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Symmetric Laser Compression of Argon-Filled Glass Shells to Densities of 4–6 g/cm^3

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Argon-filled plastic-coated glass shells were imploded with the six-beam ZETA laser system with short (~ 50-psec) pulses of energy ~ 100 J. Densities in the range 4–6 g/cm^3 [N_e = (1.0–1.5)×10^{24} cm^{-3}] temperatures ~ 1 keV were deduced from the Stark profiles of various Ar^{16+}, Ar^{17+} x-ray lines. These densities are achieved because of the shell thickness and radiational cooling of the high-Z fill gas and show that symmetric illumination can lead to high-volume convergence (> 1000).

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Most current implosion experiments in laser fusion are directed toward the compression of targets to densities significantly higher than previously achieved (0.1–0.5 g/cm^3) in the so-called explosive-pusher regime. We report here on high-compression experiments with use of thick shell targets filled with argon and imploded with short high-intensity laser pulses. The role of the argon was two-fold: (1) to mitigate partly the effect of preheat through radiational cooling and thereby enable a higher compression, (2) to serve as a direct diagnostic of the compressed density (ρ) and the quality of confinement (ρR). The relevance of these experiments to DT-filled target implosions is that for a given mass density (or electron density) the compressed core pressure (due to both electrons and ions) in both cases will be comparable. More importantly, the measurement of the density (with x-ray line Stark broadening[1]) permits an experimental verification of whether a given predicted compression (with any fill) can actually be achieved or whether it is prevented by the lack of perfect spherical symmetry, instability or shell-fill mixing.

The calculation of the Stark profiles used here[2] will be described in detail elsewhere. If we fit these profiles to the observed lines, this uses methods similar to those used to interpret various neon-filled target experiments.[3] The various lines are predicted to have different widths and *very different shapes* and therefore a consistent agreement with this large number of observables constitutes a highly reliable determination of the compression.

The experiments were conducted on the symmetrical irradiation, six-beam Nd-glass laser facility ZETA.[4] X-ray spectra were measured with Ge ($2d$ = 6.5 Å) and gypsum ($2d$ = 15.15 Å) crystals, using a slit for spectral imaging of resolution of ~ 11 μm. The film (Kodak 2497) was calibrated at a few wavelengths (recorded argon lines usually had a diffused density on film of

TABLE I. Typical data are given for three out of a series of 30 shots producing high density (thick shells) which showed similar and very consistent spectral results.

Shot no.	Power (TW)	Diameter (μm)	Wall thickness (μm)	Polimer coating (μm)	Ar-fill pressure (atm)	Ar-Lymanβ Width (eV) Measured	Computed (LILAC)	Inferred density (g/cm^3)	Inferred compression ratio
3231	1.8	52	1.86	1.58	16	46 ± 3	41	6.0 ± 1.5	250
2495	2.0	51	0.50	4.20	7	42 ± 3	39	5.2 ± 1.3	470
3264	2.0	50	1.90	1.88	< 3	43 ± 5	37	6.0 ± 2.0	> 1000
2416	1.7	45	0.48	1.60	8.7	20 ± 2	18	< 1.5	< 100

less than 0.3 o.d. for which film density is proportional to exposure). Sample data are given in Table I.

In order to employ the observed lines for ρ and ρR determinations we need to estimate the temperature during the time of emission, and the opacity (self-absorption) of the lines. The core temperature has to be known only approximately for Stark profile fitting, especially in the case of heliumlike ions. For example, in going from $T = 0.8$ to 1.2 keV, keeping $N_e = 1\times 10^{24}$ cm^{-3}, the width of the Ar^{16+}, $1s^2$-$1s3p$ line increases by less than 4%. The temperature also determines the Doppler broadening (~1.5 eV) which along with the instrumental width (~1 eV) were included in the Stark profiles (although their effect is very small). For the high-density shots, T_e was found to be about 0.8 keV with use of various line intensity ratios. The optical depth at an energy distance ΔE from the center of a spectral line depends on the line profile $S(\Delta E)$ through[3] $\tau(\Delta E) \sim \rho R b S(\Delta E)$, where b is the population fraction of ions in the absorbing level. For Stark-broadened lines the optical depth close to the line center is approximately independent of the compressed density ρ, since $S \sim \rho^{-2/3}$ whereas $\rho R \sim \rho^{2/3}$. For example, the opacity at the peaks of the Ar^{17+} Lyman-β line is given by $\tau_m \sim 0.1 b P^{1/3} R_0$, where P is the fill pressure (atm) and R_0 the initial radius (μm). For one-electron ions[3] $b \lesssim 0.4$ and we find for typical high-density shots $\tau_m \lesssim 1.5$ (or $\tau_0 \lesssim 0.5$ for the line center). This means that Lyman-β lines can yield the density but a small opacity correction may be required. For Lyman-γ lines the opacity is negligible whereas for Lyman-α lines we find $\tau_m = \tau_0 > 100$ and these lines can therefore be used to yield the ρR value. For the $1s^2$-$1s3p$ line we find $\tau_0 \lesssim 2$ (here $b \lesssim 0.9$).

An example of density determination is shown in Fig. 1 for shot No. 3231. The Lyman-β line was fitted with a profile of electron density $N_e = (1.5 \pm 0.4)\times 10^{24}$ cm^{-3} (which corresponds to $\rho \sim 6$ g/cm^3) without any opacity correction; a small correction would further improve the agreement with the experiment. The discrepancy around line center could be due to omission in the theory of additional broadening mechanisms[1b] as well as low-density contributions to the observed, integrated line profile; neither would significantly alter the rest of the profile.[5] The peak separation is relatively insensitive to opacity (or to background subtraction and corrections to the theory) and is very useful in obtaining a first estimate of the density.

Figure 1 shows that the profile shapes of argon lines agree with theory: The Lyman-β line is split in the center whereas the Lyman-γ profile has a sharp central peak. At the density deduced here the line $1s^2$-$1s4p$ should broaden to the point of being very similar to the Lyman-γ profile (transition from quadratic to linear Stark effect). This is indeed the case in Fig. 1 where the widths of these two lines (62 and 58 eV, respectively) compare well with the predicted full width at half-

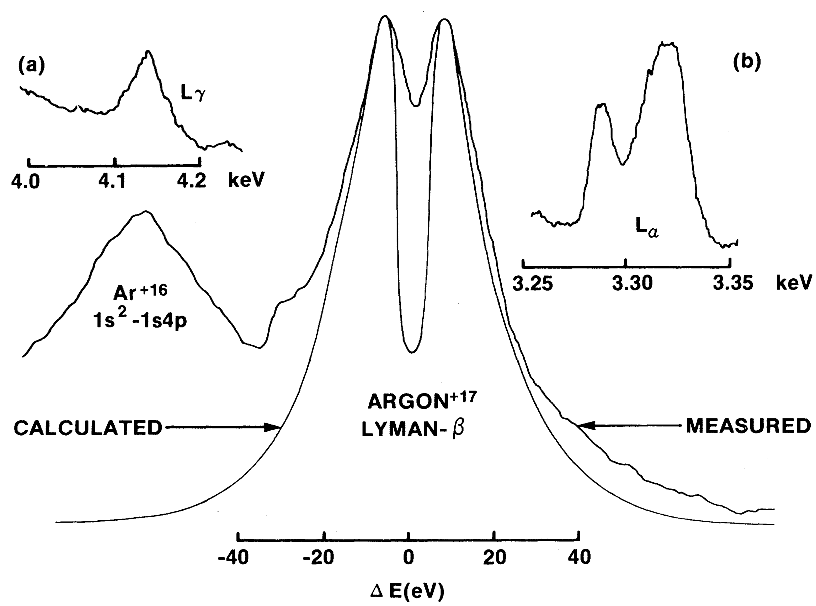

FIG. 1. Argon lines from shot No. 3231 (quartz target, no K or Ca lines appear). The insets show the profiles of the Lyman-γ and Lyman-α lines of Ar^{17+}.

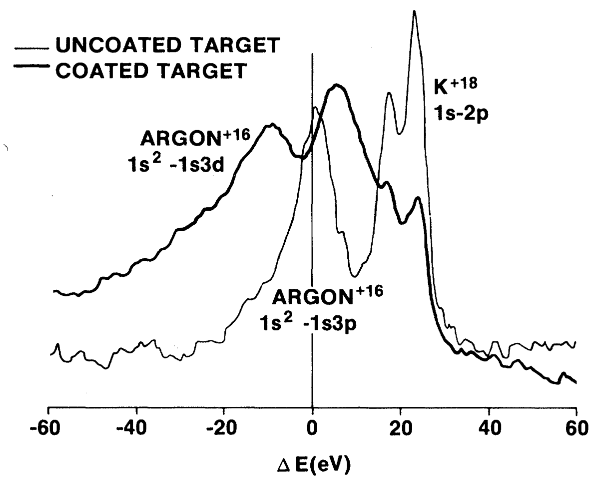

FIG. 2. Argon lines from a thin uncoated and from a coated target (shot No. 2495).

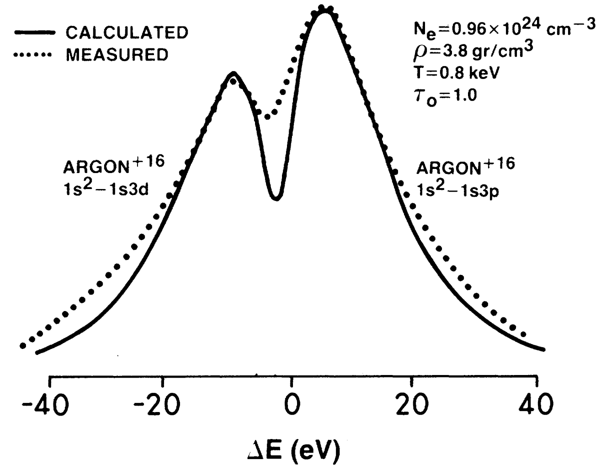

FIG. 3. Density determination by fitting the observed lines in Fig. 2 with a computed Stark profile. Note that the 3s level has a small contribution to the forbidden line and is included in the calculation.

maximum (FWHM) of 64 eV for the Lyman-γ line at a density $N_e = 1.5\times10^{24}$ cm^{-3}.

Some of the more dramatic profile changes with density are shown by the spectral profile of the $1s^2$-$1s3p$ line of Ar^{16+} and its forbidden neighbor $1s^2$-$1s3d,3s$. Figure 2 shows a comparison of the profile of these lines for a high-density shot (No. 2495) and for a lower-density shot (No. 2416). At high plasma densities the quadratic Stark effect[1] should cause the forbidden line to increase in intensity and the two lines to move apart and broaden. All these features are clearly seen in Fig. 2. Stark profile fitting (Fig. 3) yields an electron density $N_e = (0.96\pm0.24)\times10^{24}$ cm^{-3} ($\rho\sim3.8$ g/cm^3). The Stark profile for this density has the correct peak separation but is too narrow; we then introduce[3] opacity and increase it until good agreement with the experiment is achieved. The opacity correction *does not significantly change the peak separation* and therefore the observed profile cannot be fitted with a profile corresponding to a lower density and higher opacity. The opacity needed for good agreement in Fig. 3 agrees with its estimated value (above). Also, the Lyman-β line corresponding to Fig. 3 was well fitted with a profile of density $N_e = 1.3\times10^{24}$ cm^{-3} ($\rho\sim5.2$ g/cm^3) after including a small correction for opacity ($\tau_0 = 0.5$).

Stark profiles yield only the total electron (or mass) density in the emission region. However, the opacity-broadened Ar Lyman-α line yields the ρR for argon alone and can show whether the measured density corresponds to an argon-glass mixture. The Stark width of this line at the density deduced from the Lyman-β line would be smaller than the fine-structure splitting (4.7 eV). The observed additional broadening to a FWHM of 28 eV is due to opacity. At the half-intensity points $\tau\sim\ln2$ and the value of the Stark profile at $\Delta E = 14$ eV for a density $N_e = 1.5\times10^{24}$ cm^{-3} is 3×10^{-3} eV^{-1}. Since $b\lesssim0.4$ we find from the definition[3] of τ that $\rho R \gtrsim 1\times10^{-3}$ g/cm^2. For such large values of ΔE the profile is well known and is independent of the uncertainties as to the narrow (< 2 eV) central Stark component. If we assume a uniform density of 6 g/cm^3 in a compressed argon sphere (which overestimates ρR) we get $\rho R < 2\times10^{-3}$ g/cm^2. Thus, to within ± 30% we find $\rho R = 1.5\times10^{-3}$ g/cm^2, which is consistent with the assumption that the total initial argon mass is compressed. Targets with lower fill pressures yielded about the same density but necessarily a higher compression ratio (> 1000 for shot No. 3264). We can conclude from this shot that no more than $\sim3\times10^{-10}$ g of glass could be mixed with the argon or the Lyman-α line would be measurably narrower. Additional indication of no shell breakup is shown by the spectral images of the target obtained through the spectrograph slit: Argon lines are emitted from a central spot of diameter 11 μm (resolution limited) whereas for Ca lines the diameter is 16 μm and for Si lines it is 38 μm.

In high-density implosions the inner part of the glass shell is recompressed to a moderately high density. In Fig. 4 we compare part of the silicon spectrum for shot No. 2495 with that of a low-den-

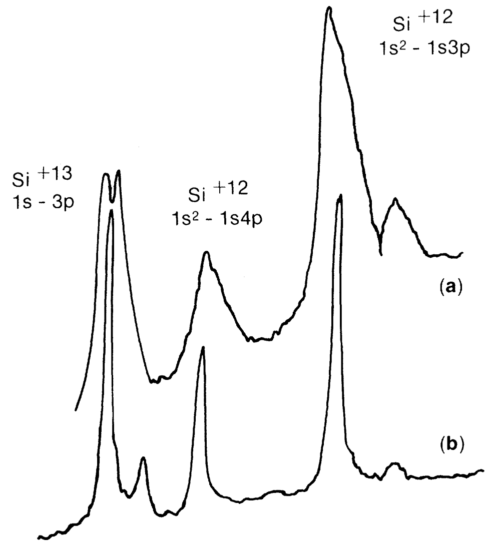

FIG. 4. Curve a, silicon lines from shot No. 2495; curve b, a low-compressed-density shot for comparison.

sity shot. The broad lines are very similar in shape to the corresponding transitions in argon: $1s^2$-$1s3p$ is blueshifted (see Fig. 2), $1s^2$-$1s4p$ is centrally peaked, and $1s$-$3p$ (of width 22 eV) is split in the center. These Stark profiles yield a density ~ 2 g/cm^3, which agrees with numerical predictions.

The precision of the calculated Stark profiles away from the center depends partly on that of the electric field distribution which had been shown by comparison with Monte Carlo calculations to be better than ± 5%.[1] Integration over time and space in the experiment results in the far profile wings being ralted to a higher density than the closer wings; in that sense our profile fitting constitutes a lower bound on the peak density. The main factors limiting the precision are the opacity and the background subtraction. By varying these parameters we could estimate a precision of ± 25% in the determined density.

Extensive simulations of radiationally cooled targets, including these experiments, were done with use of the one-dimensional laser-fusion code LILAC and will be reported separately. The simulations show that Ar^{17+} lines are emitted mostly during a ~ 10-psec time interval when the average fill density is about 5–6 g/cm^3 and the temperature ~ 0.8 keV. This explains why spectral line profiles from the code, transported through the target and self-consistently tied to an atomic rate-dependent model, agreed quite closely with Stark profiles calculated for a single density (as well as with the experiment, see Table I).

In conclusion, we have demonstrated that short, intense laser pulses are capable of compressing targets to relatively high densities through the combined effect of thick shells and radiational cooling to mitigate fast electron preheat. Consequently, a high-Z fill gas is being considered as one component in a multishell high-yield target designs with the special role of providing a low-temperature, high-density piston for compressing the thermonuclear fuel.

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