Final technical report

Measurement of High Ion Temperature using the Doppler Width of the Kr He? Line (0.8 Å) from Kr-doped Target Implosions

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ABSTRACT

In a recently-published paper[1], diagnostic methods for laser implosions were proposed, using Krypton K-shell x-ray lines, particularly the He-? line at 15.43 keV (or 0.8 Å). Strong Kr K-shell lines were indeed observed on Kr-doped implosions on OMEGA and were used to determine the electron temperature. To determine the ion temperature, on the other hand, would require far greater spectral resolution. It was the purpose of this proposal to use a focusing spectrometer ("Rowland circle spectrometer") to determine the ion temperature, for the first time using the Doppler broadening. In the OMEGA experiment, electron temperatures of 3 - 4 keV were measured and ion temperatures of up to 13 keV were measured, using neutron spectra. For these conditions and the expected density, the total line profile has been calculated[1]. There are two diagnostic signatures: (a) The ion temperature can be deduced from the line width, and (b) the density can be deduced from the relative intensity of the "shoulder" or the forbidden component calculated to appear on the shorter-wavelength wing of the line. To resolve the details of the profile a spectral resolution E/?E much higher than ~550 is required. A flat, non-focusing spectrometer has a resolution of E/?E ~300, much less than the minimum required. To address this problem we proposed to use a focusing Rowland spectrometer, whose resolution was predicted to be typically E/?E ~2000 - 3000. this is sufficient resolution to resolve the profile of the Kr He-? line.

TECHNICAL REPORT

Strong Kr K-shell lines were observed on Kr-doped implosions on OMEGA and were used to determine the electron temperature. However, to determine the ion temperature, as suggested in recently-published paper, would require far greater spectral resolution. It was the purpose of this proposal to use a focusing spectrometer ("Rowland circle spectrometer") equipped with new crystals, appropriate for the wavelength range required, and to determine the ion temperature, for the first time using the Doppler broadening.

In a recently-published paper,[1] diagnostic methods for laser implosions were proposed, using Krypton K-shell x-ray lines, particularly the He-? line at 15.43 keV (or 0.8 Å). It was predicted that thin-shell targets doped with 0.01 - 0.03 atm Kr and imploded on OMEGA would produce these lines. This in fact has been the case: Strong Kr K-shell lines were observed on Kr-doped implosions on OMEGA[2] and were used to determine the electron temperature. However, to determine the ion temperature, as suggested in Ref. 1, would require far greater spectral resolution. It was the purpose of this proposal to use a focusing spectrometer ("Rowland circle spectrometer") equipped with new crystals, appropriate for the wavelength range required, and to determine the ion temperature, for the first time using the Doppler broadening.

In hydrodynamic code simulations for Kr-doped targets it was predicted[1] that the peak density would be in the range of 1 - 5 g/cm^3. We showed the calculated spectrum[1] for the Kr He-? line at an ion temperature of Ti = 10 keV and an electron density of Ne = 1x10^{24} cm^{-3}, corresponding to a mass density of ~3.3 g/cm^3. In the OMEGA experiment, electron temperatures of 3 - 4 keV were measured[2] and ion temperatures of up to 13 keV were measured, using neutron spectra.[3] However, the density was not measured. We therefore look at the predicted spectrum at an intermediate density of 3.3 g/cm^3. The spectrum in the figure shows the line profile due only to the Stark effect, and due to both the Stark and Doppler effects. The Stark profile depends mainly on the density but also on the temperature, whereas the Doppler profile depends only on the ion temperature (width ~ Ti$^{1/2}$). At very low densities only the strongest component would show up in the spectrum. As the density increases, and with it the local plasma electric field, the components which are normally forbidden become partially allowed because of level mixing. Only at much higher densities will these components merge and from then on, increasing the density will broaden the total profile. Here, because of the Doppler effect, there is no density information in the width, but there is temperature information. On the other hand, the density has the effect of creating the shoulder around 15.42 keV. So we had here two diagnostic signatures:

(a) The ion temperature can be deduced from the line width, and
(b) the density can be deduced from the relative intensity of the "shoulder" or the

forbidden component.

The profile did not include the instrumental width, and this was the main concern in the proposed experiment. The investigation showed that to resolve the line shape, the instrument had to resolve a width of ~28 eV, or to have a resolution much better than

$$E/?E = 15460/28 = 550. \qquad (1)$$

In the experiment referenced here[2], a flat-crystal spectrometer was used. When using a flat, non-focusing spectrograph, the resolution depends on the size of the emitting source and is not a property of the instrument. The resolution was given by

$$E/?E = \tan(?_B/??), \qquad (2)$$

where $?_B$ is the Bragg incidence angle on the crystal and the broadening ?? is given by D/L, where D is the diameter of the emitting source and L is the distance from the target to the film (along the ray). If we assume for D~200 mm, and since L was ~30 cm, we find a spectrometer resolution of E/?E ~300, much less than the minimum required, as given by Eq. (1).

To address this problem we proposed to use a focusing Rowland spectrometer, whose resolution was predicted to be typically E/?E ~2000 - 3000. this is sufficient resolution to resolve the Kr He-? line.

A question arose regarding the relationship between the Krypton ion temperature measured by the Doppler broadening and the fuel ion temperature (which was measured by the neutron spectrum). It turns out that the energy transfer collisions between the two kinds of ions are frequent enough to keep the two groups at the same temperature. The energy transfer time[5] between Kr ions and deuterium ions (the former would tend to be higher because of the higher mass) was given by

$$??= (2M_{Kr})^{1/2}\,(3kTi/2)^{3/2} / (4?\,e^4\,Z^2_{Kr}\,N_D \ln ?). \qquad (3)$$

Assuming Ti = 10 keV, $Z_{Kr} = 34$, and $N_D = 1\text{x}10^{24}$ cm^{-3}, the collision time is shorter than 1 psec.

The principal investigator of this proposal (Q. S.) spent about a year recently, working at LLE on simulation and analysis of spectroscopic measurements relevant to future experiments on OMEGA, and had the benefit of cooperation of scientists at LLE, primarily the co-investigator B. Yaakobi. We have carried out the proposed projects with results reported in the refereed scientific journals (citation included at the very end). The current work on fusion target imaging has also motivated the PI's research interest in the problem of noninvasive imaging techniques for potential applications in a wider context. The PI acknowledges the generous support from DOE via the current program. He intends to submit a new proposal for the next round of NLUF.

References

1. "Diagnosis of High Temperature Implosions Using Low- and High-Opacity Krypton Lines", B. Yaakobi, R. Epstein, C. F. Hooper, D. A. Haynes, and Q. Su.

2. "High Temperature of Laser-compressed Shells Measured with Kr^{+34} and Kr^{+35} X-ray Lines", B. Yaakobi, F. J. Marshall, and R. Epstein, Phys. Rev. **54**, 5848 (1996).

3. Laboratory for Laser Energetics, LLE Review **64**, 145 (1995).

4. "Focusing X-ray Spectrograph for Laser Fusion Studies", B. Yaakobi, T. Boehly, and P. Audebert, Rev. Sci. Instr. **61**, 1915 (1990).

5. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, NY, 1956).

APPENDIX

LIST OF REVEVENT LLE PUBLICATIONS

(with the participation of the Principal Investigator)

1 "Bridging the micro- and macro-scopic theories for light reflected from disordered plane-parallel dielectric slabs"
S. Menon, Q. Su and R. Grobe, **Phys. Rev. A** (submitted).

2 "Areal-density measurement of laser targets using absorption lines"
B. Yaakobi, R.S. Craxton, R. Epstein, and Q. Su, **J. Quant. Spectrosc. Radiat. Transfer** 58, 75 (1997).

3 "Diagnosis of high-temperature implosions using low- and high-opacity Krypton lines"
B. Yaakobi, R. Epstein, C.F. Hooper, Jr., D.A. Haynes, Jr., and Q. Su, **J. X-ray Sci. Technol.** 6, 172 (1996).

4 "Diagnosis of core-shell mixing using absorption and emission spectra of a doped layer"
B. Yaakobi, R.S. Craxton, R. Epstein, Q. Su, **J. Quant. Spectrosc. Radiat. Transfer** 55, 731 (1996).

5 "X-ray backlighting imaging of mixed imploded targets"
B. Yakkobi, D. Shvarts, R. Epstein, and Q. Su, **Laser and Particle Beams** 14, 81 (1996).

6 "Mono-chromatic backlighting as a laser-fusion diagnostic"
B. Yaakobi, F.J. Marshall, Q. Su, and R. Epstein, **J. X-ray Sci. Technol.** 5, 73 (1995).

7 "Target imaging and backlighting diagnosis"
B. Yaakobi, D. Shvarts, F.J. Marshall, R. Epstein, and Q. Su, **Rev. Sci. Instrum.** 66, 731 (1995).

8 "New diagnostic features in the laser implosions of Argon-filled targets"
B. Yaakobi, R. Epstein, F.J. Marshall, D.K. Bradley, P.A. Jaanimagi, and Q. Su, **Rev. Sci. Instrum.** 66, 728 (1995).

9 "Quantitative measurements with X-ray microscopes in laser-fusion experiments"
F.J. Marshall and Q. Su, **Rev. Sci. Instrum.** 66, 725 (1995).

10 "New diagnostic features in the laser implosions of Argon-filled targets"
B. Yaakobi, R. Epstein, F.J. Marshall, D.K. Bradley, P.A. Jaanimagi, and Q. Su, **Opt. Commun.** 111, 556 (1994).