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REVIEW OF X-RAY SPECTROSCOPY
FROM LASER-PRODUCED PLASMAS

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Review of X-Ray Spectroscopy from
Laser-Produced Plasmas*

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Abstract

Recent progress in x-ray spectroscopy from laser plasmas is reviewed. Advances in the use of K-shell spectra as a diagnostic tool is discussed. Much activity in understanding complex spectra especially from Ne I and Ni I isoelectronic series have been made. Much of the progress has been due to observation of amplification from $\Delta n=0$ transitions from these configurations. The spectroscopy will be discussed and examples of spectra of the amplified lines will be shown. Finally, recent work on using x-ray spectroscopy to diagnose high density implosions will be discussed.

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Introduction

Significant progress has been made in the field of x-ray spectroscopy from laser-produced plasmas since the last IAU conference in Washington DC.¹ At that time, most of the interest in x-ray spectroscopy from laser-produced plasmas was in developing spectral diagnostics for characterizing plasma conditions and in diagnosing ICF implosions. In the last three years, the observation of x-ray lasing from laser-produced plasmas² has accelerated interest in understanding ionization and radiation physics in these plasmas. X-ray laser research has especially contributed to the understanding of more complex systems, such as Ne I and Ni I isoelectronic ions and in the development of modeling capabilities for understanding line production and transport in laser-produced plasmas.

In the past three years, there have been significant advances in new, large laser facilities for ICF research. The Nova laser at Lawrence Livermore National Laboratory, presently the world's most powerful laser, was activated in 1985. The Nova laser can irradiate targets with 20 kJ of 0.35 μm light with plans to increase the energy to greater than 50 kJ in the next few years. The 24 beams of the Omega laser at LLE-University of Rochester have been upgraded and frequency converted to produce 2 kJ of 0.35 μm light for target irradiations. Gekko XII at the University of Osaka, is now operating with 8 kJ of 0.53 μm light on target. In addition, the Phebus laser at the Centre d'Etudes de Limeil has been completed and is delivering 6 TW of 0.53 μm light in two beams for target experiments. These facilities will allow the study of ablative implosions of ICF microspheres producing high density, high temperature

implosions. Such implosions offer the potential for x-ray spectroscopy at temperatures and densities not previously accessible in the laboratory. These multi-terawatt sub-micron wavelength lasers also can produce high temperature and density sources for interesting x-ray spectroscopy studies.

The following are highlights of some of the new advances in the field of x-ray spectroscopy from laser-produced plasmas.

K-Shell Spectra

K-shell spectra have been used extensively in the past to characterize laser-produced plasmas. The application of various spectral features and their application as a plasma diagnostic has been extensively reviewed.³ Recent advances in experiment and analysis in using K-shell spectra as a plasma diagnostic have been in studying the detailed evolution and dynamics of laser-produced plasmas. Time-resolved crystal spectrographs have been developed to measure the time evolution of the x-ray spectrum from laser-produced plasmas.⁴⁻⁶ These instruments can nominally measure the time dependence of x-ray lines or continuum with temporal resolution of less than 50 ps and resolving powers of 500 or greater. These time scales are on the order of times for ionization and hydrodynamic expansion allowing detailed study of the plasma evolution.

Detailed analytical tools have been developed to understand ionization and radiation from laser-produced plasmas. Large hydrodynamic simulation codes such as LASNEX⁷ have been used extensively for modeling the laser-plasma energy deposition and hydrodynamic motion. Such codes include ionization and radiation physics pertaining to energy

balance in the plasma, but usually the models are not sufficient to calculate detailed x-ray spectra. Duston, et al. have modeled line emission from laser-produced plasmas by coupling hydrodynamics with a detailed treatment of the ionization physics and radiation transport.⁸ The modeling calculates the time-dependent ionization and emission even from the large spatial gradients in temperature and density existing in laser-produced plasmas. These initial results, although calculated in only one-dimensional geometry, are computationally large and time consuming because of the large number of atomic levels and atomic rates that must be included. More recently, several other detailed modeling codes have been developed to model x-ray laser dynamics.^{9,10}

As an example of experiments and analysis studying plasma dynamics, I review results from a thin exploding foil experiment performed on the Novette laser at LLNL.¹¹ Such exploding foils are similar to those used as a lasing medium for x-ray lasers. In this experiment 0.53 μm laser light heats a thin plastic foil producing a well characterized large scalelength plasma for studying instability production in laser-plasma coupling. In order to characterize the plasma, sulfur is added in low concentrations to the plastic foil and the time-dependence of the sulfur K lines are measured. The data and preliminary analysis has been presented in the last conference.¹ The preliminary analysis showed that the plasma could not be modeled as being in steady state at a single temperature and density.

For a more accurate treatment of line production, the plasma motion is calculated using a hydrodynamics simulation, and the results are post-processed using an atomic kinetics code. A two-dimensional LASNEX

simulation calculates the plasma motion using the diffusion approximation for electron transport. An example of the simulation results is shown in Fig. 1. The grid represents different equal mass zones. For these experiments, only the center section of the foil denoted by the crossed hatched areas has been doped with sulfur. To model the line production in the sulfur, the LASNEX output is post-processed using RATION.¹² RATION calculates the time-dependent ionization balance in each of the mass cells. The line intensities are summed from all of the zones containing sulfur assuming the plasma is optically thin. This is a good assumption for these experiments because of the low doping concentrations of sulfur.

Results of the modeling are shown in Fig. 2 compared with the data for the Ly α line and the He-like $1P_1$ line. From such modeling details of the ionization and line production in the plasmas can be investigated. An advantage of decoupling the hydrodynamics and the atomic kinetics is that physics assumptions can be checked without repeating the entire calculations. For example assumptions about electron transport and hydrodynamics can be tested in the hydrodynamics code and compared with other physical observations without solving the detailed atomic kinetics. On the other hand, the sensitivity of line production to model parameters such as atomic rates, or plasma temperatures can be tested independent of the hydrodynamics. Implicit in this approach is that the hydrodynamics code includes calculations of radiation losses pertaining to the energy balance of the system and that detailed kinetics will not greatly alter the energy balance.

Complex Spectra

Much of the recent effort in laser-plasma spectroscopy has been in the understanding of more complex spectra. Much of this interest has been generated by recent advances in the production of x-ray lasers. Lasing schemes have been identified in Ne I and Ni I isoelectronic series. Complex spectra have also been investigated as bright pulsed sources of x rays for x-ray lithography and x-ray radiography applications.^{13,14}

Laser-produced plasmas have been recognized as a spectroscopic source of complex spectra for over ten years. L-shell spectra have been measured as high as Sn XLI from directly irradiated plasma¹⁵ and Xe XLV from an imploded microballoon.¹⁶ Most of the spectral studies have concentrated on isoelectronic series of Ne I and neighboring ionization levels since they are most easily excited although most of the L-shell transitions from Ne I through Be I have been studied.^{15,17} Most of the work with L-shell spectra have been in line identification. Recently, Feldman, et al. have identified some x-ray lines that could possibly be used as a density diagnostic,¹⁸ but as yet no experiments have applied these transitions as a plasma diagnostic. Also, Goldstein, et al. have investigated experimentally using the dielectronic satellites of the Ne I configuration in Br to measure ionization balance, but time-dependence of the plasma compromised the analysis.¹⁹ Much work both theoretically and experimentally is needed to develop these techniques to the same level of understanding the K-shell spectra.

Significant work has also been done on M-shell spectra although these spectra are extremely complicated due to the large number of transitions possible. As an example of the complicated nature of the

M-shell spectra, I show in Fig. 3 an Au spectrum from the Nova laser produced by a single beam of 2 kJ of 0.35 μm light to irradiate planar Au foil. Although a few sharp lines can be seen in Fig. 3, most of the spectrum consists of many unresolved lines. I have identified several of the prominent lines from the Ni I series. The Ni I series has been most widely studied since they consist of a relatively few strong transitions due to the ground state being a closed shell.²⁰ Recently, Busquet, et al. have analyzed the Au spectrum in detail identifying a number of features from other ionization states.²¹

Since most configurations produce a large number of spectral lines that are not resolvable, these analyses of multiply ionized configurations do not result in unique line identification, but features are assigned to a manifold of transitions. The M-shell spectra have been analyzed in terms of these manifolds, or unresolved transition arrays (UTA), in several papers by Baucke-Arnolt, et al.²² by calculating statistical moments of the UTA's. This technique has been successful in modeling the overall spectral shape when some distribution of configurations is assumed. An alternative statistical approach has been made by Albritton to model the M-shell spectrum.²³ Albritton uses Monte Carlo techniques to populate the upper levels and calculates its radiative decay branches. These results are compared in Fig. 3 with the data. The calculations assume the plasma is in LTE. The advantage of this approach over the UTA method is that it can treat self consistently configurations with numerous lines. The calculated spectrum is seen in Fig. 3 to predict a narrower group of lines than observed. This may be due to the

assumption that the distribution of charge states are in LTE which has been shown not to be valid for these laser-produced plasmas.

X-Ray Laser Spectroscopy

Although the status of x-ray laser research will be reviewed by M. Key at this conference, I would like to present some recent results from LLNL since they also offer some insights into spectroscopy of complex ions, especially at low energy in the XUV region. Gain was first observed in $\Delta n=0$ transitions from $2p^5 3p-2p^5 3s$ Ne I transitions in Se.² Such measurements have been extended to higher Z ions in the Ne I isoelectronic series.²⁴ Examples of low energy spectra from laser output are shown in Fig. 4. The lines at 20.7 and 21.0 nm are the $j=2-1$ transitions first observed in Se.² Gain on these transitions have been measured to be 4 cm^{-1} with gain-length products as high as 14 having been observed. These lines in Fig. 4 are purposely saturated to observe other lower features. The transition at 18.24 nm is the $j=0-1$ transition which had not been observed in the first experiments. The gain on this line is not as high as calculated and therefore the line is only observed at the higher gain-length products. It is interesting to note from a spectroscopy point of view that these lines are only observable above continuum because of the amplification. As seen in the figure, these systems have been extended to shorter wavelength using Y^{29+} at 15.5 and 15.9 nm and Mo^{32+} at 13.1 and 13.3 nm. Unfortunately, the gain scaling of these systems to shorter wavelength is not favorable. Laser energies greater than 1 MJ are estimated to be needed to produce significant gain below 44 Å, the carbon absorption edge.

Analogous transitions in Ni I configurations have also been investigated as potential x-ray lasing lines. Several transitions between the $3d^9 4d-3d^9 4p$ levels have been identified as having significant gain for Eu^{+35} .²⁵ This system has been investigated experimentally and gain has been observed on two of the transitions.²⁶ Examples of spectra are shown in Fig. 5 for various length targets showing the lasing transitions emerging from the continuum as the target is lengthened. The Ni I lasing schemes are interesting because their lasing transitions are at shorter wavelength than the Ne I schemes for similar pump laser irradiances. Power requirements for scaling to sub-44 Å lasers may be less for these Ni I schemes making this goal more attainable.

Implosions

With the completion of the latest high powered lasers, the emphasis in implosion spectroscopy has been to develop techniques to diagnose denser, more ablative implosions. Stark-broadening of Ne or Ar seeded in the DT fuel have been successfully used as an x-ray spectroscopic diagnosis of the final core density.^{27,28} These larger lasers are expected to produce denser implosions at similar fuel temperature with higher fuel areal densities, *pr.* Although the new lasers are only now beginning to produce high quality implosions, several experiments have begun investigating potential problems and new techniques on less optimum targets.

Optical depth effects on line broadening may become more important for the higher density implosions. Not only will ρr of the core be larger, but the higher densities may pressure ionize some of the higher series lines now used to reduce optical depth effects.²⁹ Optical depth effects on the lower series lines have recently been investigated by Delmater, et al.³⁰ Opacity effects can alter the line profile by depressing line center making the lines appear broadened more than from pure Stark broadening. In these experiments, implosions from Ar and Ar/Ne cores are analyzed using the Ly series. By varying Ar concentrations, line profiles from similar densities with different optical depths could be analyzed. The analysis indicates that lines with optical depths at line center as great as 100 could be used if the optical depth is known.

More recently, Delmater, et al.³¹ investigated extending spectroscopic diagnostics to L-shell lines of Kr. At high densities Ar lines become too broad to be observable. For example, at $5 \times 10^{23} \text{ e}^-/\text{cm}^3$, equivalent to 10x liquid DT density, the Ar Ly β line is 37 eV wide. For $5 \times 10^{24} \text{ e}^-/\text{cm}^3$, which should be attainable by the present lasers, the width is over a factor of three times wider and could be lost in the background.³² Ar and Kr spectra are shown in Figs. 6 and 7 from the same implosion from the Omega laser at the University of Rochester. The implosions are not optimized for high density but are designed to develop the basic spectroscopy for Kr. The spheres are pure CH polymer shells which have low opacity for accessing higher density. Hydrogenic Ar is easily observed from the core and a number of ionization

states of Kr up to Li I are also observed. Analysis is presently under way to identify density sensitive features in Kr that may be usable as a high density spectroscopic diagnostic.

Ar features have also been observed recently at LLNL from radiation driven implosions. An example for the spectrum is shown in Fig. 8 of the Ar XVII α -lines and their dielectronic satellites. The dielectronic satellites should be density sensitive in this density range. Predicted line ratios of the $(abcd+qr)/jkl$ are also shown in Fig. 9 calculated using RATION.¹² Fits of the data imply that the core densities range between $5 \times 10^{23} \text{ e}^-/\text{cm}^3$ and $2 \times 10^{24} \text{ e}^-/\text{cm}^3$. The data is noisy and the fits are very sensitive to the peak widths resulting in the large uncertainty. Synthetic spectra have been calculated from the RATION results and are compared with the data in Fig. 9. The spectrum is consistent with a core density of greater than $10^{24} \text{ e}^-/\text{cm}^3$ since below this density the lower energy peak is predicted to be greater than the high energy peak. At higher densities, the peak intensities reverse consistent with the data. Even using the lower density estimates, these are the highest densities inferred from spectroscopic measurements in ICF.

One of the most difficult regions to diagnose in ICF implosions is the pusher region. The pusher region is the cold dense region of the imploding shell. At peak compression, the fuel stagnates on axis heating and burning the fuel. Recently absorption spectroscopy has been used to study the pusher at peak stagnation by Hauer, et al.³³ In these experiments, Cl absorption features from Cl and K ions imbedded in the pusher layer. Similar absorption features in Ar can be seen in Fig. 6

arising from temperature gradients in the core. The absorption features are produced by the hot core continuum from the stagnated plasma escaping through the cold pusher. From such features estimates of temperatures and areal densities of the surrounding pusher can be made.

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Fig. 1. Example of a two-dimensional hydrodynamic simulation of an exploding foil. The cross hatched region has been doped with sulfur for spectroscopic diagnostics.

Fig. 2. Comparison of sulfur line emission from the hydrodynamics simulations with experiment.

Fig. 3. Au M-shell spectrum showing Ni I transitions. Model spectrum calculated using Enrico.²³

Fig. 4. Z scaling of the spectrum from x-ray laser output demonstrating gain in the $\Delta n=0$ transitions from Ne I configurations.²⁴

Fig. 5. Length dependence of the spectrum from $\Delta n=0$ transitions from Ni I configurations.

Fig. 6. Ar spectrum from the stagnated core of a directly irradiated Ar/Kr field microballoon.³¹

Fig. 7. Kr spectrum from the same stagnated core as Fig. 6.³¹

Fig. 8. Calculated line ratios of dielectronic satellite lines for Ar He α . Range of ratios measured from a radiation driven implosion is shown.

Fig. 9. Comparison of synthetic spectra with Ar He α data from a radiation driven implosion. The data indicates that the Ar samples density greater than 10^{24} e $^-$ /cm 3 .