Spectroscopy of compressed high energy density matter

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A theoretical and experimental time-resolved spectroscopic investigation of indirectly driven microsphere implosions is described. The plasma dynamics is studied for several fill gases with a trace amount of argon. Through an analysis of the line profile of Ar XVII $1s^2-1s3p\ ^1P$, with a line center position at E_ν=3684 eV, the evolution of the plasma density and temperature as a function of fill gas is examined. The theoretical calculations are performed with a fast computer code, which has been previously benchmarked through the analysis of specific complex ionic spectra in hot dense plasmas. The experimental aspect of the work utilizes the Lawrence Livermore National Laboratory Nova 10 beam laser facility to indirectly drive the implosion of a gas filled plastic microsphere contained in a gold Holhraum target. The dynamical density measurement is derived from a streak camera linewidth measurement and a comparison with the computed profile. Calculations demonstrate that in certain cases there can be a substantial ion dynamics effect on the line shape. The frequency fluctuation model is used to compute the effect on the line profile and a comparison with the experimental spectra provides evidence that ion dynamics may be affecting the line shape. This study provides a method for obtaining an improved understanding of the basic processes dominating the underlying plasma physics of matter compressed to a state of high energy density. [S1063-651X(96)06206-X]

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The use of spectral line profiles as a diagnostic of the conditions in hot and dense plasmas has become a standard technique for the study of the high energy density conditions of interest to inertial confinement fusion (ICF) programs [1–4]. X-ray line radiation from highly ionized emitters is of special interest to the ICF research program since it has the potential to provide a time-dependent measure of the density dynamics in implosions, together with temperature information in some instances. It has also been pointed out [4] that line formation in stellar interiors occurs in similar environments so that studies of this type are of astrophysical interest. In the following discussion we explore, with spectroscopic methods, the dynamics of the creation of high energy density matter.

In particular, the Stark broadened lines emitted by highly ionized argon atoms are investigated, particularly the Ar XVII $1s^2-1s3p\ ^1P$ transition. The Ar is introduced in trace amounts as a nonperturbing dopant in the gas fill of the microspheres of the implosion experiments. The profiles of the lines emitted by the Ar ions are then used as a diagnostic by comparing the experimental linewidths with theoretical predictions. The computations are performed with a fast computer code [5], which is designed to handle the large level arrays of complex ionic species. An extension that models the effect of ion dynamics on the line shape has recently been developed [6]. The code has been benchmarked by comparing the plasma parameters predicted by computed line profiles to accurate experimental spectra taken under carefully controlled circumstances [7,8,1]. The calculated line shapes are found to be sufficiently reliable so that dependable diagnostics of the emitter environment is possible [2]. At present there is no definitive proof of the role of ion dynamics in these extreme plasmas. In the work of Haynes *et al.* [9] it has been implied that ion dynamics effects are important; however, no experimental proof is supplied to support this supposition. For a review of ion dynamics effects see [10] and the references therein.

The line shape computation of the emission by complex, many-electron ions in hot, dense plasma conditions requires an efficient method for the treatment of large level arrays interacting with a perturbing Stark field. A single radiative transition of a highly ionized emitter may, typically, involve

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at least 20 states in the lower and 50 states in the upper subspace. In addition, the probability distribution of the random plasma ion microfield perturbation commonly requires approximately 50 or more ion microfield values, and this results in a basis that can involve more than 50 000 states. A model has been formulated that permits calculations of the spectra emitted by an arbitrarily complex ion perturbed by very general plasma environments [11]. The computational approach to modeling the shape of the spectral lines emitted, used in the following, begins with a consideration of the time-dependent coupling of the emitting ion with the plasma environment. The first step in the procedure is to remove the time dependence in the plasma-emitter interaction. This is performed through two assumptions. First, the perturbing plasma ions are considered to be stationary and, second, the effect of the plasma electrons on the emitting ion is taken to be perturbative in nature due to their short collision durations with respect to the average lifetime of the emission process. In the standard theory of Stark broadening of spectral lines, this is customarily referred to as the quasistatic ion, impact-electron approximation. The result is a spectral line shape with separate inhomogeneous ion and homogeneous electron contributions. The line profile becomes a pure sum of independent electron-impact broadened static Stark components.

For almost all hot, dense plasmas, the electrons can be considered in the impact approximation, but there are transitions and plasma conditions for which the standard quasistatic treatment of the ions must be modified. For example, whenever there is a strong ion Stark effect on the line and, at the same time, the ion field fluctuations cannot be neglected, the ion-emitter interaction can no longer be taken to be stationary [12]. In this case, the inhomogeneous ion broadening is modified by the fluctuating ion perturbation acting on the homogeneous electron-impact broadened resonance. This modification of the line shape is commonly referred to as the ion dynamics effect and is included in the present computations through the frequency fluctuation model (FFM) [6,13], which was developed specifically for this purpose. This model is based on defining a set of radiative channels to replace the static Stark components of each radiative transition in the spectral line (by doing so reduces the amount of data required for complex ion calculations). The channels are defined as the smallest set of observable resonant features that form the quasistatic profile. A Markovian exchange process between the channels is assumed to represent the fluctuations of the ion microfield and model the ion dynamics effect. The line shape, initially described by an independent sum of static Stark components, now becomes a line composed of radiative channels, which, through the mixing process, are caused to merge into a dynamic combination of inhomogeneous line components. To confirm that the FFM accurately describes the ion dynamics effect for a wide range of plasma conditions, comparisons with computer experiments based on a full simulation of the plasma have been performed [1,6,14]. However, at the present time, no definitive experimental measurements of the effect exist, although there have been indications that the ion dynamics effect might play a role in the observed shape of several spectral lines [2,6,7].

We have performed experiments with indirect drive, i.e., the laser impinges on the inside walls of a gold *Hohlraum*

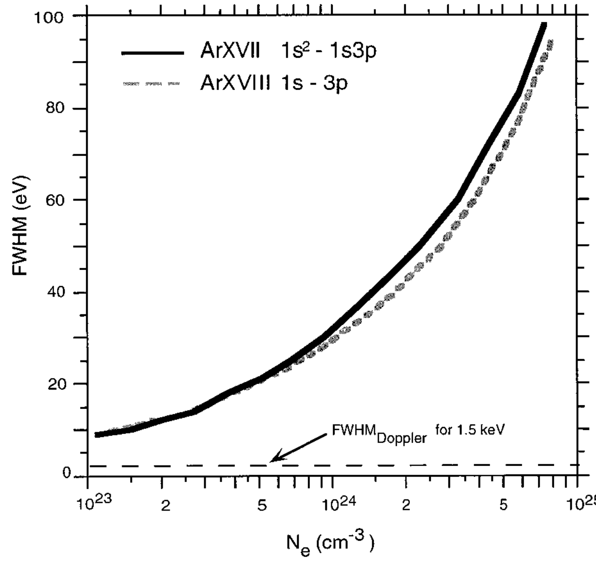

FIG. 1. Full width at half maximum of the Ar XVII $1s^2$-$1s3p$ (E_v=3684 eV) He-like lines and the Ar XVIII $1s$-$3p$ H-like transition as a function of electron density.

target [4] to convert the incident laser radiation into a uniform x-radiation field that heats the microsphere target. The *Hohlraum* target has dimensions 2550×1600 μm^2 and the target is a plastic microsphere 60 μm thick, 220 μm in internal radius, filled with 50 atmospheres of D_2 and 0.1 atmosphere of argon. The gas fill was optimized to prevent the Ar from perturbing the implosion dynamics and at the same time maintaining conditions to ensure that the emitted spectral lines are observable and optically thin. A variety of pulse shapes and laser energies were utilized from the Nova 10 beam laser [1,3,15], but typically, the drive was by a 1-ns square pulse of 353-nm light with 19 kJ of total energy [4]. The experiment was instrumented with high and low resolution x-ray spectrometers coupled to x-ray streak cameras, which were used to detect the Ar K line spectra. The time-dependent emission was intended to provide a measure, derived from the linewidth of the Ar XVII $1s^2-1s3p$ ^1P transition of the density dynamics of the imploding microsphere. The spectra from these indirectly driven targets included both the Ar XVII $1s^2$-$1s3p$ He-like lines as well as the Ar XVIII $1s$-$3p$ H-like transition. The 1-2 transitions, the He resonance line and Ly-α, were optically thick and therefore less useful as a diagnostic for plasma analysis. In Fig. 1 the sensitivity of the full width at half maximum (FWHM) of the He-like and H-like 1-3 transitions, He-β and Ly-β, of Ar to the electron density can be seen. As these transitions furnish a robust diagnostic of the plasma conditions, this figure indicates clearly the interest for those engaged in high energy density experiments, e.g., ICF.

It is important to note, however, that the linewidth plotted in Fig. 1 is not the FWHM of a simple Lorentzian line. For this reason it is necessary to look at the intrinsic shape of this transition and examine a number of different contributions to the broadening process. In addition to the plasma electron density, the line formation is sensitive to a variety of different parameters, such as the composition of the fill gas, the temperature, the resulting kinetics of the implosion, and density gradients that may be present. The change in the line shape as a function of the plasma conditions can be seen in

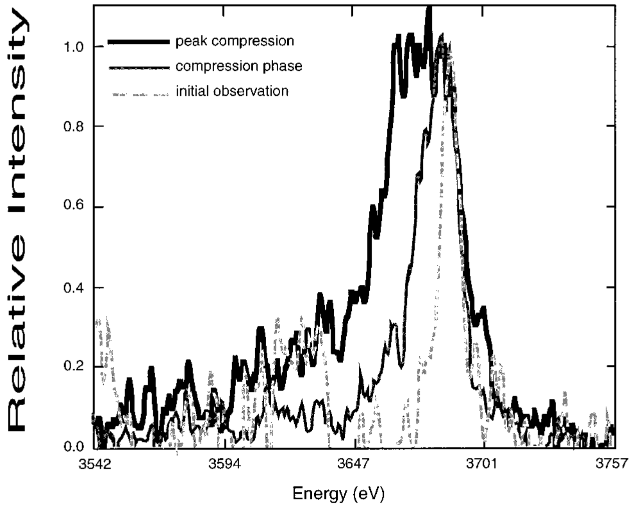

FIG. 2. Ar XVII $1s^2-1s3p\ ^1P$ transition for three times during the implosion. The centroid of the transition shifts to a longer wavelength.

Fig. 2, where the time history of the spectral profile of the Ar XVII 1-3 transition is displayed as recorded by a streak camera at three different times during the plasma evolution. A theoretical fit to the line at peak density (broadest curve in Fig. 2) indicates the peak electron density is approximately 1×10^{24} cm^{-3} with an electron temperature of 1.5 keV. These fits are shown in Fig. 3. The plasma is compressed and heated in the time between the successive line profile snapshots displayed in the figure. A redshift of both the line centroid and the apparent line peak with increasing plasma compression is observed in the data. The long wavelength wing of the Ar XVII $1s^2-1s3p\ ^1P$ line provides a potential temperature diagnostic. The modification to the line shape, as shall be discussed, results from lithium-like dielectronic satellite lines. A significant conclusion here is that the rationale for the line shape must be understood if precise diagnostics are to be derived from calculations of line profiles.

The line profile of the Ar XVII $1s^2-1s3p\ ^1P$ transition, calculated with the traditional plasma broadening assumption that treats the ion-emitter interaction as quasistatic, is shown in Fig. 3(a), compared with the spectral data. The instrument width in this spectrum is about 1 eV, so that the line is well resolved. It is apparent that the experimental spectrum does not display the clear central dip present in the computed profile. In Fig. 3(b) a calculation of this line based on the FFM [4], taking into account the dynamics associated with ion motion in the plasma, is presented. The improved agreement in the central dip of the profile is quite evident. The improvement of the accord with the data, however, does not include the features on the long wavelength wing, which remains poorly described by the calculation. Nevertheless, the agreement in the central dip would seem to indicate that ion dynamics is an important factor in the formation of this line and that this effect must be considered if correct diagnostics are to result from comparisons with lines formed in similar plasma conditions.

In the transition considered in Fig. 3(b), the improved theoretical fit with the observed line center and width when ion dynamic effects are included in the computation indicates that the line was formed at a plasma density in excess of 10^{24} cm^{-3} and a temperature near 1.5 keV. For comparable plasma conditions, there are other possible explanations for the absence of the central dip that could, if correct, affect the foundation of the diagnostic. First, in the compression process, there can be, and probably are, electron density gradients in the imploded core, as this often occurs with similar imploding systems [3]. If this were the case, the existence of a less dense but sufficiently hot region would radiate a somewhat narrower line filling the central region of the broader profile formed at higher density. In addition, there is the information in Fig. 2, obtained from the same streak camera spectra, that indicates a shift to longer wavelength as the implosion compresses the fill gas. This shift could result from a combination of optical depth and density gradient effects as well as plasma kinetics effects involving possible overlapping transitions.

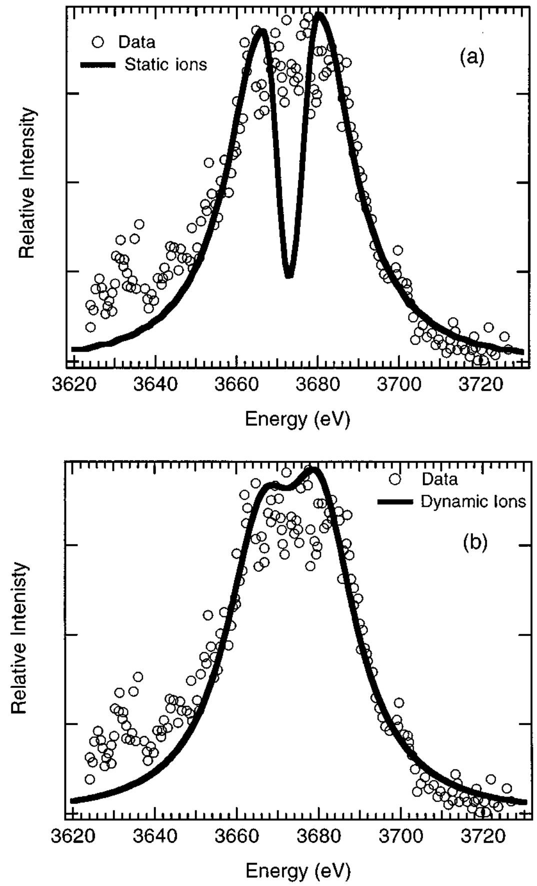

FIG. 3. Line profile of the Ar XVII $1s^2-1s3p\ ^1P$ He-like transition. (a) Calculation with the quasistatic approximation and compared with the spectral data. (b) Calculation based on the FFM, taking into account the ion dynamics, and compared with the data.

We are particularly interested in the influence of ion dynamics on line formation at these high energy densities. The hypothesis is that the motion of the relatively light, perturbing deuterium ions results in the filling of the central feature in the Ar XVII 1-3 line. With heavier ions, this motion is suppressed and a central dip should become more pronounced. The physical interpretation given by the FFM is that the radiative channels derived from the static ion Stark components of the line, fluctuate in frequency as the perturbing ions move. The fluctuation results in a collapse of the

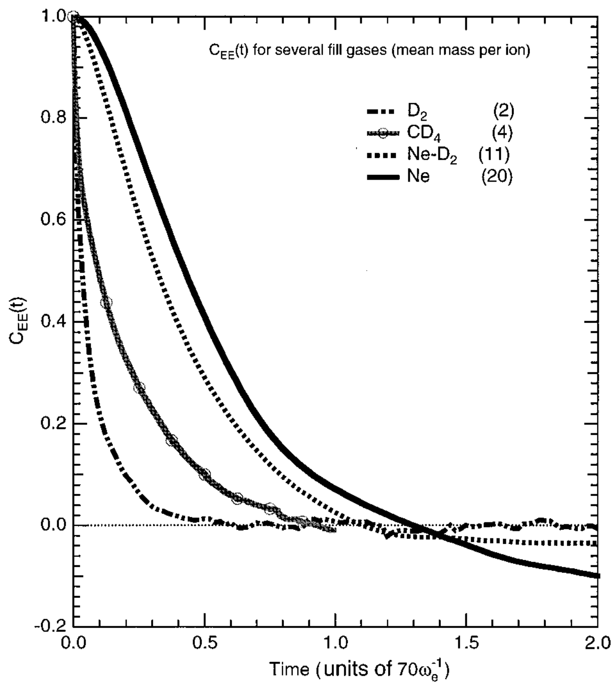

FIG. 4. Electric field autocorrelation function for four different fill gases at N_e=1.2×10^{24} cm^{-3} and T_e=1.55 keV. The abscissa is in units of 70 times the inverse of the electron plasma frequency.

affected radiative channels toward the center of gravity of the line. This has been compared to the Dicke narrowing process in which velocity changing collisions reduce the Gaussian Doppler profile to the underlying Lorentzian collision shape [5]. The ion motion is, of course, greater for lighter ions at a given temperature and thus the large effect for the deuterium fill gas displayed in Fig. 3.

To quantify the ion motion effect, the ion field autocorrelation function has been calculated by a simulation technique [16] for several proposed fill gases under plasma conditions equivalent to those of Fig. 3. The autocorrelation function gives a measure of the mean time for ion field changes to occur. When the inverse of the mean time, the mean fluctuation frequency of the ion field, is comparable to the electron fluctuation frequency (roughly, the electron plasma frequency), the static ion approximation fails and ion dynamics must be considered. In Fig. 4 the ion field autocorrelation function $C_{EE}(t)$ is plotted against time in units of the 70 times the inverse electron plasma frequency for electron density 1.2×10^{24} cm^{-3} and ion temperatures of 1.5 keV. We have explored the $C_{EE}(t)$ for ions heavier than deuterium, the case of deuterium, deuterated methane, a 50%-50% mixture of deuterium and neon, and pure neon as fill gases are displayed. An exponential fit to the long time behavior of the autocorrelation function permits the extraction of a mean decay time and hence a fluctuation frequency for the different fill gases. Note the rapid decrease in the ion field fluctuation frequency with increasing mean mass of the fill gas. In fact, by the time the mean mass is that of the 50%-50% mixture of neon and deuterium, the dynamics is almost the same as that of pure neon. This decrease in fluctuation frequency is reflected in the ion dynamic effect on the line shape as can be seen in Fig. 5. In this figure the static ion line shape is compared with the profile calculated with ion dynamics for the indicated fill gases. The central dip almost completely disappears for deuterium, is partially filled in for the methane case, and then approaches the static case when neon is the fill gas. We conclude that by varying the fill gas, it is experi-

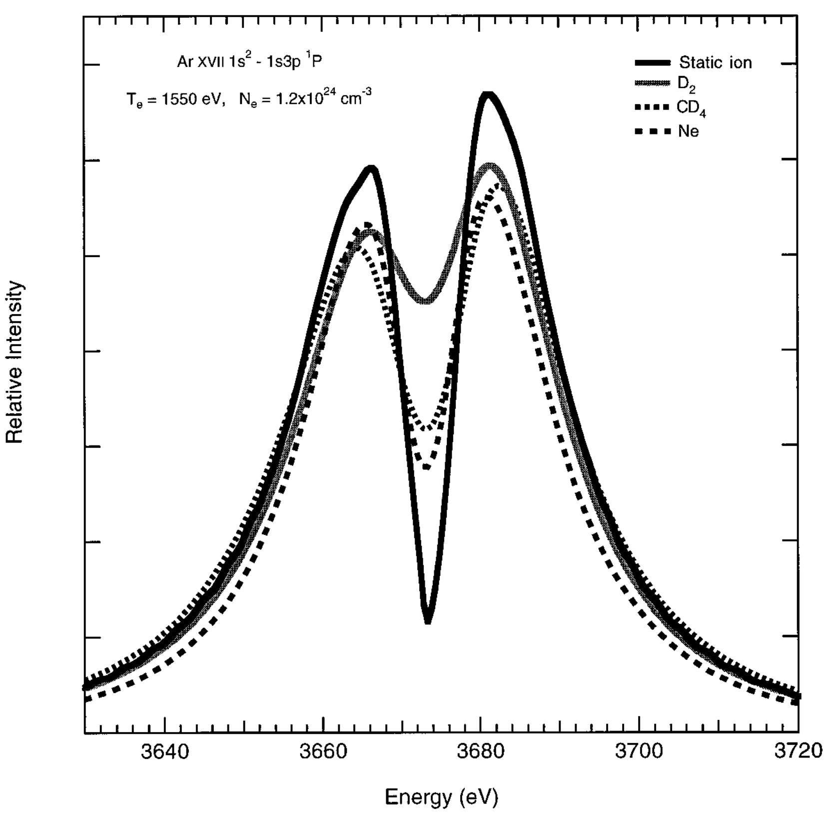

FIG. 5. Static ion line shape compared with the profile calculated with ion dynamics for the indicated fill gases.

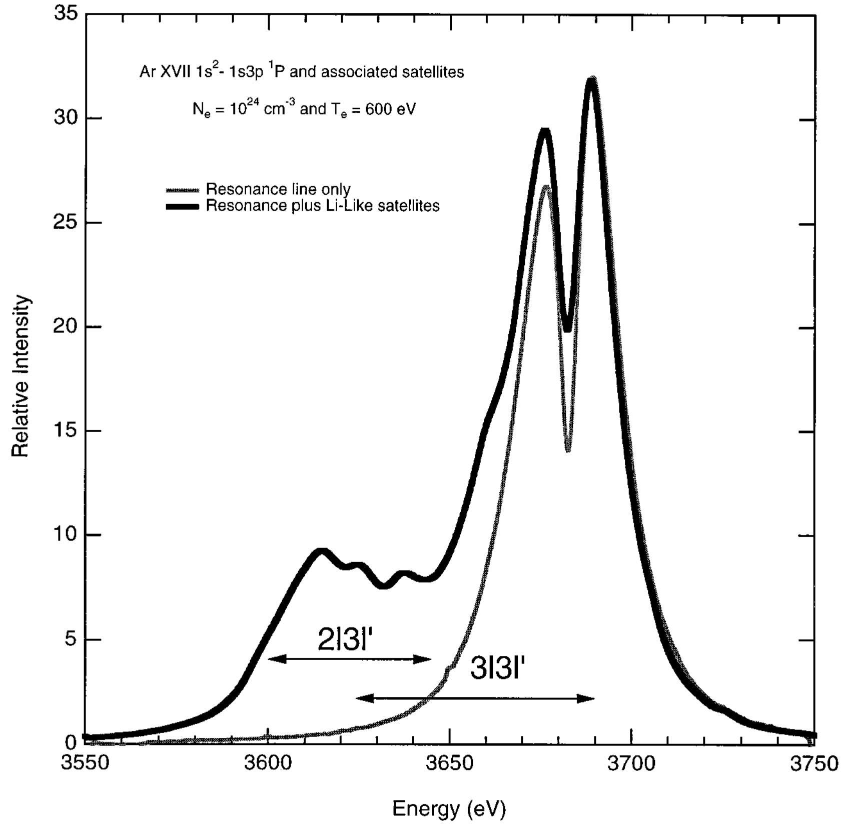

FIG. 6. Effect on the static line profile of the Li-like $2l3l'$ and $3l3l'$ dielectronic satellite lines for the Ar-D_2 case.

mentally possible to determine whether ion dynamics are important in line formation at these densities and temperatures. This assumes that the intrinsic line profiles are observed.

The enhanced red wing is an intensity feature of the experimental line profile that is not accounted for in the computation presented in Figs. 3 and 5. A calculation that includes Li-like dielectronic satellite lines has been performed to demonstrate that this feature can be attributed to satellite transitions and that these satellites hold out the possibility of determining the temperature from the relative contributions of satellites to resonance profiles. The result is shown in Fig. 6, where the effect on the static line profile is illustrated. A large number of states is involved in the calculation. The

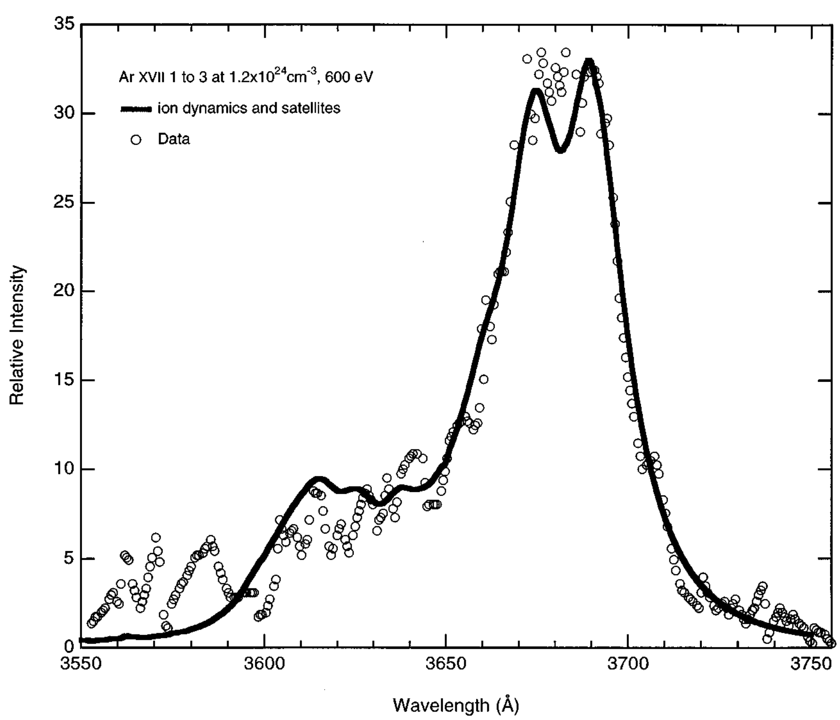

FIG. 7. Comparison of the full ion dynamics calculation including the Li-like satellites with the data.

$2l3l'$ and $3l3l'$ transitions involve 710 states and their respective contributions are indicated in the figure. The addition of the tail of these satellites results in a fairly uniform increase in intensity at the central dip, forming a pedestal below the line. This excludes, at least at higher temperatures (i.e., $T_e<1000$ eV), the possibility that the satellites are involved in the mechanism responsible for the disappearance of this feature in the experiment. Figure 7 displays a comparison of the full ion dynamics calculation including the Li-like satellites with the data. The excellent agreement is further evidence for an important ion dynamics effect in this experiment.

Once the intrinsic line shape has been determined and an understanding of the role ion dynamics effects on line formation are understood, a study of the detailed kinetics and gradient structure of the imploded high energy density core plasma is possible. As found from the above analysis of the $C_{EE}(t)$ for the fill gases, these higher mass fill gases should have much less of an ion dynamics effect on the line than that which occurred with deuterium. The same Ar to ion atomic number ratio can be maintained in an attempt to obtain the same maximum electron density in the plasma during an implosion. Assuming that the implosion dynamics are not greatly changed, this permits the evaluation of the role played by kinetics, since the satellites are formed relative to the resonance lines, and the gradients and line radiative transfer affect the line formation.

We have explored this possibility by running a series of radiation-hydrodynamic simulations. If we follow the simple procedure of replacing the 50 atm of D_2 with 10 atm of neon (to maintain equal numbers of electrons in the fill gas) and retaining the same 0.1 atm of argon in the microsphere target, then hydrodynamics simulations reveal that the dynamics of the implosion differ dramatically for different fill gases. This is illustrated in Figs. 8(a) and 8(b). In Fig. 8(a) we show the time history of the radius of the gas and the electron temperature and electron density in a region near the central part of the target for the Ar-D_2 experiment. Note that the time of maximum electron density is well matched to the time of maximum electron temperature and minimum target radius. Next, in Fig. 8(b), the case where 10 atm of Ne replaces the 50 atm of D_2 is presented. In contrast to the Ar-D_2 time history, in this case there is a substantial mismatch in the time of occurrence of the maximum temperature and density. We predict that this mismatch will lead to a substantial decrease in the emission in the K lines of Ar, which will result in the loss of observability of these lines of interest for these conditions. Although the absolute values of electron temperature and density in Fig. 8 are not particularly accurate, the qualitative changes from the D_2 filled to the Ne filled microsphere are significant.

The requirement that the implosion conditions pass through the same N_e and T_e points is particularly stressing on any experimental design and needs to be resolved before a series of experiments can be undertaken. In the case of neon, further hydrodynamic simulations are required to optimize the target design and fill gas mixture in order to maximize the He-like Ar emission relative to the continuum. For the CD_4 case, the ionization balance of the low Z fill is reasonably well understood and there is little doubt that the carbon will become fully ionized; still the details of the implosion dynamics will depend critically on the exact kinetics including radiation cooling, which is certainly present. A reasonable kinetics model with correct rate equations for the carbon is required for a full simulation of the microsphere implosion to ensure that a high level of control over the dynamics can be maintained in these experiments. This in turn implies that careful simulations need to be performed as a function of Z fill.

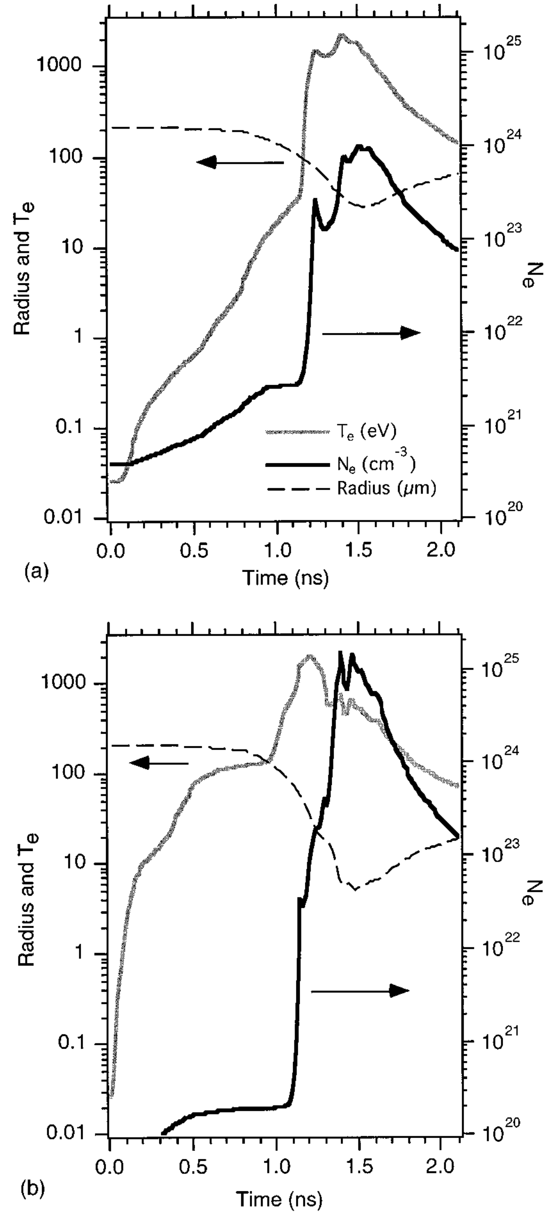

FIG. 8. (a) Time history of the radius of the gas and the temperature and density in a region near the central part of the target for the Ar-D_2 case. (b) Time history of the radius of the gas and the temperature and density in a region near the central part of the target for the Ar-Ne case.

In summary, spectroscopic calculational codes have now reached a stage of sophistication that permits very large level manifolds to be considered in addition to more subtle effects. In this way, the effect of satellite lines on the resonance line profile as well as ion dynamics can be considered. These codes have been extensively tested against molecular dynamics simulations and will permit extremely precise plasma diagnostics. We have compared, where possible, the predictions of these codes with precise experimental data and have shown ion dynamics effects are potentially an important process in line formation at the densities and temperatures achieved in ICF type plasmas. However, experimental proof of the role of ion dynamics in these plasma conditions remains for future experiments. Detailed line shape calculations for the Ar XVII 1-3 transition in different fill gases have been demonstrated. These simulations have suggested experiments that may provide indisputable evidence for the role ion dynamics. We have shown that satellites are not responsible for the filling in of the dip in the Ar XVII 1-3 line shape at peak temperature and in fact are a sensitive temperature diagnostic.

Varying the Ar to ion atomic number ratio enables one to study the detailed kinetics and the effects of radiative transfer on the line formation in high energy density plasmas. For this purpose, a series of experiments to measure the implosion dynamics of indirectly driven targets are necessary. The hydrodynamic simulations we have presented show that care is needed to ensure that the experiments are well design. Thus we have demonstrated the utility of the line shape calculations to determine density and temperature of the imploded core plasmas. The range of validity of these results has also been presented, as well as the possible experimental effects that may comprise these diagnostics.

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