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K-α emission spectroscopic analysis from a Cu Z-pinch

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ABSTRACT

Advances in diagnostic techniques at the Sandia Z-facility have facilitated the production of very detailed spectral data. In particular, data from the copper nested wire-array shot Z1975 provides a wealth of information about the implosion dynamics and ionization history of the pinch. Besides the dominant valence K- and L-shell lines in Z1975 spectra, *K*-α lines from various ionization stages were also observed. K-shell vacancies can be created from inner-shell excitation and ionization by hot electrons and from photo-ionization by high-energy photons; these vacancies are subsequently filled by Auger decay or resonance fluorescence. The latter process produces the *K*-α emission. For plasmas in collisional equilibrium, *K*-α emission usually occurs from highly charged ions due to the high electron temperatures required for appreciable excitation of the *K*-α transitions. Our simulation of Z1975 was carried out with the NRL 1-D DZAPP non-LTE radiation-hydrodynamics model, and the resulting K- and L-shell synthetic spectra are compared with measured radiation data. Our investigation will focus on *K*-α generation by both impacting electrons and photons. Synthetic *K*-α spectra will be generated either by self-consistently calculating the K-shell vacancy production in a full Z-pinch simulation, or by post-processing data from a simulation. The analysis of these *K*-α lines as well as K- and L-shell emission from valence electrons should provide quantitative information about the dynamics of the pinch plasma.

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1. Introduction

Recently, there have been significant improvements in diagnostic techniques on the refurbished Z facility at Sandia National Laboratories (SNL) for multi-material wire-array and gas-puff configurations. Spatially and temporally resolved spectra can now be obtained, and improved signal-to-noise ratios permit weaker spectral features to be observed. Temporal resolution allows phenomena such as Doppler splitting and line self-absorption to be seen with more clarity [1,2], and spatial resolution provides information about gradients in the flow and axial non-uniformities. The Z-machine is currently the largest Z-pinch device in the world, capable of driving currents in excess of 20 MA through a load [3]. Because of improvements in wire-array technology [4], the resulting implosions tend to be reproducible and axially uniform. The use of nested arrays has made it possible to achieve total X-ray powers exceeding 200 TW [5]. Z-pinch simulation models have also improved, due both to substantial advances in the understanding of the underlying physics [6,7], and to the development of more detailed and accurate atomic databases. Until recently, only the K-shell portion of the spectra was of interest. Now, with better diagnostic and modeling capabilities [8] L- and M-shell spectral data will be receiving increased attention. In this paper, we examine data obtained from the copper nested wire-array SNL shot Z1975. This wire-array configuration is simulated with the 1-D DZAPP radiation-hydrodynamics code [6], developed at the Naval Research Laboratory (NRL), and the resulting spectra are compared with the measured radiation data. Because lines of Ni, Fe and Cr were observed in the experimental Z1975 spectra, we performed the calculations with a mixture of these elements: 94.0% Cu, 4.0% Ni, 2.4% Fe and 0.6% Cr. The copper wires employed in the experiment had a nominal 4% Ni component; the Fe and Cr components presumably originated in the stainless-steel cathode. X ray emissions in the time-integrated experimental K-shell spectrum were also accompanied by *K*-α lines of Cu, Ni and Fe. We will investigate the possible sources of these lines, make quantitative predictions of their intensities, and compare these with the experimental data. Cu wire arrays were also previously analyzed on the Z machine showing an abundance of radiation from the K- and L-shell ionization stages providing reliable diagnostics capabilities [9].

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Most X-ray spectroscopic models use intensities of allowed and forbidden lines along with dielectronic satellite lines that provide key diagnostics of plasma parameters of highly ionized plasmas. These models are typically based on the assumptions of thermal electrons and they are thereby described by Maxwellian velocity distributions. However, the existence of energetic electrons in the final phase of pinching plasmas such as Z-pinch, X-pinch, and gas-puff is well known [10]. A small amount of hot electrons that may exist in these plasmas will alter the diagnostics drastically [11]. Thus the plasma parameters such as electron temperature and density inferred from a Z pinch might be inaccurate. In fact the neglect of hot electrons, in most cases, gives rise to overestimation of the electron temperature and density. Validation of theoretical spectroscopic models depends strongly on agreement with experimental data. Predictions of such models using atomic data obtained from an inaccurate determination of plasma parameters can lead to incorrect conclusions. *K-α* emission is associated with 2p→1s inner-shell-electron radiative transitions in highly charged ions [12,13]. In Fig. 1 we show an energy level diagram of the *K-α* lines. These lines have the appearance of satellite lines in the X-ray spectra of laboratory and astrophysical plasmas. In a Z-pinch, *K-α* emissions may arise from inner-shell photoionization and photo-excitation by K-shell emission from the hot plasma near the axis. *K-α* emission can also originate from collisional processes involving hot electrons. In this investigation, we consider the population dynamics of the upper-levels of these *K-α* lines due both to electron collisional processes from electron beams and to photo-ionization from K-shell photons. For precise interpretation of high-resolution X-ray data, which may involve the analysis of blended spectral features of many lines, it is necessary to model accurately all the fine structure levels for the ions emitting those lines in the energy range. We are investigating the *K-α* features from the Z-1975 data in the relevant range of 8.05–8.15 keV for Cu, 7.49–7.52 keV for Ni and 6.415–6.470 keV for Fe. Most of the *K-α* features in these energy ranges are from F-like and Ne-like ionization stages in each of these species.

2. Atomic and radiation model

We employ a full non-LTE (NLTE) collisional radiative equilibrium (CRE) method for ionization balance; a full time-dependent treatment of the atomic populations is also possible with our model. Atomic structure data including energy levels and radiative transition probabilities as well as the collisional excitation and ionization rates and the collisional, radiative and dielectronic recombination rates were self-consistently generated using the Flexible Atomic Code (FAC) suite of codes [14,15]. Non-local photo-pumping that affects the atomic populations is included in the rate equations. The electrons in the plasma are assumed to have a Maxwellian velocity distribution and are the dominant species in populating the levels for the K- and L-shell spectra. Thus the rate coefficients for all the processes are obtained by integrating the cross sections over a Maxwellian electron distribution. A detailed description of the generation of atomic data and model is given in Refs. [16,17].

A simulation of the doubly-nested copper wire-array SNL shot Z1975 was performed with the DZAPP code. The wire arrays had a total mass of 2.57 mg, with a 2:1 outer to inner mass ratio. The initial array radii were 1.625 and 3.25 cm, and the wires were 2.0 cm in length. As was mentioned in the Introduction, lines of Cu, Ni, Fe and Cr were observed in the experimental spectra. Thus, the calculations were performed with an appropriate mixture of these elements: 94.0% Cu, 4.0% Ni, 2.4% Fe and 0.6% Cr. The Ni abundance was chosen because the copper wires employed in the experiment had a nominal 4% Ni component; the Fe and Cr abundances were selected to approximately match the respective He-α intensities of the experimental spectrum. The relative abundances are consistent with the Fe and Cr components coming from the stainless-steel cathode.

The DZAPP radiation hydrodynamics code is a 1D coupled MHD, detailed non-LTE atomic physics, and radiation transport code, incorporating a transmission line circuit model, developed for the simulation of Z-pinch implosions. The code is very nearly a "first-principles" code; the only phenomenological "adjustable" variable is an electron-ion equilibration multiplier. A large fraction of the plasma energy is radiated away in a typical Z-pinch. Thus, it is important to treat the atomic and radiation physics in a coupled, self-consistent manner. Detailed atomic models for Cu, Ni, Fe and Cr are used in the simulation of shot Z-1975: The model for Cu includes 779 atomic levels and 1609 transported emission lines. The models for Ni, Fe and Cr have 778, 776 and 774 levels, respectively, and, since they are minor constituents, 450 lines are transported for each. The radiation transport includes the effects of photoionization and photoexcitation. Radiation couplings from each zone to every other zone are computed for each bound–bound,

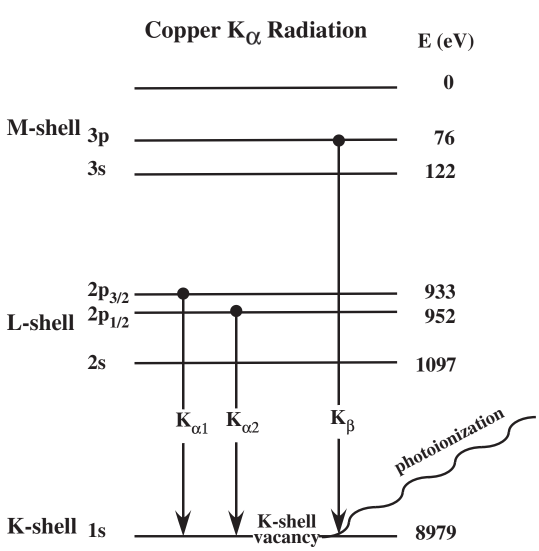

Fig. 1. Energy level diagram of *K-α* lines.

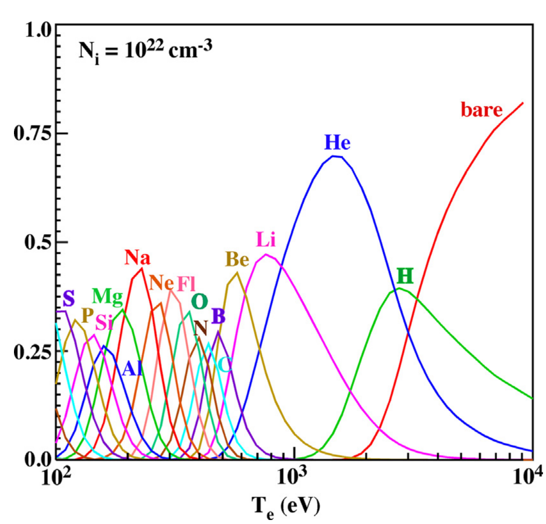

Fig. 2. Copper fractional abundances at ion density of $10^{22}/cm^3$. Fully stripped Cu is denoted as "bare" in the figure.