K_α Spectral Diagnostics for Mg and Al Plasmas Irradiated by Intense Li Beams

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FUSION TECHNOLOGY INSTITUTE

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J.J. MacFarlane, P. Wang, J.E. Bailey, T.A. Mehlhorn, R.J. Dukart

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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J. J. MacFarlane and P. Wang
Fusion Technology Institute
University of Wisconsin
1500 Johnson Drive
Madison, WI 53706

J. E. Bailey, T. A. Mehlhorn, and R. J. Dukart
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185

Abstract

K_α spectroscopy can be a valuable diagnostic method for determining plasma conditions in ion beam-heated targets. In intense light ion beam experiments, K_α emission lines can be observed as $2p$ electrons drop down to fill $1s$ vacancies created by beam-impact ionization. In this paper, we present results from collisional-radiative equilibrium (CRE) calculations for Al and Mg target tracer layers being irradiated by an intense Li beam. Presently, 9 MeV Li beams with power densities of 1-2 TW/cm^2 can be generated in Particle Beam Fusion Accelerator-II (PBFA-II) experiments at Sandia National Laboratories. It is shown that both emission and absorption K_α spectra show good sensitivity to temperature and density for the range of plasma conditions typically achieved in present PBFA-II experiments.

I. Introduction

K_α satellite spectroscopy has been shown to be a valuable technique in determining plasma conditions in high energy density plasma experiments [1-7]. K_α lines result from electronic $2p \leftrightarrow 1s$ transitions. Thus, in intense light ion beam experiments emission lines can be produced as $2p$ electrons drop down to fill $1s$ vacancies created by the ion beam. K_α absorption lines can be seen in the presence of an x-ray backlighter when the target ions have at least one vacancy in the $2p$ subshell. Bailey et al. [2] reported the first spectroscopic measurements of K_α x-ray satellites in an intense proton beam experiment. K_α emission spectra have also recently been measured in intense Li-beam experiments on PBFA-II [8].

The purpose of this paper is to show how K_α satellite spectroscopy can be used to diagnose conditions in target plasmas heated by intense Li beams. To do this, we have performed a series of collisional-radiative equilibrium (CRE) calculations to generate K_α emission and absorption spectra for Mg and

Al plasmas. In previous light ion beam experiments, only K_α satellite emission spectra from single-component tracers (i.e., Al) have been used for diagnosing plasma conditions [2,5,8-10]. However, it is expected that multicomponent tracers will be utilized in upcoming experiments to provide additional information for constraining the plasma temperature and density. This paper presents our initial results for Mg/Al tracers.

II. Theoretical Models

Next, we briefly describe the major features of our CRE and atomic physics models. Additional details can be found elsewhere [5,9-11]. Atomic level populations are determined by solving multilevel statistical equilibrium equations self-consistently with the radiation field and ion beam properties. Our atomic models for intermediate-Z tracer elements (here, Mg and Al) typically consist of $\sim 10^3$ energy levels distributed over all ionization stages. Roughly 60% of these are autoionization states with K-shell vacancies. Atomic structure and radiative data are computed using a configuration interaction (CI) model with Hartree-Fock wavefunctions. Ion beam-impact ionization is included in the statistical equilibrium equations, including multiple ionization transitions (i.e., the simultaneous ejection of a K-shell and one or more L-shell electrons). Ion-impact ionization cross sections are computed using a plane-wave Born approximation model with corrections for Coulomb-deflection, binding energy, and relativistic effects. Multiple ionization cross sections are then obtained using an independent event binomial distribution model [11]. Auger rates and fluorescence yields are calculated for each autoionizing level using a LS coupling formalism with Hartree-Fock wavefunctions. Calculated emission and absorption spectra include contributions from bound-bound, bound-free, and free-free transitions. In the calculations described below, radiation is transported using an escape probability model. Resonant self-absorption effects are included in computing both the photoexcitation rates and the emergent spectra. Line profiles include the effects of natural, Doppler, Auger, and Stark broadening.

III. Results

A series of calculations were performed independetly for thin, planar Mg and Al tracers of uniform temperature and density. Temperatures were varied between 30 and 50 eV. In all cases the tracer density was $n = 10^{-3}$ $n_{\rm solid}$ and the thickness was 200 μm, which corresponds to a 2000 Å foil which has expanded by a factor of 10^3. The ion beam was assumed to be composed of Li^{+3} with an energy of 9 MeV per ion. All calculated spectra include instrumental broadening, where a resolution of $\lambda/\Delta\lambda = 1500$ was assumed.

Calculated emission and absorption spectra for K_α satellite spectral region of Mg are shown in Fig. 1. The absorption spectra (shown in lower panels) probe the lower state populations of the K_α bound-bound transitions, and therefore provide a direct measure of the ionization distribution. For instance, B-like and Be-like Mg are the dominant ionization stages at $T = 40$ eV, while Li-like and Be-like Mg are prevalent at $T = 50$ eV. K_α satellite emission spectra (upper panels) reflect the populations of the upper levels of the K_α transitions (i.e., the autoionizing levels), which are populated by ion beam-impact ionization. Because of this, lines from one to two ionization stages higher are seen in emission. For example, the He_α line ($1s2p\,^1P \rightarrow 1s^2\,^1S$) and Li-like satellites are strongest in emission at $T = 40$ eV.

Additional information about plasma conditions can be obtained by performing experiments with multi-component tracers.

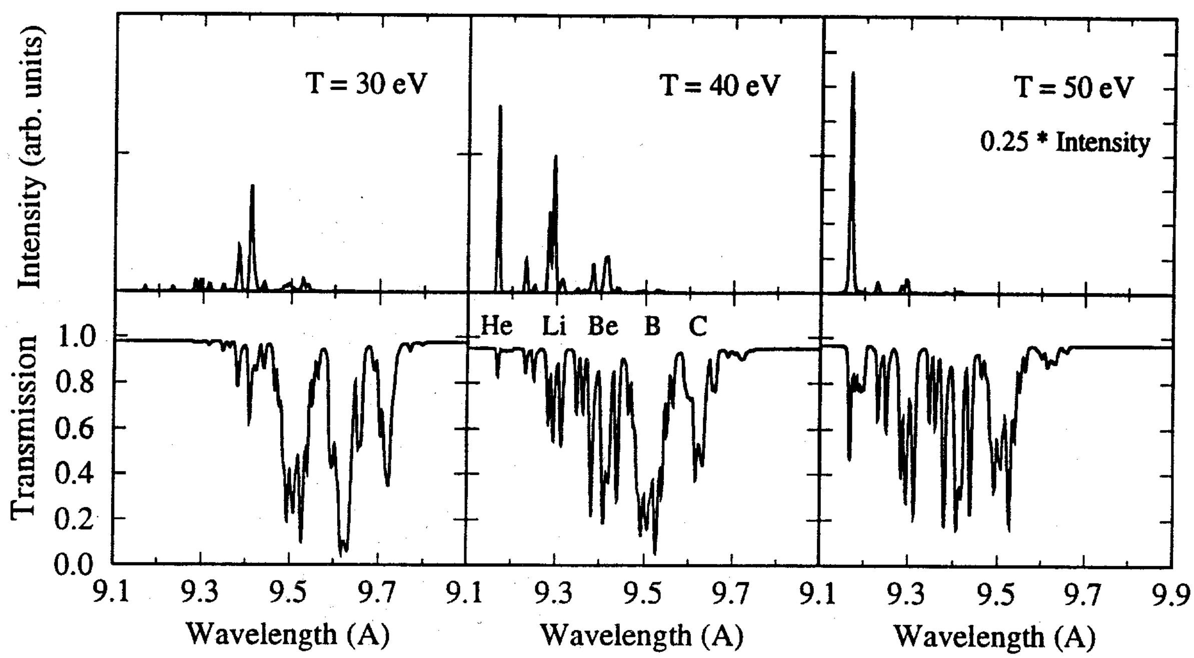

Fig. 1. Calculated Mg K_α emission (top) and absorption (bottom) spectra at $T = 30, 40$, and 50 eV. In each case, $n = 10^{-3}\, n_{\rm solid}$ and $L = 200\,\mu$m. The satellite ionization stages are shown with the $T = 40$ eV absorption spectrum. Note the larger scale in the $T = 50$ eV emission plot due to the strong He_α line at 9.168 Å.

Figure 2 shows the K_α emission spectrum calculated for Al at $T = 40$ eV, along with the K_β absorption spectrum (involving $1s \rightarrow 3p$ transitions) for Mg at $T = 50$ eV. Here, we examine whether K_α emission from one of the tracers can be absorbed by the other. Note that in several instances the K_β lines of Mg are capable of absorbing K_α line emission from Al. In particular the Mg He_β line at $\lambda = 7.850$ Å lies directly between the two strongest Li-like Al K_α emission features. Also it is seen that Li-like Mg K_β satellites between 8.0 and 8.1 Å can absorb line radiation from the B-like Al K_α satellites. The overlap of part of the Al K_α spectrum with the Mg K_β satellites, however, need not necessarily lead to significant problems in analyzing the spectra. This is because the K_α satellite emission from the highest ionization stages (He-, Li-, and perhaps Be-like) will most likely be utilized to determine the peak temperatures obtained in light ion beam experiments, in which case only the Mg He_β line is capable of producing significant absorption.

Our results therefore indicate that K_α satellite emission spectra obtained from two-component Mg/Al tracers should provide enough information to accurately determine target plasma temperatures in the 30 eV to 50 eV range. New data from Mg/Al tracers will be obtained in upcoming PBFA-II Li beam experiments. Similar data will be obtained from NaF tracers in proton beam experiments at the Karlsruhe Light Ion Facility (KALIF) in Germany [12]. We also expect to utilize line intensity ratios from the He-, Li-, and Be-like K_α satellites to determine plasma temperatures

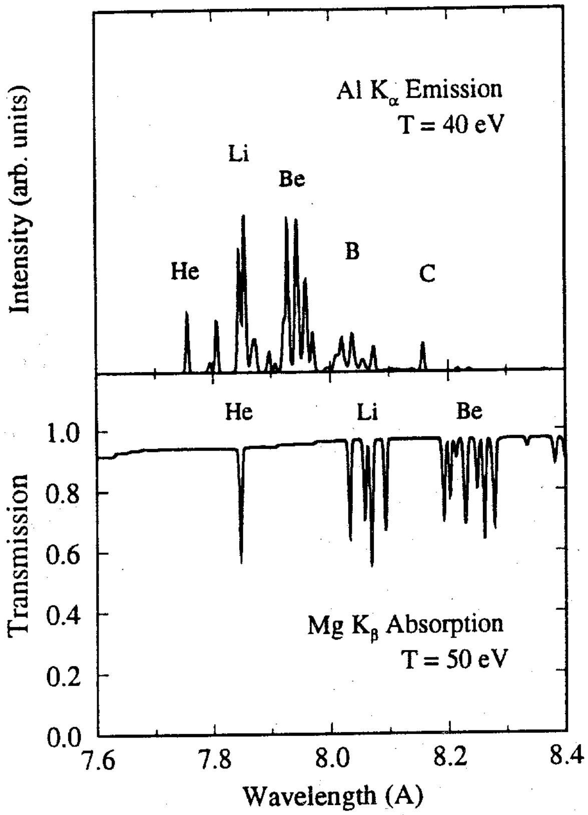

Fig. 2. Calculated Al K_α satellite emission spectrum at $T = 40$ eV and Mg K_β absorption spectrum at $T = 50$ eV. In each case, $n = 10^{-3}\, n_{\text{solid}}$ and $L = 200\,\mu$m. Note that at several wavelengths Al K_α emission lines can potentially be absorbed by Mg K_β lines.

and densities. This work will be described in detail elsewhere [13].

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References

1. Nardi, E. and Zinamon, Z., 1981, *J. Appl. Phys.* **52**, 7075.

2. Bailey, J., et al., 1990, *Lasers and Particle Beams* **8**, 555.

3. Perry, et al., 1991, *Phys. Rev. Lett.* **67**, 3784.

4. Chenais-Popovics, C., Fievet, C., Geindre, J. P., Gauthier, J. C., Luc-Koenig, E., Wyart, J. F., Pepin, H. and Chaker, M., 1989, *Phys. Rev. A* **40**, 3194.

5. MacFarlane, J. J., Wang, P., Bailey, J., Mehlhorn, T. A., Dukart, R. J. and Mancini, R. F., 1993, *Phys. Rev. E* **47**, 2748.

6. Abdallah, J., Clark, R. E. H., and Peek, J. M., 1991, *Phys. Rev. A* **44**, 4072.

7. Foster, et al., 1991, *Phys. Rev. Lett.* **67**, 3255.

8. Bailey, J. E. et al., 1993, presented at the 6th International Workshop on Atomic Physics for Ion Driven Fusion, Santa Fe, NM.

9. Wang, P., MacFarlane, J. J. and Moses, G. A., 1993a, *Phys. Rev. E* **48**, 3934.

10. MacFarlane, J. J., Wang, P., Bailey, J. E., Mehlhorn, T. A., and Dukart, R. J., 1994, *Lasers and Particle Beams*, in press.

11. Wang, P., MacFarlane, J. J., and Moses, G. A., 1994, *Lasers and Particle Beams*, in press.

12. Goel, B., Ludmirsky, A., Baumung, K., Bluhm, H., Buth, L., Höbel, W., Meisel, G., Rusch, G., Stolz, O., MacFarlane, J. J., and Wang, P., 1994, these proceedings.

13. MacFarlane, J. J., Wang, P., Bailey, J. E., Mehlhorn, T. A., and Dukart, R. J., 1994, in preparation.