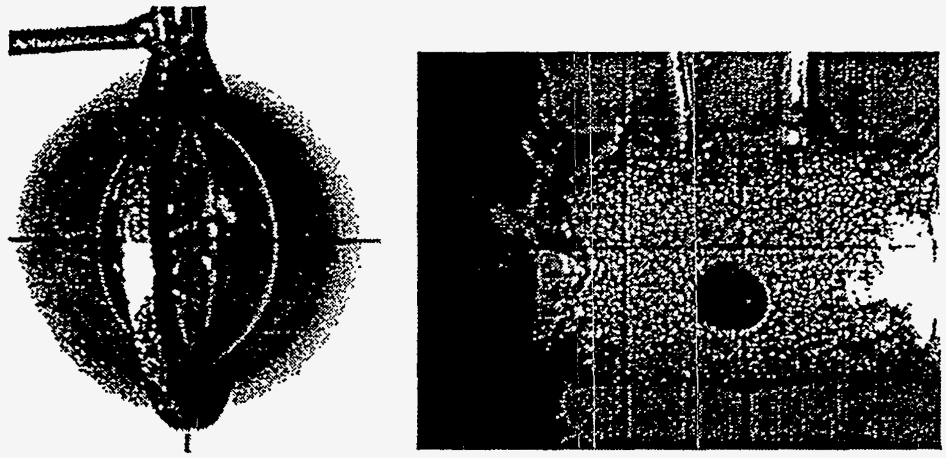
Plasmas generated by irradiating targets with ~ 20 kJ of laser energy are routinely created in inertial confinement fusion research. In laser-produced plasmas, a single observed lineshape may be a convolution over several transitions instead of the result of a single transition. Furthermore, individual spectral lines can be affected by radiative transfer or ion dynamic effects. The experiments we discuss are motivated by both theory and applications. For instance the study of line formation can test basic physics models such as Stark broadening theory. However, spectroscopy can also be used to diagnose plasmas relevant to laser fusion, astrophysics, and atomic phyiscs in the laboratory. Some examples are experiments that explore beam propagation, ionization physics, and opacity (1-3).

In these studies, emission spectra provide non-perturbative diagnostics of the laser-produced plasmas. Spectroscopic diagnostics have been used to diagnose the electron temperature, T_e, by the ratio of line intensities, electron density, N_e, by

Stark broadening or line intensity ratios, and ion temperature, T_i, by Doppler broadening(4). The analysis of spectra often requires information about the atomic kinetics which involves vast amounts of atomic data and rate equation models. It also requires additional information about the hydrodynamic evolution of the plasma, and, if the plasma is rapidly evolving, time-dependent analysis may be required.

Figure 1 shows photographs of the two types of targets used to study the physics of hot, dense matter, gasbags and hohlraums (5,6) . The gasbags are formed by inflating CH membranes which are glued to both sides of a 2.75 mm diameter washer. The gas-filled hohlraums are Au cylinders 2.5 mm long and 1.6 mm in diameter. Thin CH membranes are placed over the endcaps of the cylinder to prevent the gas from escaping. These targets are irradiated by the Nova laser, a Nd:glass laser which can deliver a total of ~ 25 kJ of laser light at 0.35 μm in 1 ns. The targets are irradiated by ten laser beams. Gasbags are irradiated in a uniform manner since the lasers are incident in two cones of beams that are 50 ° from the axis of the gasbag washer. Hohlraums are irradiated on the inside wall by laser beams which enter through the ends of the cylinder which create a plasma inside which is bathed in a radiation field created by the plasma formed at the Au wall.

The spectroscopic measurements are designed to diagnose laser-produced plasmas having electron densities of $n_e > 10^{21}$ cm^{-3} and temperatures T_e from 0.5 to 5 keV. The gasbags are open geometry targets that enable tests of atomic models, atomic kinetics, and benchmarks of hydrodynamic codes. Hohlraums, on the other hand, are closed geometry targets that enable studies of plasmas in extreme conditions of N_e, T_e, and T_r that cannot otherwise be achieved in laboratory plasmas. These closed geometry targets produce confined plasmas that may be subject to intense radiation fields produced by the conversion of laser light into x-rays at the inside wall.



GASBAG HOHLRAUM

FIGURE 1. The gasbag is formed by confining gas between two thin CH membranes. The plasma is formed by overlapping five laser beams on each membrane. The gas-filled hohlraum is an Au cylinder in which the laser beams enter through the endcaps which are covered by a thin CH membrane to enclose the gas.

Both targets produce mm-sized plasmas in approximately 300 ps, which is the time required to ablate the thin CH membranes and ionize the gas-fill of the target. Precision fabrication of these targets allows us to use different elements or gas fills to systematically vary the density, temperature, Z, or other plasma parameters of interest. The experiments are diagnosed with time-resolved Bragg crystal spectrometers and x-ray pinhole cameras.

Line shapes can be affected by practical constraints on the experiments as well as by physical processes. In this paper, three examples will be given from different experiments on the Nova laser: Ar spectra from gasbags, Xe spectra, also from gasbags, and Ar implosion spectra from hohlraums. In each of these examples, we will illustrate an aspect of the experimental analysis and for the last case, the Ar implosions, we will show detailed calculations that require sophisticated models to fit the entire lineshape.

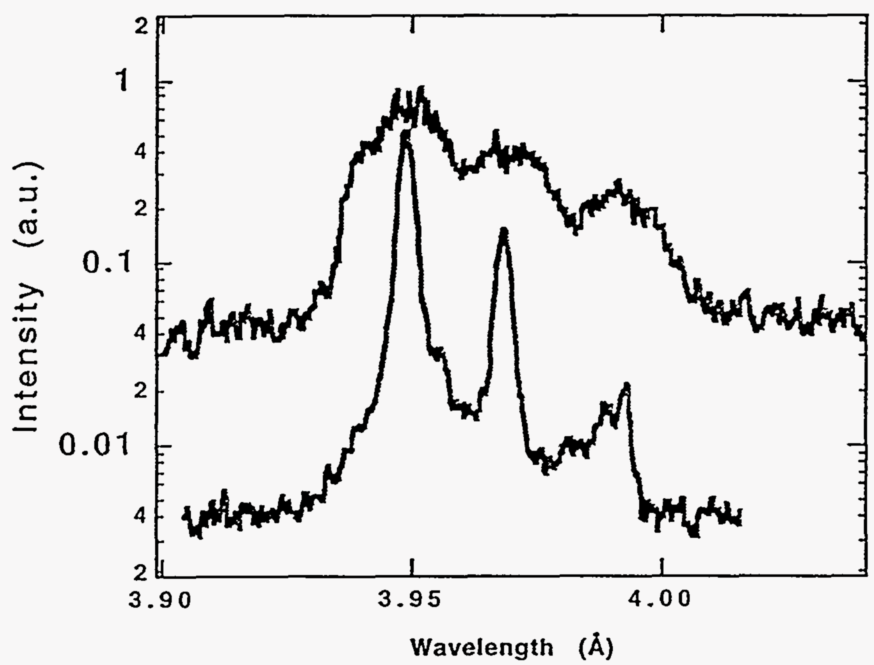


FIGURE 2. X-ray spectra of the ArXVII n=1-2 resonance line (3.949 Å) and its satellites (3.990 Å , 3.994Å) from an Ar doped gasbag. The upper spectrum is from a ~ 2 mm diameter source which broadens the spectral features. The lower spectrum is the same source viewed through a 250 μm slit that reduces the effective source size seen by the spectrometer.

Ar spectra are obtained from gasbag targets that are filled with neopentane gas, C_5H_{12}, which is doped with 1 % Ar. The Ar dopant concentration was chosen to remain optically thin for the plasma T_e and N_e of interest. These plasmas are nearly spherical with an average diameter of ~ 2.5 mm. Because the plasma is large, the experimental linewidth in this case is dominated by source broadening. The K-shell emission from these types of targets usually exhibit resonance lines and their associated satellites which have been used for temperature and density sensitive diagnostics. In the case illustrated in Figure 2 above, T_e is determined from the ratio of the n=2-1 resonance line of He-like Ar (He-α) to the Li-like satellites, labeled jkl in Gabriel notation (7). However, when the source size dominates, these individual features are washed out and cannot be resolved. We have employed 250 μm slits mounted 8 mm from the center of the targer to reduce the effective source size from the target that is observed by the spectrometer. Figure 2 shows an example of the gasbag spectra having a T_e of 3 keV with and without a source limiting slit. As can be observed, the detailed lineshapes cannot be analyzed if the plasma source size dominates the spectral line shape.

For the case of Xe spectra, another complication in interpreting the line shapes arises due to the presence of multiple ionization stages in the plasma. Xe spectra from Nova plasmas emit L-shell spectra that can be used for plasma diagnostics. For instance the n=4-2 lines can be used to diagnose T_e and the n=3-2 lines can be used to diagnose N_e (8). Unfortunately, L-shell spectra are extremely difficult to model because of the multitude of transitions present in the spectra. Gasbag plasmas at densities of 10^{21} cm^{-3} can exhibit emission from F-like to Mg-like ions

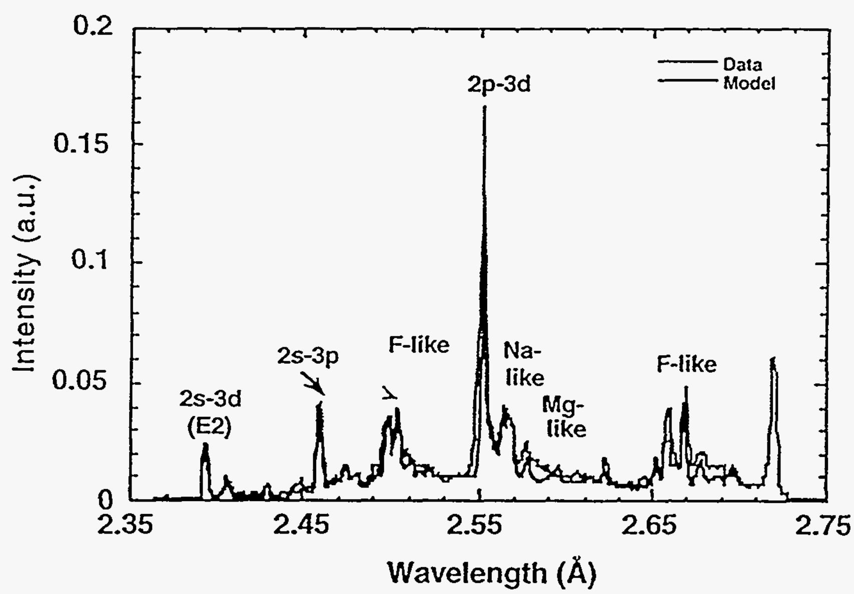


FIGURE 3. Spectra of the n=4-3 transitions of an Xe-filled gasbag. The plasma conditions measured by spectroscopy were $T_e = 3.5$ keV and $N_e = 2 \times 10^{21}$ cm^{-3}. To model this spectrum over 2000 transitions from a Xe atomic model were included.

when temperature approach 3 keV. For a realistic model of these transitions, over 2000 transitions are included in the atomic model used to fit the spectrum. The detail is necessary to isolate emission features that are sensitive to plasma conditions and that can be used to produce line intensity ratio diagnostics. In figure 3, we show the n=3-2 lines of Xe. Here the quadrupole line, identified as E2, relative to the F-like 2s-3p line has been found to be a sensitive measure of the density. Even with high resolution spectrometers, overlapping transitions in the L-shell spectra are unavoidable and make it imperative to have modeling capabilities to assist in finding good spectroscopic signatures.

From the experimental point of view, gasbag targets are a good testbed of atomic physics calculations important to line shapes. This point can be illustrated by a comparison of gasbag K- and L-shell spectra. Gasbags can be filled with a mix of gases, as already discussed, therefore, when more than one gas dopant is present in the gas mixture, the spectroscopic diagnostic from each can be cross calibrated for the same plasma conditions. For instance, we have performed experiments on gasbags filled with 1% Ar, 2% Xe, and 97% neopentane. The K-shell spectra from Ar are primarily determined by the Doppler and instrumental width. As before, the ratio of Ar He-like He-α to the jkl satellites can be used as a reliable temperature diagnostic in this case. On the other hand, line emission ratios from the L-shell spectral features of Xe, are not yet well-established diagnostics. Since the spectrum is a sum over lines from many ionization stages, the atomic model as well as the electron temperature may have an important effect on the intensity and width of the calculated spectral features. Thus, the comparison of L-shell line intensity ratios with the more reliable K-shell ratios allows us to validate the Xe spectroscopic diagnostics.

The modeling tools necessary to produce plasma diagnostics generally consist of three types of codes. The hydrodynamic behavior of the target is calculated by codes such as LASNEX (9). After generating temperature and density temporal histories, kinetics codes solve a system of rate equations to determine the populations of various levels and ionization states (10). These kinetics codes depend on data from large-scale atomic codes to calculate energy levels of the ion (11). Once the populations are calculated, the synthetic spectra can be generated. Given the large amount of data that can be accumulated during laser-produced plasma experiments, it is of great advantage that the line shape information is stored in an easily accessible database for use in real-time analysis.

With the experimental techniques and modeling capability in hand, we now consider an experiment that draws on both for a careful study of line shapes. For this case, we will look at the line shapes from an imploding capsule inside of a hohlraum. These experiments are performed with a hohlraum that is 2.5 mm in length and 1.6 mm in diameter. The hohlraum is heated by ten 0.35μm wavelength laser beams in 1 ns, producing x-rays which ablatively implode a 270 μm radius CH capsule that is filled with 50 atm of deuterium, D_2, and 0.1 atm of Ar. This target is diagnosed with time-resolved x-ray spectrometers that record the emission of the Ar XVIII $1s^2$ ($^1S_0$) - 1s3p ($^1P_0$) transition. Time-resolved x-ray pinhole cameras record 2-dimensional images of the imploding core, directly measuring the size of the imploding capsule and gas. Satellite lines on the long wavelength side of the transition, primarily due to contributions from Li-like Ar ions, cause the line to be asymmetric, but they provide spectral features which can be used to determine the T_e. In addition, at the high densities produced in these plasmas, the transition is strongly Stark broadened and the width provides an electron density diagnostic. Hence, the full analysis of this line shape can provide T_e and N_e as a function of time, as well as reveal other physical processes occuring in the implosion.

The Ar concentration is optimized by considering two criteria. The first is that the emission from the expected K-shell lines must be observable. Second, spectroscopic diagnostics are more sensitive when the emission is optically thin. In addition, for systematic studies, it is advantagous if the concentration is low enough to insure that the presence of the Ar does not significantly perturb the evolution of the deuterium plasma.

The plasma conditions in the imploding core are expected to produce a line shape that has a central intensity dip. Roughly speaking the dip is caused by splitting of the Stark components that comprise that transition due to ion microfields. In addition, each of these components is broadened by electron collisions. Calculations of the line shape, integrated over the predicted capsule conditions with spatial gradients in N_e and T_e, show a clear dip at the line center, see Figure 4.

Simulations of the temperature and density of the imploding capsule evolve on a ns timescale. Both T_e and N_e peak at approximately 1.8 ns after the start of the 1 ns square laser pulse when the capsule attains its minimum radius. At peak density, the temperature is gradient is expected to vary from 0.8 - 1.0 keV and the density is expected to compress to 1.3 - 1.5 x 10^{24} cm^{-3}.

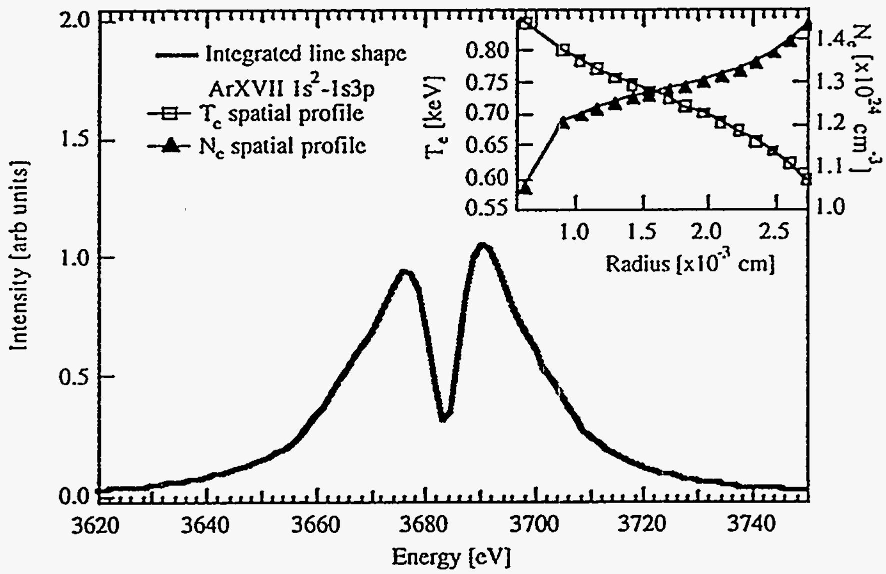


FIGURE 4. Calculated lineshape for the Ar XVII n=1-3 resonance line for the plasma conditions of an imploding capsule in a hohlraum. Temperature and density gradients are included in the calculation and they are shown as a function of radius in the inset box. The line shows a central dip due to the strong Stark effect at these high densities.

Spectroscopic data of very high quality have been obtained from imploded capsules inside of hohlraums. One spectrometer provides a survey of the spectral region from the He-like Ar $1s^2$ - 1s2p transition to the H-like Ar 1s-3p transition. The spectral resolution is ~ 500, which is sufficient to use the features of the lines for T_e diagnostics. A high resolution spectrometer, with resolving power of ~ 1800, records the He-like Ar $1s^2$ - 1s3p transition and is able to resolve the dip in the profile (12). The data and fits from the calculations show dramatic changes in the line shape as a function of time from the high resolution spectrometer. This can be observed in figure 5 where the lineouts at different times are shown for comparison. In these data, the Li-like satellites transition intensities increase late in time as the capsule cools.

In the analysis, the calculated spectra is iteratively fit to the data until the relative intensity of the Li-like satellites to the He-like resonance line were well matched. In the 10^{24} cm^{-3} electron density regime, this diagnostic is most useful from 400 to 900 eV. At temperatures outside this range, the satellites are not pronounced enough, or the contribution is too large to reliably determine the resonance lines width. When the high and low resolution Ar XVII spectra are analyzed we find that the temporal evolution of the core plasma is close to that predicted by hydrodynamic simulation. This indicates that the at the onset of the transitions of interest, the temperature is approximately 400 eV, while at the peak, the T_c has risen to 800 eV.

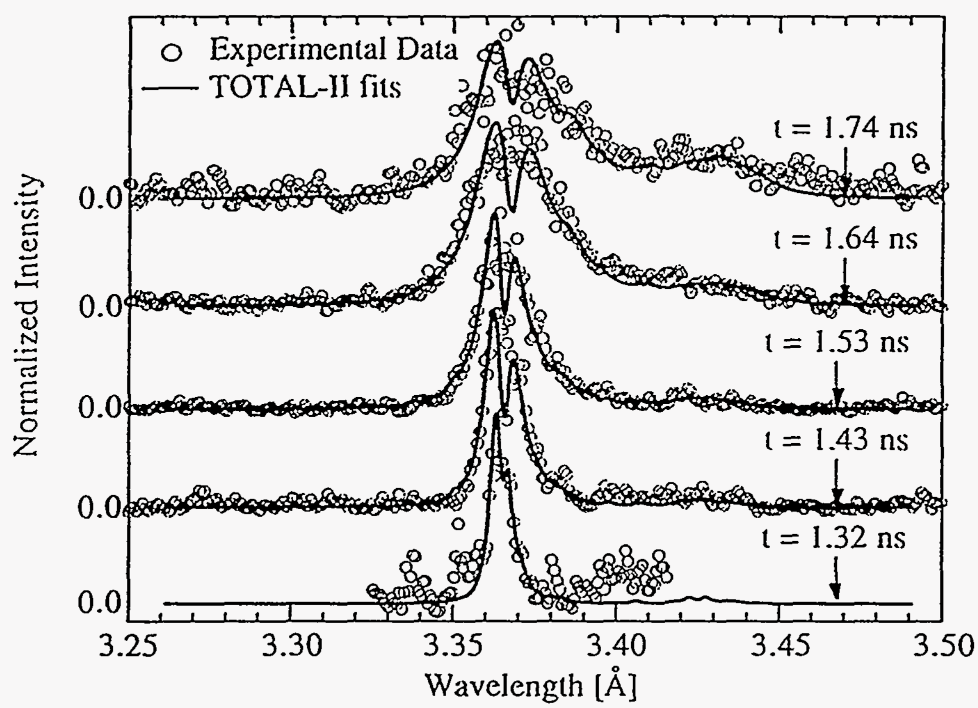


FIGURE 5. The data and calculations compared for the Ar XVII n=1-3 lineshape shown in Fig. 4. The data is obtained on an x-ray streak camera and lineouts of intensity vs wavelength are integrated over 100 ps and taken the times indicated in the figure.

The density is measured on the same experiments by using the full-width-at-half-maximum (FWHM) of the He-like Ar $1s^2$ - 1s3p transition. Since the density varies roughly as the 2/3 power of the FWHM it is a very sensitive measure of the plasma conditions, especially since the width of the line profile is relatively insensitive to changes in the electron temperature (13). Further, we have found excellent reproducibility of the data over a series of ~ 10 shots. The Doppler contribution to the line shape is negligible for this case.

Since this plasma is fairly well characterized in temperature and density, it is meaningful to look deeper at the details of the line shape. Figure 6 shows the calculated detailed line shape compared to the data. As mentioned before, the n=3-1 line should have a central dip for quasi-static line broadening calculations. However, figure 6 shows that there is no dip observed. The high quality of the data suggest that the absence of the dip is real and may be due to physical effects not yet included in the model. The reasons for the lack of the central dip could be one or more of the following. First, the satellites to the higher n levels, which for nln'l' n'≥4 fall under the transiton, are not included in the atomic model and the presence of emission from these transitions may fill in the dip. The n' =4 satellites have recently been observed by P. Beiersdorfer on the electron beam ion trap (EBIT) and the wavelengths are near the line center position (14). However, the dip in the line shape is absent even early in time when the n=3 satellites do not make a strong contribution ot the line shape. Therefore, this does not seem to be the mechanism that fills in the dip. The second possibility is that there are stronger temperature gradients in the experiment than those predicted by the simulations. In

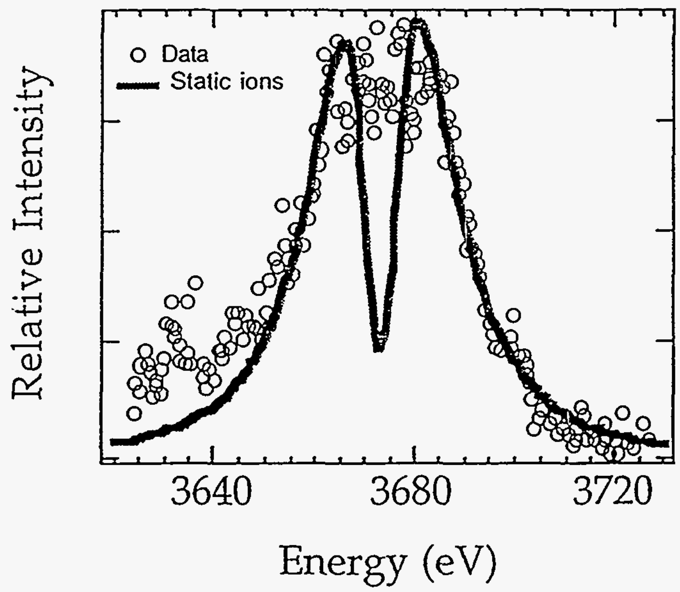


FIGURE 6. Calculated lineshape for the Ar XVII n=1-3 resonance line for the plasma conditions of an imploding capsule in a hohlraum. Temperature and density gradients are included in the calculation and they are shown as a function of radius in the inset box. The line shows a central dip due to the strong Stark effect at these high densities.

this case, the central dip is not as pronounced because emission from lower temperature Ar in the core will fill in the central portion of the line shape. This possibility is difficult to eliminate without further experiments and if experimentally confirmed, it would imply that the hydrodynamic simulations are not correctly modeling the plasma.

The most interesting explanation for the lack of a central dip is that ion dynamics of the D_2 gas is important. For most plasmas, the ion microfield is assumed to be slowly varying and the ion-emitter interaction is assumed to be quasi-static. However, for the implosion in which the ions are highly charged, the density is high, and the ionic perturbers are of relatively low mass, the ion microfield fluctuations may not be negligible. In this case, ion dynamics would fill in the dip by smearing it out (15). Fortunately for this n = 1-3 line shape, this effect would not significantly affect the FWHM of the line profile. Evidence of ion dynamics has been observed on low density gas-liner pinch experiments (16), but it has not yet been conclusively shown on high density plasmas(17, 18). Future experiments are planned to vary the different fill gases and thus change the ion dynamics(19). The challenge is that changing the gas fill can also affect the hydrodynamic evolution of the capsule because of differences in the radiative cooling of the gas. To conclusively demonstrate ion dynamics, it is desirable that N_e and T_e peak at the same time. Therefore experiments need to be carefully designed.

CONCLUSIONS

Experimental techniques and simulation capabilities for complex ions have been advanced enough to enable tests of complex line shape calculations. High-powered lasers can create mm-sized plasmas and multi-ionized species that can create special difficulties for line shape measurements. However, well characterized plasmas, such as those in hohlraum capsule implosions, can be produced. These extremely hot and dense plasma conditions are difficult to achieve in other plasma devices and the study of detailed line shapes can be fruitful. Experiments in the laboratory also afford the possibility of varying targets to explore effects such as ion dynamics in controlled experiments. For real-time analysis of the data, line shape calculations for these plasmas must either run quickly or rely on large databases.

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