X-RAY PROCESSES IN HIGH-INTENSITY LASER-MATTER INTERACTIONS

by

Frederick P. Adams

B. Sc. (Physics), University of Manitoba, 1984

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in The Faculty of Graduate Studies Physics

We accept this thesis as conforming to the required standard

UNIVERSITY OF BRITISH COLUMBIA
September 1986

© Frederick P. Adams, 1986
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Physics

The University of British Columbia
1956 Main Mall
Vancouver, Canada
V6T 1Y3

Date Sept. 19 1986
ABSTRACT

In laser-matter-interaction studies there is a continued interest in the emission and transport of x-rays in laser-irradiated solids. We have irradiated metal foil targets with 0.532 µm laser light with pulse lengths of 2.4 to 2.6 ns at absorbed irradiances of 10^{12} to 10^{13} W/cm^2. Calorimetric measurements of the energy of x-ray emission by the laser-produced plasma on the target frontside indicate that copper is a better emitter than aluminum or molybdenum in an x-ray band \geq 800 eV.

Measurements comparing x-ray transmission through irradiated foil targets with that through identical, unperturbed filters indicate enhanced transmission of x-ray energy through the targets. Temporally-resolved measurements on aluminum targets show that x-ray transmission through the target is strongly time-dependent, with x-ray power transmission through the targets, with the greatest contribution being that resulting from 2D rarefaction of the target after shock breakout. This corroborates earlier observations of delayed x-ray heating of the target rear surface.

Enhanced transmission of x-rays through the targets at the moment of shock breakout was also observed, consistent with a shift of the K-shell x-ray absorption edge in the shocked aluminum plasma allowing increased transmission of the aluminum He\alpha and IC x-ray lines. Other models which may yield similar enhanced x-ray transmission are investigated and rejected on the basis of experimental measurements on layered targets composed of an aluminum substrate and a copper layer as an x-ray source. Similar enhanced x-ray transmission has also been observed in laser-irradiated magnesium targets. The results provide the first experimental evidence of substantial increase in x-ray transport due to a shift of the K-shell photoabsorption edge induced by shock-compression of a dense plasma.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ix</td>
</tr>
<tr>
<td>CHAPTER 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 X-Rays in Inertial Confinement Fusion Research</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Objectives of Present Work</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Thesis Outline</td>
<td>4</td>
</tr>
<tr>
<td>CHAPTER 2 Theoretical Background</td>
<td>5</td>
</tr>
<tr>
<td>2.1 X-Ray Emission</td>
<td>5</td>
</tr>
<tr>
<td>2.1.1 Bremsstrahlung Emission</td>
<td>5</td>
</tr>
<tr>
<td>2.1.2 Recombination Radiation</td>
<td>9</td>
</tr>
<tr>
<td>2.1.3 Line Radiation</td>
<td>12</td>
</tr>
<tr>
<td>2.2 X-Ray Absorption in Normal Solids</td>
<td>16</td>
</tr>
<tr>
<td>2.2.1 Absorption and Scattering Processes</td>
<td>16</td>
</tr>
<tr>
<td>2.2.2 X-Ray Absorption by Photoionization</td>
<td>17</td>
</tr>
<tr>
<td>2.3 X-Ray Absorption in Shocked Targets</td>
<td>18</td>
</tr>
<tr>
<td>2.3.1 Shifting of the K-Edge—General Consideration</td>
<td>23</td>
</tr>
<tr>
<td>2.3.2 K-Edge Shift—Electron Degeneracy</td>
<td>25</td>
</tr>
<tr>
<td>2.3.3 K-Edge Shift—Electron-Electron and Electron-Ion Interactions</td>
<td>27</td>
</tr>
<tr>
<td>2.3.4 K-Edge Shift—Continuum Lowering</td>
<td>30</td>
</tr>
<tr>
<td>2.3.5 K-Edge Shift—Conclusion of Theory</td>
<td>33</td>
</tr>
<tr>
<td>CHAPTER 3 Experimental Facilities</td>
<td>37</td>
</tr>
<tr>
<td>3.1 Laser and Target Chamber</td>
<td>37</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.2 X-Ray Calorimeters</td>
<td>41</td>
</tr>
<tr>
<td>3.3 PIN Diodes</td>
<td>45</td>
</tr>
<tr>
<td>3.4 Biplanar Vacuum X-Ray Diodes</td>
<td>46</td>
</tr>
<tr>
<td>3.4.1 General Considerations</td>
<td>47</td>
</tr>
<tr>
<td>3.4.2 Temporal Response</td>
<td>50</td>
</tr>
<tr>
<td>3.4.3 Spectral Response</td>
<td>54</td>
</tr>
<tr>
<td>3.5 Shock Diagnostics</td>
<td>58</td>
</tr>
<tr>
<td>3.5.1 Rear Surface Luminous Emission</td>
<td>59</td>
</tr>
<tr>
<td>3.5.2 Rear Surface Reflectivity</td>
<td>62</td>
</tr>
<tr>
<td>CHAPTER 4 Experimental Results</td>
<td>65</td>
</tr>
<tr>
<td>4.1 X-Ray Emission Measurements</td>
<td>65</td>
</tr>
<tr>
<td>4.2 X-Ray Transmission Measurements</td>
<td>67</td>
</tr>
<tr>
<td>4.2.1 Time-Integrated PIN Diode Measurements</td>
<td>67</td>
</tr>
<tr>
<td>4.2.2 Time-Resolved XRD Measurements</td>
<td>70</td>
</tr>
<tr>
<td>4.2.3 Magnesium Experiments</td>
<td>80</td>
</tr>
<tr>
<td>4.2.4 Copper-Coated Aluminum Experiments</td>
<td>82</td>
</tr>
<tr>
<td>CHAPTER 5 Interpretation of Results</td>
<td>88</td>
</tr>
<tr>
<td>5.1 X-Ray Production</td>
<td>88</td>
</tr>
<tr>
<td>5.2 X-Ray Transmission Following Shock Breakout</td>
<td>90</td>
</tr>
<tr>
<td>5.3 X-Ray Transmission Through the Shocked Targets</td>
<td>94</td>
</tr>
<tr>
<td>5.3.1 Ablation and Hydrodynamic Effects</td>
<td>97</td>
</tr>
<tr>
<td>5.3.2 L-Shell and K-Shell Opacity Lowering</td>
<td>99</td>
</tr>
<tr>
<td>5.3.3 K-Edge Shift</td>
<td>100</td>
</tr>
<tr>
<td>5.3.4 Effect of Finite Temporal Response of the XRD</td>
<td>103</td>
</tr>
<tr>
<td>5.3.5 Copper-Aluminum Layered Target Experiment</td>
<td>105</td>
</tr>
<tr>
<td>CHAPTER 6 Discussions and Conclusions</td>
<td>109</td>
</tr>
<tr>
<td>6.1 X-Ray Emission Studies</td>
<td>109</td>
</tr>
<tr>
<td>6.2 X-Ray Transmission Studies</td>
<td>109</td>
</tr>
</tbody>
</table>
6.3 Future Research ......................................................... 110
APPENDIX A X-Ray Transmission and Detection Calculations .......... 117
APPENDIX B Detector Response-Time Effect Calculations ............. 122
LIST OF FIGURES

1-1 Laser-Driven Implosion of a Fusion Pellet. ............................................. 2
2-1 Density and Temperature Profiles in a Laser-Irradiated Target. .................. 9
2-2 Level Diagram for Highly Ionized Aluminum. ......................................... 12
2-3 Calculated X-Ray Continuum (Duston et. al1). ........................................ 13
2-4 Level Diagram for K-Shell Processes at Low Ionization. ............................ 15
2-5 Al X-Ray Mass Absorption Coefficients. ................................................. 18
2-6 x - t Plot of Laser-Induced Flow. ......................................................... 18
2-7 K-Edge Shift Due To Ionization. ............................................................. 21
2-8 Predicted Ionization of Shocked Aluminum. ............................................. 35
3-1 Laser and Target Chamber Layout. ......................................................... 37
3-2 Temporal Profile of Laser Pulse. ............................................................ 39
3-3 X-Ray Calorimeters. ................................................................................. 42
3-4 X-Ray Calorimeter Calibration. ................................................................. 43
3-5 Typical Calorimeter Signal. ..................................................................... 45
3-6 Biplanar X-Ray Vacuum Photodiode. ....................................................... 47
3-7 Gold Photoelectric Efficiency. ................................................................. 48
3-8 XRD FWHM Response Times. ................................................................. 52
3-9 XRD x-ray signals. ................................................................................. 54
3-10 B-10 Foil Transmission Curve. ............................................................... 54
3-11 Filtered Detectro Response Curve. .......................................................... 56
3-12 Spectral Content of X-Ray Signals Observed by a Filtered XRD. ............... 57
3-13 Attenuation in X-Ray Signal by Aluminum Filters. .................................. 57
3-14 Shock Diagnostics Layout. ....................................................................... 60
3-15 Streak Record of Rear Surface Emission at Shock Breakout. ..................... 61
List of Figures

3-16 Streak Record of Rear Surface Reflectivity at Shock Breakout. .......... 63
4-1 X-Ray Emission from Laser-Irradiated Targets of Different Z. ............. 65
4-2 Measured Back-side PIN Signal. ........................................ 69
4-3 Measured Front-side PIN Signal. ....................................... 69
4-4 Shock Trajectory. .......................................................... 71
4-5 XRD Signals — (a) Front, (b) Back. .................................... 74
4-6 Time-Integrated XRD Signals. ........................................... 75
4-7 Full-Irradiance XRD Signals. ............................................ 78
4-8 Reduced-Irradiance XRD Signals. ....................................... 78
4-9 Back/Front X-Ray Signal Ratio for Aluminum Targets. .................... 80
4-10 Frontside X-Ray Signal for a Copper-Coated Aluminum Target. ......... 84
4-11 X-Ray Signals for Copper-Coated Aluminum Targets. ...................... 85
4-12 Back/Front X-Ray Signal Ratio for Copper-Coated Aluminum Targets. ... 85
5-1 XRD Measurements for a 25 μm aluminum target. ........................ 94
5-2 XRD measurements for a 34 μm aluminum target. ........................ 94
ACKNOWLEDGEMENTS

I would like to thank Hubert for his appropriate advice in regards to my many and various technical difficulties, as well as for his voluntary lending of such vital pieces of research equipment as the nitrogen laser with which the temporal response of the x-ray vacuum photodiodes was determined. I would also like to thank Peter, Dean, Luiz, Dr. Ng, and Dr. Gazitt for their cooperation and assistance in the all-important matter of actually carrying out the experimental measurements, and to doubly thank Dean and Peter for their aid in dealing with the computer system. I would finally like to thank Al and everyone in the machine shop for their advice in the design of and their excellent work in the final construction of the several electrical and mechanical items which I needed to have built for my own work.
1.1 X-Rays in Inertial Confinement Fusion Research

With the advent of high-power lasers, there has been considerable interest in their use to produce fusion reactions for power generation. The principal approach has been the implosion of a small pellet of deuterium-tritium (D-T) fuel mixture to conditions of high density, \((\geq 20 \text{ g/cm}^3)\) and high temperature, \((\sim 10 \text{ keV})\). The thermal energy is required to overcome the Coulomb potential barrier between the nuclei and allow fusion. The high density is needed to yield a large number of collisions between the deuterium and tritium nuclei within the fuel. These collisions then lead to a large number of fusion reactions between the nuclei. For "break-even" energy yield at a temperature of \(\sim 10 \text{ keV}\), the required conditions are usually expressed as the Lawson criterion, \(n \tau > 10^{14} \text{cm}^{-3}\), where \(n\) is the plasma density and \(\tau\) is the time for which inertia holds the imploded pellet together. The derivation of this criterion assumes a practical generation system with an overall thermal cycle efficiency of 33%.

In the present inertial confinement fusion schemes, high-intensity short-wavelength lasers ablate the surface of a pellet, and the recoil momentum due to the ablation of the material produces high pressures. These pressures drive the surface
Chapter 1: Introduction

2

• Figure 1-1 Laser-Driven Implosion of a Fusion Pellet. The laser light ablates the pellet shell. The recoil momentum of the expanding plasma drives a pressure wave inwards, compressing the D-T fuel to the point of thermonuclear reaction.

of the pellet inwards, producing a shell of dense material moving towards the centre of the pellet. This process is illustrated in Figure 1-1.

The spherical symmetry of the convergence of this shell increases the pressures and densities further inward. The centre of the pellet reaches the greatest extremes of density and temperature, igniting the thermonuclear burn, the fusion of the deuterium and tritium nuclei. The products of the reaction at the centre of the pellet are neutrons and alpha particles. The pellet density-radius product must be great enough to trap the alpha particles, \( \rho R \approx 1 \sim 3 \text{ g/cm}^2 \), so that their kinetic energy will spread the nuclear burn throughout the pellet and the bulk of the D-T
fuel will be consumed. Although the outer layers of the fuel mixture are at densities which are not sufficient to ignite thermonuclear burn, they can thus sustain the burn which begins at the pellet's centre. This is known as inertial confinement fusion (or ICF), because during the nuclear burn phase the pellet is held together by its own inertia, while the energy released causes the pellet to rapidly decompress.

Current ICF experiments have yielded measurable thermonuclear burn, but the densities reached have not produced $\rho R$ products sufficient for consumption of a significant fraction of the D-T fuel. The required $\rho R$ can be achieved using achievable (megajoule) laser systems by minimizing any premature heating (or preheat) of the fuel. Such heating raises the pressure required to yield a given compression and is therefore detrimental to the fusion process. X-rays can readily transport thermal energy into a fusion target, heating the fuel without compressing it. Thus, there is a strong interest in understanding the deposition of energy within fusion targets by x-rays emitted by the laser-produced plasma on the fusion target surface. X-ray preheat will create difficulty in producing thermonuclear burn in fusion targets, if it affects the core of the pellet. As well, the loss of absorbed laser energy in the form of x-rays radiated by the target surface will reduce the effective absorption of laser energy by the target.

1.2 Objectives of Present Work

We have been operating a sub-micron laser facility for research on laser-target interactions, including topics of interest to inertial confinement fusion research. The material in this thesis covers some of the recent work which we have done on the role of x-rays in laser-matter interactions. These studies include quantitative measurements of x-rays radiated by laser-produced plasmas. The x-rays emitted by these plasmas may also find applications in x-ray microscopy, in which the short
wavelength ($\sim 20 \text{ Å}$) of these x-rays may allow high-resolution microanalysis of biological specimens.

More importantly, an examination of the theory of x-ray absorption in shock-compressed aluminum indicates the possibility of enhanced transmission through laser-irradiated targets. Small shifts in the energy at which K-shell photo-ionization becomes an important absorption mechanism may allow strong aluminum x-ray emission lines to penetrate the target material. Using 0.532 $\mu$m laser light to irradiate aluminum foils, we perform an experimental study of the enhancement of x-ray transmission through aluminum foil targets by a time-dependent comparison of x-ray signals observed through the irradiated targets with x-ray signals observed through identical foils in front of the targets. The transmission of x-rays through the disassembling targets after the breakout of the shock wave at the rear of the foil is a closely related topic. The study also focusses on the effects of the hydrodynamic flow of the target material at times during and after laser irradiation of the target. These are necessary for a clear interpretation of the observed enhanced x-ray transmission.

1.3 Thesis Outline

In Chapter 2 a general overview of the relevant theory is presented. Chapter 3 describes details of the equipment used. Results of the experiments performed are presented in Chapter 4. In Chapter 5 we give interpretation of the results through simulations and calculations based on concepts presented in Chapter 2. Finally, in Chapter 6 overall conclusions to our studies are summarized. Suggestions are given as to further work to be done in examining the theoretical models and their possible extrapolations.
2.1 X-Ray Emission

The plasma produced by laser irradiation on the front of a target emits x-rays over a broad range of photon energies. For our purposes, we may ignore x-rays with photon energies less than 200 eV. Such soft x-rays cannot penetrate the thin entrance windows used to prevent laser light or target debris from reaching the detectors. These x-rays may play an important role in the transport of energy in the frontside ablation region, where thermal gradients exist. Here, the mean free path of the soft photons is of the order of the thermal gradient scale lengths—one micron or less. The harder x-rays are the ones that interest us here. These x-rays may carry energy deep into the target foil, ahead of any thermodynamic processes such as shock heating.

2.1.1 Bremsstrahlung Emission

An important process generating soft x-rays in a hot plasma is bremsstrahlung radiation, also known as free-free radiation\(^1\). The acceleration of charged particles produces electromagnetic radiation. The free electrons and ions in a plasma collide with one another due to random thermal motions. The particles in these collisions
interact electrostatically, and the resultant force accelerates the colliding particles. This electrostatic acceleration of charged particles leads to radiation of photons whose energy is equal to the energy lost by the particles in the collision. This is known as free-free radiation because although the electrons lose energy, they are free particles both before and after the collision.

A complete classical derivation of the bremsstrahlung emission spectrum for the case of a plasma of ionization state $Z$ at a temperature $T$ can be found in reference 2. Briefly, the collision between an ion and an electron of speed $v_e$ (with respect to the ion) is described by the impact parameter $b$, the closest separation between the electron and the ion if they were to continue in straight lines along their initial paths. For collisions involving small-angle deflections of the electrons, the radiated power $W$ from a single collision is

$$W(b, v_e, \omega) = \begin{cases} \frac{8Z^2e^6}{3\pi c^2m_e^2v_e^2b^2}, & \text{for } b \ll v_e/\omega, \\ 0, & \text{for } b \gg v_e/\omega, \end{cases}$$  

(2.1)

where $Z$ is the ionization state of the ions, $e$ the electron charge, $c$ the speed of light, $v_e$ the electron speed, and $m_e$ the electron mass. We define the expression

$$\frac{\partial \sigma_{ff}}{\partial (\hbar \omega)}(v_e, \hbar \omega)$$

to be the differential cross-section for production of photons of energy $\hbar \omega$ by electrons of speed $v_e$, per unit electron speed and per unit photon energy. This is derived by integrating the right-hand side of equation 2.1 over all possible values of $b$. For optically thin plasma, the emitted power $P_{ff}$ per unit photon energy per unit plasma volume can then be expressed as

$$P_{ff}(\hbar \omega) = \hbar \omega n_e n_i \int_0^{+\infty} \frac{\partial \sigma_{ff}}{\partial (\hbar \omega)}(v_e, \hbar \omega)v_e f(v_e) \, dv_e,$$  

(2.2)
where $\hbar \omega$ is the photon energy, $n_e$ the electron density, and $n_i$ the ion density. A text-book version of the analytical formula is provided here:

$$P_{ff}(\hbar \omega) = 1.6 \times 10^{-30} Z^2 n_e n_i T^{-1/2} e^{-\hbar \omega / k_B T} \bar{g}_{ff},$$  \hspace{1cm} (2.3)$$

in units of Watts cm$^{-3}$ keV$^{-1}$. Here, $T$ is the plasma temperature in degrees Kelvin, $n_e$ is the free electron density in cm$^{-3}$, $n_i$ is the ion density in cm$^{-3}$, $Z$ is the average ionization of the plasma, $k_B$ is Boltzmann's constant in keV/$^\circ$K, and $\hbar \omega$ is the photon energy in keV. The Gaunt factor $\bar{g}_{ff}$ is generally the ratio between the results of a complete quantum-mechanical analysis and the results of an approximate classical analysis, such as that in reference 2. This factor is not a constant, but is a slowly-varying function of $\hbar \omega$ and $k_B T$ which is approximately equal to one. The discrepancy arises from quantum-mechanical effects involved in the electron-ion interaction and in the production of photons whose energy is of the order of the initial electron energy. Setting $\bar{g}_{ff} = 1$, equation (2.3) will be valid as long as we have $\hbar \omega \approx k_B T$ and $\hbar \omega \approx 13.6 Z^2$ eV to within a few orders of magnitude. In cases of a mixture of ionization states or of a mixture of atomic species, the radiation effects due to each ionic specie are calculated separately and the effects are added directly. This is possible due to the fact that the factor $n_i$ occurs only as a proportionality constant in the above expressions.

The temperature, mass density, and average ionization are not constant within a laser-produced plasma, but vary as shown in Figure 2-1. This is a result of the deposition of laser energy at the critical density surface, at which point the electron plasma frequency is equal to the frequency of the incident laser light. From this point thermal conduction carries energy inward up to the ablation surface, where the target material is transformed into an expanding plasma which moves outwards into regions of higher temperature and consequently greater ionization. Thus the emission given by an analytic formula based on $n_e$, $Z$ and $T$ must be
found for each point in the plasma and the emission from these regions must be added together. The scalings of bremsstrahlung emission with ionization, density and temperature mean that the most important region for the consideration of bremsstrahlung emission at high photon energies will be the critical density surface.

In Figure 2-1 the temperature, ionization and free electron density are indicated by $T_c$, $Z_c$ and $n_c$ respectively at the critical density surface. For a laser-produced aluminum plasma characteristic of our experimental condition, we might have $T_c \approx 400 \text{ eV}$, $Z_c \approx 11$ and $n_c = 3.9 \times 10^{21} \text{ cm}^{-3}$.

- Figure 2-1 Density and Temperature Profiles in a Laser-Irradiated Target. This is a schematic of the steady-state profile of the laser-matter interaction region of the foil.
2.1.2 Recombination Radiation

Given the coexistence of ions and electrons in the plasma, an ion of ionization state \( Z \) can interact with the surrounding plasma to produce ions of lower or higher ionization states \( Z - 1 \) or \( Z + 1 \). In the production of lower ionization states, the interaction releases an energy \( \chi_R \), the recombination energy for the original ion state \( Z \). If an initially free electron of mass \( m_e \) has a speed of \( v_e \) with respect to such an ion, the pair have a kinetic energy \( \frac{1}{2} m_e v_e^2 \) and the total energy \( \chi_R + \frac{1}{2} m_e v_e^2 \) can be imparted to a photon of energy \( \hbar \omega \), in a process known as radiative recombination. Recombination radiation is also known as free-bound radiation because a free electron enters a bound state in the recombinative process. This process is similar to the bremsstrahlung process, but produces photons with \( \hbar \omega \) no less than \( \chi_R \):

\[
P_{fb}(\hbar \omega) = \begin{cases} 
\hbar \omega n_e n_i \int_0^{+\infty} \frac{\partial \sigma_{fb}}{\partial (\hbar \omega)}(v_e, \hbar \omega)v_e f(v_e) \, dv_e & \text{if } \hbar \omega \geq \chi_R, \\
0 & \text{otherwise};
\end{cases} 
\]

or

\[
P_{fb}(\hbar \omega) = \begin{cases} 
1.6 \times 10^{-30} Z^2 n_e n_i T^{-1/2} e^{-\hbar \omega / k_B T} \bar{g}_{fb} \left( \frac{\xi}{n_0^3} \frac{\chi_R}{k_B T} e^{\chi_R / k_B T} \right) & \text{if } \hbar \omega \geq \chi_R, \\
0 & \text{otherwise},
\end{cases} 
\]

in units of Watts cm\(^{-3}\) keV\(^{-1}\), where \( Z \) is the plasma ionization, \( n_e \) the free electron density in cm\(^{-3}\), \( n_i \) the ion density in cm\(^{-3}\), \( T \) the plasma temperature in °K, and the Gaunt factor \( \bar{g}_{fb} \) is a function approximately equal to one, in much the same manner as \( \bar{g}_{ff} \). The factor \( \xi / n_0^3 \) is the number of quantum states available to the electron in the valence shell of the atom divided by the cube of the principle quantum number of this valence shell\(^8\). If we set \( \bar{g}_{fb} = 1 \), equation (2.4) will be valid for \( \hbar \omega \approx k_B T \) and \( \hbar \omega \approx 13.6 Z^2 \) eV to within a few orders of magnitude.
For both the bremsstrahlung and recombination emission, there is a fall-off for energies above the average electron energy in the plasma. For a laser-produced plasma with a temperature of approximately 400 eV, this means that bremsstrahlung emission in the neighbourhood of 400 eV will decrease by a factor of $e$ with every 400 eV increase in photon energy, somewhat more quickly than a blackbody emission spectrum which follows Wein's law at high photon energies and includes a factor of $\omega^3$. This region is the high-energy emission tail, and the ions in the plasma produce recombination photons with $h\omega \geq k_B T$ at a much greater rate than they produce bremsstrahlung photons in this energy range.

Consider now the particular case of an aluminum laser-produced plasma at a temperature of $T_e = 400$ eV and a density $n_e = 3.9 \times 10^{21}$ cm$^{-3}$, as in Figure 2-1. Figure 2-2 shows important radiative and nonradiative processes for highly-ionized aluminum atomic states. Collisional ionization and three-body recombination—where the recombination energy $\chi_R + \frac{1}{2}m_e v_e^2$ is imparted to a free electron—are indicated by the double-headed arrows in Figure 2-2. As a result of these collisional processes the dominant ionization species are the ones for which $\chi_R \approx k_B T$, assuming local thermodynamic equilibrium$^4$. The recombination potential for helium-like aluminum ions Al XII is of the order of the average electron energy in the plasma $\sim 400$ eV, and the recombination energy for hydrogen-like ions Al XIII is $\chi_R \approx 2000$ eV. Thus, the average free electron which will be in collision with an ion will have sufficient energy to remove an electron from a lithium-like ion, but will have insufficient energy to remove an electron from a helium-like ion. Lithium-like ions, produced by recombination of the helium-like states, will also be present in the plasma. So will hydrogen-like ions, produced by occasional collisional ionizations of the helium-like ions. Nonetheless, the most common ionization state for aluminum will be helium-like. This has also been demonstrated from results of detailed calculations$^4$ and in experiment$^5$. 
From photon energies of ~ 400 eV to ~ 2000 eV the emission spectrum will be dominated by radiation from the recombination of Al XII ions to Al XI ions, as indicated by the vertical arrow labelled RC in the Al XI level diagram of Figure 2-2. For photon energies above ~ 2000 eV, the emission spectrum will be dominated by radiation from the recombination of Al XIII ions to Al XII ions and Al XIV ions to Al XIII ions, as indicated by the vertical arrows labelled RC in the Al XII and Al XIII level diagrams of Figure 2-2.

- Figure 2-2 Level Diagram for Highly Ionized Aluminum. The double arrows are non-radiative processes, and the labelled vertical arrows are radiative processes. The vertical distances between atomic states correspond to the energy differences between the states.
2.1.3 Line Radiation

Plasmas also emit x-rays due to atomic transitions having energies in the range of the electron thermal energy. The free electrons may collisionally excite the ions into higher energy states, from which they may decay either radiationally or by Auger processes. Radiative transitions between two different bound states for a particular electron produce bound-bound or line radiation. On the other hand, in the Auger process, electrons are emitted which carry the excitational energy. States which are capable of decay by means of Auger processes are known as auto-ionizing states, and the probability of such a state decaying radiatively is its fluorescence yield.

The line radiation which interests us is again that occurring at higher energies, above the thermal electron energy. In order to be energetically significant, these lines must be from the decay of non-auto-ionizing excited levels of highly populated ionization states. Thus, energetically significant lines will be those from ionization states such as the helium-like, hydrogen-like and lithium-like states discussed in the previous section, at line photon energies below the minimum ionization potentials of such states.

Consider again the case of an aluminum laser-produced plasma at a temperature of \( T_c = 400 \text{ eV} \) and a density of \( n_c = 3.9 \times 10^{21} \text{ cm}^{-3} \), as in Figure 2-1. The strongest lines in the aluminum spectrum, then, should be the helium-like lines of energy \( h\omega < 2000 \text{ eV} \). The hydrogen-like lines may be significant at energies \( h\omega < 2300 \text{ eV} \), depending on the population of this state by collisional ionization of the helium-like ions. The lithium-like lines will also be present, but those with high energies will be from auto-ionizing states. The average fluorescence yield\(^{1,8}\) for hot aluminum is 6%, and all K-shell excitations are auto-ionizing for lithium-like or lower ionization states so that the intensities of the lithium-like K-shell lines will be much less than those of the helium-like K-shell lines.
The calculation of the line intensities is a complicated task, requiring quantum-mechanical calculations to be made on the various configurations of excited states involved. We will not go into the matter at all here, but will instead make use of the results of complete calculations performed by Duston et. al\textsuperscript{1}.

![Calculated X-Ray Continuum (Duston et. al\textsuperscript{1}).](image)

*Figure 2-3 Calculated X-Ray Continuum (Duston et. al\textsuperscript{1})*. This is the time-integrated result of x-ray emission in the irradiation of an aluminum foil by a 3-nanosecond, 1.064 $\mu$m, $10^{13}$ Watt cm$^{-2}$ laser pulse.

Let us then turn our attention to the results of their calculations, the continuum portion of which is shown in Figure 2-3. The features of the free-bound continuum spectrum are visible here. The free-free continuum radiation is dominated by this recombination radiation down to $\sim 50$ eV. Above 100 eV the
bremsstrahlung component is clearly negligible by comparison, as shown in Figure 2-3. The emission below 400 eV is due primarily to free-bound radiation from the colder plasma behind the absorption layer. The peak at this point is due to recombination from helium-like to lithium-like states. At just over 2 keV there is a double peak; the first of these features is due to the recombination from hydrogen-like to helium-like aluminum, and the second is due to the recombination from bare nuclei to hydrogen-like ions. Thus, there is a significant high-energy recombination component which is at least an order of magnitude stronger than the thermal bremsstrahlung component.

Not shown on this plot are the lines emitted by the aluminum plasma. Below the aluminum K-absorption edge are the Kα lines, whose source is photo-excitation of the cold aluminum of the target as indicated in Figure 2-4. High-energy recombination photons or line photons emitted by the laser-produced plasma at target front-side may photoionize low-ionization atoms in the target material behind the laser focus. In Figure 2-4, this process is illustrated by the dashed arrows which connect the initial, ground state of the absorbing atom and the final, ionized and excited state of the atom. Note that K-shell photoionization of atoms of initial ionization \( Z \leq 10 \) yields ions in an auto-ionizing excited state. Radiative decay of these excited states yields Kα x-rays. The Kα x-ray emissions are indicated by the solid vertical arrows in Figure 2-4, and their experimentally determined transition energies\(^{21}\) are also given in the figure. The total power radiated into Kα lines is only 0.6% of the total radiated x-ray power, but these x-rays are of interest because the aluminum opacity to these lines\(^8\) is only \( \frac{\alpha}{\rho} = 407 \text{ cm}^2/\text{g} \). The opacity for the stronger helium-like and hydrogen-like lines is over ten times this value. The lowest energy helium-like lines are the Heα and intercombination (IC) lines at 1.598 and 1.590 keV, respectively. The lowest energy hydrogen-like line is the Hα line at 1.72 keV, above the Heα and IC lines. The Heα line contains roughly 9% of the radiated x-ray power, the IC line roughly 2%, and the Hα line roughly another
5% of the x-ray power. The total radiated x-ray power is 26.4%, according to the results of reference 1. The other lines which are indicated in Figure 2-2 are not energetically significant in the spectrum of reference 1.

- **Figure 2-4** Level Diagram for K-Shell Processes at Low Ionization. The double arrows are non-radiative processes, the labelled vertical arrows are $K_{\alpha}$ fluorescence, (yield $\sim$4%), and the dashed lines are K-shell photoionization. The numbers are measured $K_{\alpha}$ line energies.

This is the source spectrum which we will use in our further discussion of x-ray processes.
2.2 X-Ray Absorption in Normal Solids

We turn now to the absorption of x-rays by materials. More specifically, we are interested in absorption of energetic x-rays by normal solid materials, at this point.

2.2.1 Absorption and Scattering Processes

For photon energies greater than the ionization potential of the inner-shell electrons of the atoms of the absorbing material, the chief process of x-ray attenuation is photoionization with absorption of the incident photon. If the photons have energies many times greater than the K-shell ionization potential of the atoms, the photoionization process is superceded by Compton scattering in which the photon is scattered rather than absorbed, and in which the bound electrons and free electrons can all be considered effectively free. This process becomes important only at photon energies much greater than 10 keV for atoms of atomic number 4 or more. Thus, in materials containing any element of atomic number 4 (beryllium) or greater, we need only consider those photoionization processes which involve no scattered photon. This includes plastics, aluminum, and heavier metals.

Another form of absorption is the inverse process of bound-bound radiation, in which a photon excites a bound electron into a higher energy level, in resonant absorption. The atom may then radiatively decay, emitting a similar photon. Alternatively, the incident photon may simply be scattered without exciting the atom, producing no excited state in the similar process of resonant scattering. Such resonant processes are of course possible only over a very narrow range of energy within the neighbourhood of an atomic transition energy. For example, in aluminum the He\textsubscript{α} x-rays are absorbed or scattered by ground-state helium-like ions, H\textsubscript{α} x-rays are absorbed or scattered by ground-state hydrogen-like ions, and so forth. Such ionization states do not occur in solid aluminum, and the processes
within the radiating plasma are not considered here. Resonance absorptions which are possible in solid aluminum will affect only energetically insignificant bands of the continuum x-rays.

There is another possible scattering process which involves the scattering of the photons by atomic electrons which remain bound at the same level, and which is therefore non-excitational and non-resonant. When such scattering occurs due to groups of atoms with no long range ordering the process is known as Rayleigh scattering\textsuperscript{50}. When it occurs due to groups of atoms with long range ordering it can yield Bragg reflection\textsuperscript{53}. There is no significant long-range ordering in the polycrystalline structure of our rolled-metal targets. Rayleigh scattering occurs but is insignificant over the energy range which interests us\textsuperscript{8}. Thus, all of the x-ray scattering processes can be neglected in the solid materials which interest us.

2.2.2 X-Ray Absorption by Photoionization

We see that the one x-ray attenuation mechanism which we must consider in some detail is photoionization.

In order to calculate the x-ray absorption cross-section due to photoionization at some photon energy $\hbar \omega$, we must consider the ionization of each electron separately, and add the effects of the various electrons together. This is done quantum mechanically, and such calculations for certain interesting photon energies and initial atomic configurations have been performed using computers. This is a complicated process when it is carried out in the necessary detail. On the other hand, it is a fairly simple matter to measure the absorption of x-ray photons by atoms in undisturbed bulk material. The absorption is measured for photons of various known energies and interpolated smoothly between these energies. This has been done for all elements of interest here and some results for aluminum are presented in Figure 2-5.
The discontinuity in the mass absorption coefficient at an energy of 1.56 keV is the result of K-shell photoionization processes. For photon energies below this K-edge, the absorption involves removal of an electron from the M or L shell of the aluminum atom. Above the K-edge, the absorption may also involve the K-shell electrons. Here, the photoionization cross-section of electrons in the K-shell is much greater than that of electrons in the outer shells. That is, the aluminum opacity to x-rays which can photoionize K-shell electrons (say 1.57 keV) is much greater than the aluminum opacity to similar x-rays which cannot photoionize K-shell electrons (say 1.55 keV). Note from Figure 2-5 that the difference between the K-shell and L-shell absorption cross-sections is indicated by the increase of roughly an order of magnitude across the K-edge.

The appropriate mass absorption coefficients are used for our calculations of the spectral transmission of x-rays through other filter materials.

2.3 X-Ray Absorption in Shocked Targets

There remains yet the matter of the absorption of x-rays by material which has been compressed by the passage of a shock wave, as indicated in Figure 2-6. The shock wave propagates from the ablation surface at the front of the foil to the foil rear side. At the moment that the shock arrives at the foil's rear surface all of the foil material behind the laser focal spot is assumed to be evenly compressed and heated, and the x-ray transmission through this material may be different from that of the unperturbed material. After this time the foil expands into the surrounding vacuum. The illustration in Figure 2-6 depicts motion over a few tens of microns in a period of a few nanoseconds, as in a typical laser experiment. Let us discuss aluminum, as this is the one target material employed in most of our x-ray transmission experiments.
**Figure 2-5** Al X-Ray Mass Absorption Coefficients. The discontinuity at a photon energy of 1.56 keV corresponds to the binding energy of K-shell electrons. Solid aluminum has a density $\rho = 2.7\text{g/cm}^3$.

The x-rays penetrating the foil targets are mostly those which lie just below the K-edge where the absorption coefficient is low and those at high photon energies where the absorption coefficient is again low. Figure 2-3 with Figure 2-5 indicate that such x-ray transmission windows coincide with regions of low x-ray emission, so that there will be a small fraction of the total radiated x-ray power in these windows. On the other hand, more than ten percent of the total radiated x-ray power is in the He$\alpha$ and IC lines just above the absorption K-edge. Accordingly, there are three plausible ways in which the x-ray absorption in the target material...
Could be affected by alteration of the absorption cross-sections of the L-shell and K-shell electrons.

The first effect would be an overall raising or lowering of the absorption cross-section for the K-shell electrons. Shock compression in our targets yields temperatures of $1 \sim 1.5 \text{ eV}$ and pressures of $2.5 \sim 3.5 \text{ Mbar}$. These are not high enough to result in the actual removal of the K-shell electrons from aluminum atoms. Removal of the outer-shell electrons has little or no effect on the x-ray absorption.
cross-sections for the inner-shell electrons, although it does affect the energy at which the K-edge is found.

The second effect is the shifting of the K-edge to higher or lower photon energies. In the event that the K-edge shifts to higher energies, the photons which are immediately above the K-edge in the normal material may no longer have sufficient energy to photoionize the K-shell electrons, so that they can penetrate the compressed target material.

One well-known process giving rise to a shift of the K-edge to higher energies is ionization. Figure 2-7 shows the results of calculations made in reference 7 giving the value of the K-edge energy corresponding to various ionization states of the isolated atoms. The important He\textsubscript{\alpha} and intercombination lines are shown by the thick vertical lines extending upwards from the bottom of the figure. Their positions on the horizontal scale indicate their photon energies, so that these may be compared with the calculated K-edge energies. Note that we have assumed that the opacity below the K-edge is proportional to the number of L-shell electrons in the ions. It may also be noted that the calculations of reference 7, which are used in reference 1, match neither the measured metallic aluminum K-edge energy of 1560 eV nor the measured K\textsubscript{\alpha} x-ray energies\textsuperscript{21} of ~ 1490 eV shown in Figure 2-4.

Evidently, the atoms with lower ionization states present in the target aluminum will continue to absorb the He\textsubscript{\alpha} and IC lines, but should sufficient ionization occur the transmission of these lines will be greatly increased. In the work of Dus-ton et. al, it has been shown that a thermal ionization of three (Al IV) would allow the transmission of the IC and He\textsubscript{\alpha} lines through aluminum with much lower attenuation. In addition to thermal ionization, significant ionization can also be effected by pressure ionization\textsuperscript{22} in the shocked material.

The third effect is the lowering of the L-shell absorption cross-section. Since the x-rays in which we are interested are all well above the L-edge energy of 87 eV,
Figure 2-7 K-Edge Shift Due To Ionization. The curves indicate the shifted edge energies and absorption coefficients considering only edge positions for isolated atoms as given in reference 7. Note the disagreement between the measured metallic value and the calculations.

we only need to consider lowering of the L-shell cross-section for the higher-energy photons. This will occur when L-shell electrons are removed from the atom, which means an ionization of 4 or more for the ground state. When electrons are removed from a shell the cross-section per electron increases, cancelling out a portion of the effect of removal of the electron⁹. Duston et. al have ignored ionizational lowering of the L-shell absorption coefficient. Setting the overall L-shell cross-section at any given energy above the L-edge to be proportional to the number of electrons present in the shell could be a simple, but better, approximation.
We have not considered shock-compression effects on the overall absorption cross-section other than that by K-edge shifts, or by ionization leading to a decrease in the number of atomic electrons available to absorb photons. One might suggest that the overall opacity might be altered by such effects as the screening of atomic electrons by free electrons and ion-ion interactions at high densities. We assume that if the removal of an outer-shell electron has a negligible effect on the photoionization cross-section of inner-shell electrons, then the presence of neighbouring ions and free electrons will also have a negligible effect. These interactions may have an effect on the K-edge position, as removal of the outer electrons does. This will be discussed in the following sections.

2.3.1 Shifting of the K-Edge—General Consideration

We must now turn our attention to the details of the change in the K-edge energy due to compression and heating of the target material. The primary result, as noted above, will be ionization with its inherent K-edge shift to higher energies. Here we wish to discuss other effects that will occur, altering the K-edge shift for a given ionization. We will discuss the minimum energy for the photoionization of isolated atoms, and then consider the change in this energy through the effect of the surrounding plasma on the photoionization process.

For an isolated aluminum atom of a given ionization state, the K-edge energy $E_{K0}$ is simply the total energy of this typical atom following removal of one of its K-shell electrons, $E_{f0}$, plus the minimum energy that this removed electron may have, $E_{e0}$, minus the total energy of the atom in its initial state, $E_{i0}$:

$$E_{K0} = E_{f0} + E_{e0} - E_{i0}. \quad (2.6)$$
This is the minimum energy which the photon must impart to the atom in order to free the K-shell electron. For an isolated atom $E_{i0} = 0$, and both $E_{f0}$ and $E_{i0}$ can be calculated\(^7\), so that $E_{K0}$ may be tabulated for the various ionization states.

Similarly, for an aluminum atom surrounded by some medium—such as a shock-compressed aluminum plasma—we have

$$E_K = E_f + E_e - E_i,$$ (2.7)

where the effect of the medium on the edge energy is through its effect on the individual terms:

$$E_K = E_{f0} + \Delta E_f + E_{e0} + \Delta E_e - E_{i0} - \Delta E_i$$

$$= E_{K0} + \Delta E_f + \Delta E_e - \Delta E_i.$$ (2.8)

Given tabulated values of $E_{K0}$, we only need to find the values of the terms $\Delta E_f$, $\Delta E_i$ and $\Delta E_e$ for the given ionization state and surrounding medium, in order to find $E_K$.

We must now examine the terms according to the contributing physical processes, in order that each of these physical processes may be considered separately. The two terms $\Delta E_f$ and $\Delta E_i$ are similar, in that both are changes in the energies of atoms due to interactions of the atoms with the background plasma. Thus, we will consider the physically relevant terms to be

$$\Delta E_f - \Delta E_i = \Delta E_{el}$$ (2.9)

and

$$\Delta E_e = \Delta E_{ee} + \Delta E_{ei} + \Delta E_{de}.$$ (2.10)
\( \Delta E_{cl} \) is the \textit{continuum lowering} term\textsuperscript{11}, which describes the lowering of the binding energies of the atomic electrons due to the interaction with the free electrons. \( \Delta E_{ee} \) is the \textit{electron-electron interaction} term. The free electrons interact electrostatically with each other, leading to a positive potential energy for the free electrons in the plasma. On the other hand, the free electrons also interact with the ions in the plasma, leading to a negative potential energy. This is the \textit{electron-ion interaction}, and it yields the term \( \Delta E_{ei} \). Since the plasma as a whole is quasi-neutral an electron will see a net positive charge in its vicinity, and the overall potential energy will be negative. Finally, we must consider the fact that electrons are fermions, which means that no two free electrons can occupy the same unbound continuum state in the plasma. As a result, the lower-energy continuum states will be occupied by free electrons, up to roughly the \textit{Fermi energy}\textsuperscript{23}. In order to add any further electrons to the continuum, they must be given sufficient energy to place them in continuum states having energies at least as great as the lowest-energy unoccupied state. This quantum-mechanical process leads to the \textit{degeneracy term} \( \Delta E_{de} \). These terms will be considered in more detail in the following subsections, for aluminum atoms in a dense aluminum plasma.

\subsection{2.3.2 K-Edge Shift—Electron Degeneracy}

A plasma is said to be \textit{degenerate} if the electron thermal energy is less than the Fermi energy for the free electron cloud. In the shock-compressed material, the free electrons have a low average thermal energy, of the order of \( 1 \sim 1.5 \text{ eV} \textsuperscript{26} \). In such a degenerate plasma, quantum mechanical effects begin to alter the energy distribution of the free electrons. Many of the free electron states having kinetic energies below the Fermi energy will be occupied by the existing free electrons. When an electron is added to this degenerate continuum, it is forced to occupy one of the empty higher-energy states, in accordance with the Pauli exclusion principle.
Thus, although the absolute minimum kinetic energy which can be given to a newly freed electron is zero, this is possible only if such a state is unoccupied. The cross-section for photoionization by photons near the K-edge is proportional to the probability of finding the necessary empty free-electron state\(49\). The K-edge is therefore shifted upwards from the minimum energy necessary for ionization of the isolated atoms by an amount approximately equal to the Fermi energy. At very low electron temperatures the probability will be one for free electron energies above the Fermi energy and zero for free electron energies below the Fermi energy. The K-edge is then a sharply-defined point which is shifted upwards by the Fermi energy. At higher temperatures the K-edge becomes a steeply-sloping continuous function of photon energy with a width of the order of the electron thermal energy, according to the Fermi-Dirac distribution of free electron occupation of the continuum states\(^{51}\). The averaged position of the edge will be raised up by an energy equal to the chemical potential \(\mu\) of the free electron continuum in the plasma\(^{51}\). The chemical potential is approximately equal to the Fermi energy for plasma temperatures well below the Fermi energy, and decreases as the temperature increases.

At very high temperatures, of course, the quantum effects become negligible as the electron population becomes dispersed throughout state-space, with occupation probabilities of low-energy states becoming low. Then, the cross-section is always multiplied by a factor only slightly less than 1, and the K-edge is unshifted.

How can we determine the degeneracy term for conditions created by the passage of a strong shock? We use \(\Delta E_{de} \approx E_F(n_e)\), where \(E_F\) is the Fermi energy expressed as a function of the free electron density \(n_e\). This will be valid for the temperatures of our shock-compressed aluminum targets, \(1 \sim 1.5\) eV, which are much lower than the normal aluminum Fermi energy\(^{34}\) of 11.6 eV. Thus, for free electron density \(n_e\) and electron mass \(m_e\), the degeneracy shift in the K-edge energy
is given by 23

\[
\Delta E_{de} \approx E_F(n_e) \\
\approx \frac{\hbar^2(3\pi^2 n_e)^{2/3}}{2m_e},
\]

(2.11)

where \( n_e \) is the free electron density in \( \text{cm}^{-3} \) and \( m_e \) the electron mass.

### 2.3.3 K-Edge Shift—Electron-Electron and Electron-Ion Interactions.

The energy of an electron at rest in a field-free vacuum is conventionally taken to be zero, which results in \( E_{e0} \) being zero. On the other hand, a free electron in a plasma will also interact with the ions and the other electrons in the plasma. Since the plasma as a whole is quasi-neutral, the electron will be surrounded by a positive charge which is sufficient to neutralize the electron's own charge. Electrostatic interaction with this net positive charge will lower the minimum energy of a free electron to some amount below the energy of an electron at rest in a field-free vacuum. Thus \( \Delta E_{ee} + \Delta E_{ei} < 0 \), and we may even find

\[
\Delta E_e = \Delta E_{ee} + \Delta E_{ei} + \Delta E_{de} < 0,
\]

(2.12)

if the magnitude of \( \Delta E_{ee} + \Delta E_{ei} \) is greater than the magnitude of the Fermi energy. It may be noted that ordinary metals exhibit similar characteristics. A nonzero minimum energy, the work function, is required in order to release one conduction-band electron from the metal into a rest state in a field-free vacuum 33.

The calculation of \( \Delta E_{ee} + \Delta E_{ei} \), the lowering of the energies of the continuum electrons, can be performed using techniques of of solid state physics such as the nearly-free-electron approximation or tight-binding approximation 52. The wave functions, kinetic energies, and interaction potentials for various free electron states are calculated, and the resulting energy for each state can be determined. These
calculations are highly complicated, and require detailed modelling of the atomic potentials. Cellular methods such as the ion sphere model approximation$^{10}$ are somewhat less complicated, and this model is used here.

An even simpler approach to the free-electron interaction potential has been suggested$^{10}$. The interaction lowering of the electron continuum energy is estimated by the potential which a free electron would experience if placed equidistant between two average ions in the plasma. Although this simple model has the advantage of being amenable to straightforward calculation, it includes only the electron-ion interaction term and not the electron-electron interaction term. Conversely, both of these effects can be derived simultaneously by means of the ion sphere model. As well, the screening effect of the free electrons on the atomic electrons ($\Delta E_{el}$) may be determined using this model, as in the following section.

Let us now turn to the ion sphere model in considering the electron-electron and electron-ion interaction energy. This assumes that the quasi-neutral plasma may be considered as a neutral fluid of ion spheres. Thus, each ion sphere is independent of the rest of the plasma and contains a free electron population sufficient to neutralize the ion charge. Each ion sphere also has a volume equal to the average volume per atom in the compressed aluminum plasma, so that the mean free electron density within the ion sphere is equal to the mean free electron density throughout the plasma. We further assume a uniform free electron distribution within the ion sphere, for ease of calculation. The electrostatic potential field $V_f$ within a sphere due to $Z$ free electrons uniformly distributed throughout the sphere is$^{35}$

$$V_f(r) = \frac{eZ}{2R_0} \left( \frac{r^2}{R_0^2} - 3 \right),$$

(2.13)

with $r$ being distance from the centre of the ion sphere and $R_0$ being the radius of the ion sphere.
Including the free electrons, the atomic nucleus and the atomic electrons all in the same ion sphere combines the electron-ion and electron-electron interaction terms. Using the ion sphere model, we have the total interaction energy

$$
\Delta E_{ei} + \Delta E_{ee} = \int_{\text{sphere}} -e \left( V_a(r) + V_c(r) + V_n(r) \right) \psi_f^2(r) \, d^3r, \quad (2.14)
$$

where $V_a$ is the electrostatic potential field within the ion sphere due to the atomic electrons in the sphere, $V_c$ is the electrostatic potential field within the ion sphere due to the cloud of free electrons other than the one whose interaction energy is being considered, $V_n$ is the electrostatic potential field within the ion sphere due to the nucleus, and $\psi_f$ is the free-electron wave function within the ion sphere. All of these are expressed in terms of the distance $r$ from the nucleus at the centre of the ion sphere, and $d^3r$ is the element for volume integration.

We can more readily evaluate the integral (2.14) if we make use of the fact that the energy of the interaction of a given particle with the electrostatic potential fields of a set of other particles is identical to the energy of the interaction of those other particles with the electrostatic field due to that given particle. We assume a constant free electron density throughout the sphere, and after rewriting the integral (2.14) in this manner, we have

$$
\Delta E_{ei} + \Delta E_{ee} = 13eV'(0) + \int_{\text{sphere}} -e V'(r) \left( \psi_a^2(r) + \psi_c^2(r) \right) \, d^3r
$$

$$
= 13eV'(0) + \int_{\text{sphere}} -e V'(r) \left( \psi_a^2(r) + \frac{Z - 1}{(4/3)\pi R_0^3} \right) \, d^3r, \quad (2.15)
$$

with $V'(r) = \frac{e}{2R_0} \left( \frac{r^2}{R_0^2} - 3 \right)$,

the electrostatic potential field of the free electron. The term before the integral is the energy of the interaction of the nucleus at $r = 0$, the centre of the ion sphere,
with the field $V'(r)$ at this point. The first term within the brackets of the integrand, $\psi_a^2(r)$, is the probability distribution of the atomic electrons within the ion sphere, averaging over any angular dependence. Upon evaluation of the integral, this term yields the energy of the interaction of the atomic electrons with the electrostatic field of the one free electron whose energy is being considered. The second term within the large brackets of the integrand is the density within the ion sphere of the free electrons other than the one being considered. For simplicity, this density is approximated by its mean value of $Z - 1$ free electrons divided by the ion sphere volume $\frac{4}{3}\pi R_0^3$. Upon evaluation of the integral, this term yields the energy of the interaction of the free electron cloud with the electrostatic field of the one free electron being considered.

Upon integration of (2.15) we obtain

$$\Delta E_{ei} + \Delta E_{et} = -\frac{e^2}{2R_0} \left(3 + \frac{3}{5}(Z - 1) + \frac{r_a^2}{R_0^2}\right),$$

(2.16)

where $r_a^2 = \int \psi_a^2(r)r^2 \, d^3r$, the sum of the mean squares of the radii of the electron orbitals in the atom. The density of aluminum is 2.7 g/cm$^2$, and the average aluminum ion has 27 nucleons, so that the ion sphere radius is $R_0 = 1.59 \, \text{Å}$. In the undisturbed metallic aluminum $Z = 3$, the valence number. Assuming $\frac{r_a^2}{R_0^2} \ll 3 + \frac{3}{5}(Z - 1)$, we find that $\Delta E_{et} + \Delta E_{ei} = -19 \, \text{eV}$. This assumption of small orbital radii will be valid for $Z \geq 3$, in which case there are no M-shell electrons.

### 2.3.4 K-Edge Shift—Continuum Lowering

Now we turn our attention to the effects of the free-electron background on the atomic (bound) electrons, $\Delta E_{et}$. We consider the atomic wave-functions to be similar to those of the isolated atom, interacting with some superimposed free-electron distribution. This approach assumes that the continuum electrons
interacting with the atomic electrons form a smooth, dispersed cloud of low density. The free electrons will cause a small *perturbation* in the atomic orbital energies. This perturbation is given by the energy of the interaction of the free electrons with the atomic orbital electrons, assuming that the probability distribution of the atomic orbitals is not altered by the interaction. This method will clearly be less valid if the perturbation is of the order of the initial energies of the atomic orbitals. In general, for atomic electrons of wave function $\psi_a$ interacting with a free-electron potential $V_f$, the perturbation $\Delta E_p$ will be

$$\Delta E_p = \int_{\text{atom}} -e\psi_a^2 V_f \, d^3r. \quad (2.17)$$

In photoionization, the greatest contribution to the continuum lowering will be the reduction of the total number of atomic electrons interacting with the free electrons. This contribution will be equal in magnitude to the energy of the interaction of the free electrons with the atomic electron prior to its removal. The removal of this electron will also alter the shapes of the orbitals of the other atomic electrons. This will lead to another small change in the perturbation energy of the interaction of the ion with the electrons, which will be seen as a further contribution to the continuum lowering. Accordingly, the continuum lowering in a photoionization process is given by

$$\Delta E_{c1} = \Delta E_p(\text{final}) - \Delta E_p(\text{initial}). \quad (2.18)$$

Various approximations can be made here, such as the assumption of a constant electron density throughout the plasma, including the region around the ion core. More complete calculations are possible, determining the potential from a quantum-mechanical derivation of the free electron wave functions throughout the plasma and including the potential in the ion core region. This latter approach is, however, difficult. Such calculations have been made for cases of low plasma density
and low atomic number plasma species\(^\text{11}\), but are not yet available for aluminum plasmas at low temperatures and high densities. This is similar to the problems encountered in calculating \(\Delta E_{ei}\) and \(\Delta E_{ee}\) previously.

Returning to the ion sphere model, we have the potential field within the sphere due to the \(Z\) free electrons evenly distributed throughout the sphere from (2.14):

\[
V_f(r) = \frac{eZ}{2R_0} \left( \frac{r^2}{R_0^2} - 3 \right),
\]

with \(r\) being distance from the centre of the ion sphere and \(R_0\) being the radius of the ion sphere, so that

\[
\Delta E_p = \int_{\text{sphere}} -\frac{e^2Z}{2R_0} \left( \frac{r^2}{R_0^2} - 3 \right) \psi_a^2(r) d^3r.
\]

Upon integration, this yields

\[
\Delta E_p = \frac{e^2Z}{2R_0} \left( 3N_a - \frac{r_a^2}{R_0^2} \right),
\]

where \(N_a\) is the number of atomic electrons and we have defined \(r_a^2 = \int \psi_a^2(r) r^2 d^3r\) for the atomic electron wave function \(\psi_a(r)\) as before. In order to calculate \(\Delta E_{el}\) using this model, we require the initial and final values for \(r_a^2\). Thus,

\[
\Delta E_{el} = -\frac{e^2Z}{2R_0} \left( 3 + \frac{\Delta r_a^2}{R_0^2} \right),
\]

with \(\Delta r_a^2 = r_a^2(\text{final}) - r_a^2(\text{initial})\) and \(N_a(\text{final}) - N_a(\text{initial}) = -1\), which is the case for photoionization.

There are a couple of difficulties with this model. First, the shapes of the outer-shell orbitals of the atoms will be altered by the interaction with the free
electrons, altering $\Delta r_a^2$ in a manner dependent on plasma conditions. Furthermore, the atomic wave-functions must be recalculated in a manner consistent with the atomic and free-electron potential fields. On the other hand we can ignore $\frac{\Delta r_a^2}{R_0^2}$ altogether, as it will be small when the ionization is high:

$$\Delta E_{cl} \approx -\frac{3e^2Z}{2R_0},$$

(2.23)

for all L-shell and K-shell orbitals, when $Z \geq 3$ and the ion has no M-shell electrons. Accordingly, we have

$$\Delta E_{cl} \approx -40.8 \text{ eV},$$

(2.24)

for $Z = 3$, the valence number of metallic aluminum, and $R_0 = 1.59 \text{ Å}$, the ion sphere radius in metallic aluminum.

Note that we would also expect the free electron probability distribution to be nonuniform in the ion sphere with the greatest probability in regions of lowest energy for these electrons, near the ion core. Since this is also where the atomic electron densities are greatest, we would expect $\Delta E_{cl}$, the energy of the interaction of the atomic electrons with the free electrons, to be under-estimated by this model. In general, the inaccuracies in the solution derived here are similar to the inaccuracies in the solution derived for the interaction energy of the free electrons in the previous section. This follows from the use of a similar model in each case.

2.3.5 K-Edge Shift—Conclusion of Theory

Combining the edge-shift terms which we have derived thus far, (2.11), (2.16)
and (2.23), we have

\[ E_K = E_{K0} + \Delta E_{dc} + \left( \Delta E_{ee} + \Delta E_{ei} \right) + \Delta E_{cl} \]

\[ \approx E_{K0} + \frac{\hbar^2 (3\pi^2 n_e)^{2/3}}{2m_e} - \frac{e^2}{2R_0} \left( \frac{3Z + 12}{5} + \frac{r_a^2}{R_0^2} \right) - \frac{3e^2 Z}{2R_0} \text{ eV} \]  \hspace{1cm} (2.25)

where \( E_K \) is the shifted K-edge energy, \( E_{K0} \) is the unshifted K-edge energy, \( Z \) is the average plasma ionization, \( n_e \) is the plasma free electron density, \( m_e \) is the electron mass, \( R_0 \) is the ion sphere radius, and \( r_a^2 = \int r^2\psi_a^2 \) as before.

If we evaluate this for \( Z = 3 \), the valence of ordinary aluminum, \( E_{K0} = 1626 \text{ eV} \) for Al IV, \( R_0 = 1.59 \text{ Å} \) for uncompressed aluminum, \( n_e = 1.8 \times 10^{23} \text{ cm}^{-3} \) for uncompressed aluminum and assume that \( \frac{r_a^2}{R_0^2} \ll \frac{9+12}{5} \), then we obtain \( E_K \approx 1578 \text{ eV} \). We find that equation (2.25) does not yield the experimental value of 1560 \( \text{eV} \) for the K-edge energy in ordinary metallic aluminum. On the other hand, assuming \( Z = 4 \) at a compression ratio of 2, we use \( E_{K0} = 1670 \text{ eV} \) for Al V and the approximation \( \frac{r_a^2}{R_0^2} \ll \frac{12+12}{5} \) again, to obtain \( E_K \approx 1597 \text{ eV} \), very near the 1598 \( \text{eV} \) photon energy of the aluminum He\text{\textsubscript{a}} line. Of course, the model presented here contains many approximations. Since the electrons in the conduction band are in a lower energy than they would be in the M-shell orbital states, they would appear to be closer to the region of low potential near the nucleus. Accordingly, we might treat the continuum lowering due to the first three electrons in the conduction band—those which are in the conduction band in ordinary aluminum—separately from that due to others which may be injected into the top of the conduction band by shock-compression and shock-heating. It is not clear what the free electron density distribution would be under conditions of shock-heating and shock-compression, though. Thus we do not further modify equation (2.25), but simply note the discrepancy for metallic aluminum.
The only significant point that we may make here is that it appears plausible for a shift of the K-edge to higher photon energies to allow enhanced x-ray to occur as depicted in Figure 2-6, given that for a density compression ratio of two or greater the shocked aluminum does not contain a large fraction of atoms with ionization lower than four. Further theoretical analysis would entail a detailed quantum-mechanical self-consistent derivation of the free electron wave functions, and might include refinements to the ion sphere model.

Figure 2-8 indicates the average ionization which we would expect in the aluminum due to shock heating and shock compression, as a function of the compression ratio.\[^{22}\] We may model the plasma by a mixture of ionization states, so that on the basis of the data in the figure (\(\langle Z \rangle = 3.7\) for shock compression \(p/p_0 = 2\)) we would expect the material to be largely composed of quadruply ionized aluminum atoms, with a lesser number of triply ionized atoms present and with a few atoms of higher ionization. If we assume that the \(\text{He}_\alpha\) and intercombination lines are absorbed by neither quadruply ionized aluminum atoms nor atoms of higher ionization states, based on the K-edge shift analysis in this section, then we need only be concerned with the effect of K-shell photoionization absorption by the remaining triply ionized atoms.

This model of the shock-induced enhanced transmission of the \(\text{He}_\alpha\) and intercombination lines forms the basis for the scenario presented in Figure 2-6, as well as the interpretations of experimental results based on that scenario.
Figure 2-8 Predicted Ionization of Shocked Aluminum. These data are results of calculations by Y. Lee and D. More. The curve shown here is applicable only to shock-induced conditions and does not include any radiation heating ionization. The shock compression ratio in our experiments was 1.9 ~ 2.0, at a shock-heated temperature of 1.0 ~ 1.5 eV.
CHAPTER 3

EXPERIMENTAL FACILITIES

3.1 Laser and Target Chamber

The work presented in this thesis was performed with a Quantel Neodymium-glass laser system, NG-34, as shown in Figure 3-1. This consists of a Nd-YAG oscillator, a Nd-YAG preamplifier, and two Nd-glass amplifiers. The aperture of the final rod amplifier is 25 mm in diameter. The laser oscillator is passively Q-switched using a saturable dye absorber. It produces a single laser pulse of $\sim 2 \text{ ns}$ full width at half maximum at a wavelength of 1.064 $\mu\text{m}$ in the TEM$_{00}$ mode, with a maximum pulse energy of 12 J. The output of the final amplifier may be directed into KD*P (deuterated potassium dihydrogen phosphate) crystals for the generation of harmonic frequencies of the 1.064 $\mu\text{m}$ fundamental. All experimental results presented hereafter were obtained using the frequency-doubled 0.532 $\mu\text{m}$ beam.

The 0.532 $\mu\text{m}$ beam was routed to a target chamber by a series of dielectric-coated beam steering harmonic reflectors. The chamber entrance window was fused quartz, with an anti-reflection coating on each surface. Under ideal conditions, the efficiency of transmission of light through the relay system into the chamber should
Chapter 3: Experimental Facilities

- Figure 3-1 Laser and Target Chamber Layout. The floor plan of the facility is drawn roughly to scale, and indicates the arrangement used for the majority of the work done in this thesis.
exceed ninety percent. 0.532 μm laser pulse energies of up to 3 J, incident on the target, were utilized in our work.

Various diagnostics were used to determine the characteristics of the laser pulses either on a sampling basis or for each experimental shot. The full width at half maximum power for the laser pulse was 2.6 ~ 2.7 ns, and the temporal profile of the pulse was found to be approximately Gaussian as seen on a Hamamatsu optical streak camera\textsuperscript{37}, (as can be seen in Figure 3-16 at the end of the chapter.)

An optically flat quartz plate, (BS1 in Figure 3-1,) was introduced into the beam near the entrance to the target chamber. This beamsplitter reflected a small fraction of the incident laser light, ~ 10%, to a second beamsplitter (BS2) which in turn reflected ~ 1% of the incident laser light to various detectors. A Gentec laser pulse energy meter\textsuperscript{58} was used to determine the total laser energy incident on the target for each shot. This meter was calibrated with respect to an absolutely calibrated detector\textsuperscript{41} which was placed in the target position inside the chamber. A third beamsplitter (BS3) was placed in the laser beam incident on the Gentec energy meter. The two surfaces of this beamsplitter were not parallel, so that it produced two reflected beams. One of these was monitored by a Hamamatsu photodiode\textsuperscript{39} and the other by the streak camera. The signal from this photodiode was used for triggering of oscilloscopes, so that they could be timed relative to the incident laser pulse. Figure 3-2 shows the temporal profile of the laser pulse as recorded by this photodiode.

Inside the vacuum chamber, the laser beam was focussed onto a target positioning wheel using an anti-reflection coated lens with a focal length of 24 cm, (for a wavelength of 0.532 μm). The position of the best focus of the beam on target was determined through the observation of Brillouin backscatter\textsuperscript{40} from the laser-produced plasma. This nonlinear scattering process reflected the laser light back along its incident path. This back-reflected light was collimated by the focussing
lens and \( \sim 10\% \) was reflected by the beamsplitter (BS1) onto another Gentec energy meter. As the focussing lens position was varied, the best focus was identified by the maximum reflected signal. Detailed analysis of the laser focal spot in the past has shown that 90\% of the laser energy is incident within a circle with a diameter of 80 \( \mu m \), and that 60\% of the laser energy falls within the the central 40 \( \mu m \) of this circle.

Spatially and temporally-resolved measurements of luminous emission and reflectivity on the target backside has shown that for shock-wave study purposes, the central 40 \( \mu m \) region is the effective focal spot diameter. The shock wave reaches the target rear surface simultaneously across this zone, and reaches surrounding areas progressively later in time. Within the 40 \( \mu m \) focal spot we have \( \sim 4.8 \times 10^4 \) J/cm\(^2\) for each Joule of laser energy incident on the target. Since the laser produced a pulse with a temporal profile with a FWHM of \( \sim 2.7 \) ns, we use this time as the effective length of the laser pulse and obtain an average irradiance of \( \sim 1.8 \times 10^{13} \) W/cm\(^2\) for each Joule of laser energy incident on the target.
All experiments were carried out with the target front surface positioned at the best focus of the incident laser beam, except where otherwise stated. In order to avoid the deposition of plasma blowoff and target debris on the incident beam focussing lens, the target normal was tilted 10° away from the incident laser beam axis.

Driven by a digitally controlled stepping motor, the target positioning wheel allowed us to complete a series of shots at a few positions on each of several targets without opening the vacuum target chamber. The cylindrical target chamber, constructed of welded steel, is 24 inches in diameter and 18 inches high with a transparent Plexiglas lid sealed by Buna-N O-rings. Chamber access was a simple matter of lifting off this transparent lid. The entrance window, electronics feedthroughs, and probe beam windows were placed in the four 4-inch diameter and sixteen 3-inch diameter ports built into the chamber's sidewall. The 4-inch ports are at 90° intervals around the chamber, with twelve of the smaller ports at 22.5° intervals in between. There are four more smaller ports below the incident beam plane. These are used for the mounting of pressure gauges and other electrical connections. These lower ports were spaced at angles 45° between the 4-inch ports. All ports were sealed with Buna-N O-rings. The chamber diameter allowed room for probe beam routing and large x-ray detectors within the chamber itself.

The target chamber was pumped down to a pressure of roughly 100 mTorr by a mechanical pump. Lower pressures, down to $3 \times 10^{-6}$ Torr, could be obtained using of an oil diffusion pump mounted below the chamber.

### 3.2 X-Ray Calorimeters

In the study of x-ray processes in laser-matter interaction experiments, one of the most basic measurements is the overall conversion efficiency from incident
laser energy into x-ray emission energy. To measure the x-ray energy emitted by our laser-produced plasma, we used calorimeters. These absorb radiant energy and convert it into thermal energy which produces a measurable temperature rise in the absorber.

The detector used for x-ray energy balance measurements in these experiments was developed in this laboratory\textsuperscript{12}. It can be absolutely calibrated using thermoelectric temperature measurement to determine the total energy absorbed by aluminum absorbers, and thus the pulsed energy flux from some source\textsuperscript{13, 14}. The detector is illustrated in Figure 3-3. Although the detectors were originally designed and used for the measurement of energy carried by plasma ions from the target, the signal from the detector depends strictly on the energy deposited in the absorber and not the manner in which that energy was carried.

The detector is designed for differential measurements, with two identical absorbing masses and thermoelectric devices. This allows differential measurement of energy fluxes. This was not necessary for our measurements, but the differential arrangement also aids in eliminating thermal fluctuation effects on the output signal. Therefore, the detector was not altered; we simply masked one absorber with a massive metallic plate.

The absorbing masses of the detector were thin aluminum pads. These were not changed, as the features which make aluminum a suitable material for the deposition of the plasma ion energy also apply to the deposition of x-ray energy. First, aluminum has a low quantum efficiency for the production of secondary electrons or photoelectrons and a low reflectivity for x-rays at large angles of incidence. Furthermore, the x-ray energy absorbed by the aluminum becomes thermalized rather than going into chemical changes as might be the case for plastics or glasses.

Absolute calibration of the detectors is possible by means of resistive heating of the absorber pad, using resistors which are installed in those pads (Figure 3-3). This calibration was carried out for a range of deposited energies, yielding the
The design of the calorimeters and their signal amplification circuitry is described in detail in reference 12. Application to our own experimental needs is discussed in the text.

 calibration curve in Figure 3-4. The sensitivity was found to be $170 \pm 10 \text{ mV/mJ}$ for each absorbing pad and for differential measurements between those pads when one of the pads was covered. Note that the detectors are linear over this entire range and that all of the detectors have the same calibration constant, within the accuracy of the measurements.

The amplifier circuit configuration in reference 12 was adjusted to increase the filtering of electrical noise and thermal fluctuations with time constants of the order of a few seconds or less. This resulted in identical pulse-shapes in the output signal from the detectors for both the electrical energy deposition (calibration) and
The energy calibration was found to be $170 \pm 10 \text{ mV/mJ}$ for the four absorbers of the two detectors used and indicated by the four different symbols. It is clear that they are all effectively identical and linear in response.

The radiant x-ray energy deposition. (The calibration pulses had previously been distorted by thermalization-time effects.) Figure 3-5 is a typical calibration signal for an x-ray calorimeter, showing the smooth peak and low noise level produced by the amplifier and filtering circuitry. The signal trace was displayed at a rate of 5 sec/div. and a sensitivity of 500 mV/div.

It should be noted here that it was found necessary to introduce a large separation between the detector absorber and the x-ray filter placed in front of the absorber. When the two were in close proximity, at a few millimeters distance, there appeared to be a transfer of energy from the filter to the absorbing pad by
some means which was not fully understood. The effect was negligible when the filter was several centimetres away from the absorber, and such an arrangement was utilized for all of the measurements presented here.

![Calorimeter Signal](image)

*Figure 3-5 Typical Calorimeter Signal.* This signal was produced by a calibration discharge of 5.85 mJ. The sensitivity and sweep speed of the oscilloscope were 500 mV/div. and 5 sec/div. respectively.

### 3.3 PIN Diodes

Although the x-ray calorimeters have the advantage of linear energy response over all x-ray photon energies pertinent to our work, they are relatively insensitive with a minimum detectable energy of roughly 100 μJ incident upon the absorbers. We therefore used more sensitive detectors, such as PIN silicon photodiodes\(^\text{15}\), in the study of x-rays at low fluxes.

The PIN diodes are commercially available units with a response curve which is flat to within a factor of two from a photon energy of 600 eV up to a photon energy of 15 keV. There was a large variation in response between different PIN diodes,
and so a relative calibration between the diodes was performed. We labelled the PIN diodes 1 through 5. The sensitivities of the diodes were all calibrated relative to diode #1 by comparing their output signals in simultaneous measurements using the laser-produced plasma as an x-ray source. We found, for the relative sensitivities,

\[ R_3 = 0.63 \pm 0.07 \]
\[ R_4 = 3.7 \pm 0.3 \]
\[ R_5 = 0.45 \pm 0.06. \]

This calibration is already included in all results presented in the later chapters.

Due to a limited number of oscilloscopes available for simultaneous recording of the PIN diode signals, PIN diode #2 was not used.

Among the problems with the PIN diodes were their fragility and their lack of temporal resolution for nanosecond laser experiments. The relative calibration of the diodes also varied with time and usage, so that the sensitivity ratios presented here are only for one experimental run and may not be valid in the future. Indeed, the diodes had a high failure rate, and a few of the diodes which were used for these experiments are not functional at the present time.

3.4 Biplanar Vacuum X-Ray Diodes

The biplanar vacuum x-ray diodes, or XRD's, were developed in an attempt to improve the x-ray measurements with temporal resolution. We originally considered XRD designs developed in other laboratories\textsuperscript{16}, but the high cost of these designs resulted in our developing a similar, lower-cost device.
3.4.1 General Considerations

The theory of operation of a vacuum photodiode is simple. X-rays incident upon some conductor, the photocathode, eject electrons. These photo-electrons are quickly removed from the vicinity of the photocathode by a positively-biased anode. This produces a potential on the photocathode, which is recorded by an appropriate device such as an oscilloscope. Our XRD design is illustrated in Figure 3-6. The detectors constructed were composed largely of brass which oxidizes slowly and provides good electrical contact between the various components. Anodized aluminum would be unsuitable due to the resistivity of the anodized layer; unanodized aluminum detector components are being fabricated for future use.

As can be seen in Figure 3-6, the entrance window mount provided a reduced aperture for the incident x-rays. The edges of this aperture absorbed x-rays which would otherwise not be directly incident on the mesh anode ring. The large separation between the entrance window mount and the anode ring minimized the casing-to-anode flow of stray photoelectrons ejected from the edge of the entrance window mount.

X-rays which passed through the mesh anode struck the photocathode at normal incidence. The anode grid was a brass mesh made of wires having a diameter of 0.27 mm. Transmission through this mesh was ~ 69%. This grid was mounted on a brass ring with an opening of 11 mm. It was placed 5 mm in front of a photocathode 13 mm in diameter. The photoemissive surface of the photocathode was a gold foil of 25 μm thickness soldered to the brass cone which served as an interchangeable photocathode base. Gold was used because of its good quantum efficiency over a broad range of x-ray photon energies\textsuperscript{19}, as shown in Figure 3-7. This is a result of the high atomic number of the element, providing a large number of inner-shell electrons in energy levels appropriate for interaction with x-ray photons over a wide energy range. As well, gold was found to be easy to work
Construction of the device is outlined in the text. Materials used include brass, gold and teflon, all of which are compatible with vacuum pressures as low as 0.1 mTorr.

with and maintain in good condition. These characteristics arise from the ductility and non-reactivity of the metal.

Considering the gap between the photocathode surface and the anode electron-collecting grid as a biplanar capacitor, electrons moving in this gap will induce an electrical current on each electrode, which varies as the electrons move between the electrodes. There will be corresponding signals transmitted down both the signal cable attached to the photocathode and the bias cable attached to the anode. In order to achieve fast temporal response, the signal from the photocathode was transmitted to an oscilloscope by means of 50-ohm coaxial cables. The signal and
bias connections are in the standard HN configuration, so as to properly match the 50-ohm conical coaxial electrode casings to the 50-ohm cables. Commercially available adaptors then allowed connection to standard BNC fittings and RG-58/U coaxial cables. If we consider the photoelectron flow as a current across the electrode gap being divided between two 50-ohm loads (the cables) for a net load of 25 ohms, then the signal in volts will be the photoelectric current in amperes multiplied by 25. If the photoelectric current varies linearly with the incident x-ray intensity, the signal voltage will therefore also vary linearly with the incident x-ray intensity.

*Figure 3-7 Gold Photoelectric Efficiency. The data presented here are obtained directly from reference 19. They are shown for comparison with calculated results in later figures.*
3.4.2 Temporal Response

In measurements using the XRD, the overall temporal response of the detection system depends on the response of the detector as well as that of the oscilloscope used to record the signal. To analyze the overall system response, it is simplest to approximate all temporal response functions with Gaussian profiles, which are easily convolved with one another by summing the squares of their full widths at half maximum. Thus, given a source signal having a Gaussian temporal profile with a full width at half maximum, or FWHM, equal to $\tau_L$, we obtain an oscilloscope trace having a FWHM $= \tau_M$ which is given by

$$\tau_M^2 = \tau_L^2 + \tau_D^2 + \tau_O^2,$$

where $\tau_D$ is the FWHM of a Gaussian response function which may be associated with the detector and $\tau_O$ is the corresponding FWHM associated with the oscilloscope.

The detector response $\tau_D$ can be further analyzed in terms of: i), the intrinsic response of the detector due to signal reflections within the coaxial insulating gap inside the detector and mismatch in the electrical connections as well as signal dispersion in the coaxial cables, and ii), signal dispersion due to the finite transit time of the photoelectrons across the cathode-anode gap. Since the intrinsic response of the detector will be independent of its bias voltage, we characterize the corresponding response function by Gaussian with a FWHM of $\tau_G$. To assess the transit time effect, we note that for a bias voltage $V_0$ and a cathode-anode separation $d$, the electron in the gap will experience a constant electrostatic force and hence a constant acceleration,

$$a = \frac{eV_0}{m_e d}.$$
where \( m_e \) and \( e \) are the mass and charge of the electron, respectively. Accordingly, the transit time for photoelectrons ejected with no initial energy is

\[
t_0 = \sqrt{\frac{2d}{a}} = d\sqrt{\frac{2m_e}{eV_0}}. 
\]  
(3.3)

Approximating the transit-time response function by a Gaussian with a FWHM \( \tau_e \) and assuming that \( \tau_e \) varies with \( V_0 \) in the same manner as the transit time \( t_0 \), we have

\[
\tau_e \propto \sqrt{\frac{1}{V_0}} = \tau_C \sqrt{\frac{V_C}{V_0}},
\]

(3.4)

where we have defined \( V_C \) to be the bias voltage \( V_0 \) at which \( \tau_e \) is equal to \( \tau_C \). Thus, we can combine the two to produce a detector response function \( \tau_D \) given by

\[
\tau_D^2 = \tau_C^2 + \left( \tau_C \sqrt{\frac{V_C}{V_0}} \right)^2.
\]

(3.5)

Combining the signal-cable dispersion response function with the intrinsic detector response function, we obtain the complete signal response function

\[
\tau_M^2 = \tau_L^2 + \tau_O^2 + \tau_C^2 \left( 1 + \frac{V_C}{V_0} \right),
\]

(3.6)

where \( \tau_C \) and \( V_C \) are quantities which we determine by numerical fitting \( \tau_M \) to experimental measurements made at various values of \( V_0 \).

In these measurements we illuminated the photocathode of the XRD at various bias voltages, with a nitrogen laser pulse. The 3.68 eV photon energy of the 0.337 \( \mu \)m nitrogen laser radiation was less than the 4.8 eV work function of the detector's gold photocathode$^{33}$. A signal was observed which may have been due to either photoemissive processes involving the absorption of more than one photon,
or to photocathode impurities. As a check of possible nonlinearity in the signal produced by the nitrogen laser light, measurement of scaling of observed signal height with respect to laser intensity was made. This was accomplished by simply introducing neutral density filters into the nitrogen laser beam and observing the effect of this on the amplitude of the signals produced in the detector. Attenuation of the laser pulse by a filter of 77% transmission at a wavelength of 0.377 \( \mu \text{m} \) decreased the XRD output signal by a factor of 0.64 ± 0.04. Attenuation of the pulse by a 51% transmission filter decreased the signal by a factor of 0.32 ± 0.02. Thus, it was found that the signal height decreased with the filter transmission factor to the power 1.7 ± 0.1, resulting in a reduction in the FWHM of the photoemission pulse in the detector relative to the laser pulse FWHM by a factor equal to the square root of this number. An optical streak camera was used to measure the FWHM of the laser pulse, which was found to be 390 ps. The FWHM of the photoemission pulse in the detector was therefore 300 ps.

The results of temporal response measurements of the XRD made using nitrogen laser radiation are presented in Figure 3-8. The oscilloscope used was a Tektronix 7104 gigahertz-bandwidth oscilloscope equipped with a 7A29 preamplifier, with a nominal impulse response FWHM \( \tau_O = 300 \text{ps} \). Using a least-squares fit of the variables \( V_C \) and \( \tau_C \) in equation (3.6) to the data (the solid curve) yields \( V_C = 1200 \text{ V} \) and \( \tau_C = 340 \text{ps} \). Also presented in Figure 3-8 are the system response time given by the dashed curve,

\[
\tau_S = \sqrt{\tau_O^2 + \tau_C^2 \left(1 + \frac{V_C}{V_0}\right)},
\]

and the detector response time given by the dash-dotted curve,

\[
\tau_D = \sqrt{\tau_C \left(1 + \frac{V_C}{V_0}\right)}.
\]
The uncertainty associated with the fitted curves is $\sim 10\%$, as indicated by the error bars.

At an applied bias voltage $V_0 = 2000 \text{ V}$ the detector response time is $\tau_S = 430 \text{ ps}$. For the work presented in this thesis the detectors were biased at $V_0 = 500 \text{ V}$. This yielded a system response time $\tau_S = 700 \text{ ps}$, as indicated in Figure 3-8.

That the XRD provides sufficient temporal resolution for our x-ray studies can be seen in Figure 3-9, which displays typical x-ray signal traces obtained. The frontside signal was delayed by $50 \text{ ps}$ relative to the backside signal. Note that the
temporal features of the pulses studied are much greater than $\tau_s = 700 \text{ ps}$. Thus, the signal traces shown in Figure 3-9 reflect real temporal differences between the x-ray signals.

(a) The target frontside signal as seen through a 25 $\mu$m Al filter; (b) the backside signal as seen through a B-10 foil. The target-to-photo cathode distance for the frontside detector was 7.8 cm, and that for the backside detector was 10.4 cm.

3.4.3 Spectral Response

The relative response of the XRD to various photon energies is obtained from experimental measurements of the photoelectric quantum efficiency of gold, as given in reference 19 and Figure 3-7. Since a B-10 foil was used as the detector entrance window for all measurements, it could also be considered an integral part of the XRD. The transmission spectrum of the B-10 foil$^{20}$ is shown in Figure 3-10. This can be combined with some given x-ray emission power spectrum to predict the resultant signal output.
Figure 3-10 B-10 Foil Transmission Curve. This curve shows the nominal transmission for a B-10 foil as a function of photon energy. It corresponds to that of ~ 50 mg/cm² of aluminum deposited on a polycarbonate foil of ~ 150 mg/cm² thickness, with the polycarbonate taken to be (C₁₆H₁₄O₃)ₙ.

Additionally, the signal corresponding to the same x-rays attenuated by other filters of known absorption coefficients can be calculated as outlined in Chapter 2. A simple computer program to perform such calculations has been written and is listed in Appendix A. This provides the information presented in Figures 3-11 to 3-13. The effect of the B-10 foil entrance window has been included in these calculations. Figure 3-11 shows the response curve of the filtered (B-10) XRD. This is obtained by simply multiplying the transmission factor of the B-10 entrance
Figure 3-11 Filtered Detectro Response Curve. This is the theoretical photoelectric sensitivity of the XRD as used in experiments, obtained by multiplying the photoelectric sensitivity of the gold photocathode by the transmission factor of the B-10 filter.

Using the x-ray emission spectrum calculated by Duston et. al\(^1\) and the detector response curve (Figure 3-11) the spectrum detected through various aluminum thicknesses can be calculated. Some examples are shown in Figure 3-12. The contribution from the line radiation has been included. The aluminum mass absorption coefficient used in the calculations has been shown in Figure 2-5. The spectrum is independent of the aluminum filter density \(\rho\) and filter thickness \(d\), as long as
The calculation of the signals produced by x-rays at various photon energies indicates that for thick aluminum filters the significant regions of the x-ray spectrum are at high energies and K-edge.

The product $pd$ is a constant. The filter areal density $pd$ affects the shape of the detected spectrum.

The spectra in Figure 3-12 can be integrated over all photon energies, including summation over the important x-ray lines, in order to obtain a normalized signal corresponding to the x-rays transmitted through various aluminum filter thicknesses and detected by the XRD. The results of such integration are shown in Figure 3-13. The curve is useful in understanding changing signal strengths observed by the XRD behind the laser target in terms of the changing aluminum filter areal densities $pd$. 
3.5 Shock Diagnostics

In addition to temporally-resolved measurement of the x-rays, it is also necessary to determine the correlation of these signals with respect to the hydrodynamic processes occurring in the experiments. The laser-driven shock wave propagating in the target was characterized from measurement of the shock transit time. Two diagnostics have been used.

The arrival of the shock wave at the target backside was determined by observation of the luminous emission from the region on the foil backside directly behind the laser focal spot. Alternatively, the shock arrival was identified by a rapid decrease in the reflectivity of the foil rear surface. The significant difference between

Figure 3-13 Attenuation in X-Ray Signal by Aluminum Filters.
the two methods was the introduction of an external source of illumination for the second method, thus increasing greatly the sensitivity of the diagnostic.

3.5.1 Rear Surface Luminous Emission

- **Figure 3-14** Shock Diagnostics Layout. This is the arrangement used for observation of the shock breakout.
In this method, an optical imaging system was set up which allowed a streak camera to observe the foil backside, as indicated in Figure 3-14. The streak camera itself was optically triggered by a pulse from the Nd-glass laser as described in section 3.1. This triggering involved an electrical signal delay, which was adjusted for streak recording near the time when the shock reached the foil rear surface, the moment of shock breakout. A portion of the incident laser beam was also routed directly to the streak camera input optics through an optical delay path, which was adjusted so that the peak of this pulse was clearly visible during the recording of the streak. This pulse was used as the laser time fiducial.

Two 0.570 μm bandpass filters, (~ 100 Å bandpass,) were placed in front of the streak camera entrance optics, attenuating the 0.532 μm laser light transmitted through the disassembling target foil or any stray light by a factor of ~ 10^8. These protected the streak camera from possible overexposure damage, and helped to increase the signal-to-noise ratio in the observed signal.

Due to optical path length differences, there was a delay between the backside emission measurement and the laser fiducial. This small delay was measured and taken into account in subsequent shock measurements. To measure the relative timing between the back surface emission and the laser fiducial, we used the frequency-doubled 0.532 μm laser light from the Nd-YAG oscillator of the NG-34 laser. This pulse was identical to the amplified laser pulse with which the target was irradiated in the shock experiments except at much lower pulse energy. The laser pulse reaching the target chamber was further attenuated by a factor of 1000, to avoid nonlinear processes which might distort our timing measurements. A ground glass slide was placed at the target plane to scatter this attenuated laser light into the target backside imaging optics, producing a streak camera signal whose peak was clearly visible. Thus, the streak camera video monitor showed two temporal records of the laser pulse. Denoting the channel number corresponding to the peak of the laser pulse scattered into the backside imaging optics by \( P \) and the channel
number corresponding to the peak of the fiducial pulse by $F$, the timing offset was $O = P - F$. In shock experiments, then, we could find an absolute timing relationship between the incidence of the laser on the front of the target and the occurrence of shock breakout. This was

$$t_s \text{ (ns)} = \frac{5.42 \text{ ns}}{256 \text{ ch.}} (S - F - O),$$

where $t_s$ is the time of shock breakout relative to the peak of the incident laser pulse on target, $F$ is again the streak camera video monitor channel number for the fiducial peak, and $S$ is the channel number for the onset of backside emission due to shock breakout. The numerical factor is for the 10 ns streak camera sweep-speed setting which yielded a streak time of 5.42 ns over the 256 vertical elements of the digitized video monitor\cite{37}. This sweep speed was used for all timing measurements presented in this thesis.

Figure 3-15 shows a streak record of the target rear surface luminous emission. The onset of the emission signal at the moment of shock breakout was a reasonably clearly-defined point on the streak camera video monitor.

The rear surface luminous emission signals were not always clear, even though the shocked aluminum material reached quite a high temperature. This was due to the high f-number (~ $f/7$) of the imaging optics system, and the narrow transmission range of the filters used on the entrance of the streak camera. Low signal levels can be compensated for by increasing the gain setting of the streak camera, but at very low input light levels the signals due to the individual photons become separated by times which are visible on the streak camera monitor screen. At this point, the turn-on of the emission signal is determined by the time of the first observed photon. This introduces a random error into the measurement, as there will be a random delay between the turn-on of the emission and the observation of the first photon. This delay will be of the order of the inverse of the power of the input
optical signal, divided by the photon energy. In Figure 3-15 the individual photon signals are clearly visible. There are 15 ~ 20 such signals in the first nanosecond of the luminous emission streak record, which would correspond to a random delay of 50 ~ 60 ps in the observation of the emission onset.

In addition, the streak camera produces a background of internally-generated noise signals at these gain levels.

3.5.2 Rear Surface Reflectivity

As a result of the difficulties inherent in the emission diagnostic, we used an alternate approach. When the target rear surface becomes heated by the shock wave, its reflectivity is seen to drop rapidly. This has been attributed to the formation of a cold (1 ~ 1.5 eV) plasma on the foil backside, which expands rapidly.
into the vacuum and absorbs the incident light due to its low optical-frequency electrical conductivity\textsuperscript{24}. The moment of shock breakout was determined by observing the sudden decrease in the reflectivity of the target backside in the shocked region.

A dye laser had been developed by our research group\textsuperscript{44} as a source of high-intensity probe light with a pulse width of $\sim 2$ ns (FWHM). This dye laser was optically pumped using a small fraction of the frequency-doubled 0.532 $\mu$m output from the NG-34 laser system, so that the dye laser pulse was automatically synchronized with the target irradiation pulse. The output wavelength of the dye laser was 0.57 $\mu$m. This dye laser was used to illuminate the region of shock breakout on the target rear surface. The imaging optics collected the specularly reflected probe laser light. This imaged the foil behind the focal spot of the main laser onto the entrance slit of the streak camera.

Probe laser stray light, including that scattered by the shocked region into the collecting optics for specular reflection, will lead to a reduction in the contrast between the the specularly reflected probe laser light prior to shock breakout and that immediately following the shock breakout. The incident probe laser beam was collimated. The light specularly reflected from the foil would also be collimated as long as the target rear surface was near optically polished. We could thus aperture out the stray and scattered light while still collecting all of the specularly reflected probe laser light, by using f/11 backside imaging optics. Furthermore, surface nonuniformities would also cause nonuniform reflectivity and nonuniform shock breakout.

Figure 3-16 shows a streak record of the reflectivity of the foil rear surface behind the laser focal spot at the moment of shock breakout. The light producing the observed signal was 0.57 $\mu$m probe laser light illuminating the target foil backside. The rapid decrease in the reflected optical signal yields a clear indication of the moment of shock breakout. This allows us to measure the time of shock arrival relative to the fiducial with an accuracy of $\sim \pm 100$ ps for each individual shot.
• Figure 3-16 Streak Record of Rear Surface Reflectivity at Shock Breakout. This is an example of the streak camera signal due to 0.57 μm probe laser light reflected from the region of shock breakout. Note the sharp drop in reflectivity at the moment of shock breakout.
4.1 X-Ray Emission Measurements

The first and most basic measurements made were those of the energy of x-ray emission from the laser-produced plasma. We examined the x-ray emission for 50 μm thick aluminum, 25 μm thick molybdenum, and 20 μm thick copper targets at various irradiances. The results of the calorimeter measurements are presented in Figure 4-1. This shows the energy emitted per steradian as a function of the intensity of the incident 0.532 μm laser light. The measurements were made at angles of 20° ~ 30° from the target normal using a B-10 foil as the x-ray filter. It should be noted that we did not measure the angular distribution of the x-ray emission, which we might expect to be either isotropic or Lambertian. In the latter distribution the emission intensity will be proportional to the cosine of the angle between the target normal and the line of sight of the detector.

The laser energy was measured for each laser shot and the absorbed irradiance $\Phi_{60}$ which is indicated along the lower axis of Figure 4-1 was obtained from this measured energy according to an averaged irradiance of $1.8 \times 10^{13}$ W/cm$^2$ per Joule of laser light on target, as derived in section 3.1. In order to differentiate between
Figure 4-1 X-Ray Emission from Laser-Irradiated Targets of Different Z. This is the x-ray energy detected through a B-10 foil using a calorimeter. This energy represents a fraction of the total x-ray energy radiated away by the laser-produced plasma. \(10^{13} \text{ W/cm}^2\) corresponds to an effective laser energy of 0.56 J.

The x-ray signal and extraneous signals due to stray light, plasma blowoff, and electromagnetic pulses within the target chamber, we repeated the measurements with the detector filters replaced with aluminum plates of approximately one millimeter thickness. The detectors then yielded no detectable signal above the noise level, leading us to conclude that the signals obtained with a B-10 filter were indeed due to x-rays.

The fitted intensity scaling laws for x-ray production are also indicated in Figure 4-1. Note that the conversion efficiency will have a scaling law which is
lower by one; thus, the aluminum x-ray conversion efficiency varies with intensity to the power 0.4. We see that although the different materials have very different conversion efficiencies for x-ray energy in the spectral band transmitted through the B-10 filter, the power-law scaling for each material is very similar. The stronger x-ray emitters, molybdenum and copper, apparently have slightly lower scaling powers than aluminum. Furthermore, copper appears to be a much more efficient target material for the conversion of incident laser energy into x-ray energy than molybdenum or aluminum, for absorbed 0.532 μm laser light at intensities of $10^{13}$ to $10^{14}$ W/cm$^2$.

4.2 X-Ray Transmission Measurements

Following the energy measurements on x-ray emission, we wished to study the x-ray energy transmitted through the irradiated targets.

4.2.1 Time-Integrated PIN Diode Measurements

The x-ray calorimeters were not sufficiently sensitive for the x-ray transmission measurements. Thus, we used the much more sensitive PIN diodes. The PIN diodes used were those described in Chapter 3. They were calibrated relative to one another for each series of x-ray measurements.

For the results presented in Figures 4-2 and 4-3 the targets used were 50 μm aluminum, 25 μm molybdenum, and 20 μm copper foils, as in the measurements reported in section 4.1. The irradiation conditions were also identical to those measurements. The measurements in Figures 4-2 and 4-3 were made using PIN diodes in front of and behind the target foils. The PIN diodes all had 15 μm beryllium filters, and the PIN diodes positioned in front of the target also had filter foils identical to the target foils used.
Figure 4-2 presents PIN diode signals observed behind the target. These signals thus correspond to the x-rays penetrating the target, including any x-rays which might shine through the target as it disassembles at late times. The dashed lines at the bottom of Figure 4-2 correspond to the noise level for PIN diodes within the vacuum target chamber during a laser shot on target. This noise level was determined by firing the laser onto the target with the x-rays completely blocked from reaching the PIN diodes.

- Figure 4-2 Measured Back-side PIN Signal. The dots correspond to observation at target normal, and the circles ~ 35° from target perpendicular. The dashed lines are the background noise levels.
Chapter 4: Experimental Results

The x-ray signals presented in Figure 4-2 indicate strong angular anisotropy for the x-ray flux through the irradiated target. The PIN diode x-ray signals obtained at target normal (the dots) are up to four times higher than the signals obtained at a line of sight ~ 35° from target normal (the circles). Note from Figure 4-2 that the PIN diode x-ray signal detected behind the target is also strongly dependent on the absorbed laser irradiance. The approximate scalings of the signals measured behind the targets are indicated in the figure.

For comparison, Figure 4-3 presents the PIN diode x-ray signals observed at the front of the target through filter foils equivalent to the unperturbed target foils. There are no results for molybdenum because the x-rays from the molybdenum targets produced no detectable signal above the PIN diode noise level. The dashed lines at the bottom of Figure 4-3 represent the noise level of the PIN diodes within the target chamber.

The frontside PIN diode x-ray signals presented in Figure 4-3 do not indicate any significant anisotropy in the x-ray emission in the spectral band transmitted through the target-material filters. The PIN diode x-ray signals obtained at a line of sight ~ 50° from target normal (the dots) are approximately equal to the signal obtained at a line of sight ~ 20° from target normal (the circles). We also note from Figure 4-3 that for aluminum the PIN diode x-ray signals obtained at the front through the target-material filters do not scale with the absorbed laser irradiance as strongly as the signals detected behind the foils. Approximate signal scaling power laws are presented in Figure 4-3 for comparison with those in Figure 4-2. As well, the x-ray signals from the front PIN diodes with target-material filters are lower than the signals from the rear PIN diodes at target normal. The rear signals are ~ 5 times as high as the front signals at a laser irradiance of ~ $3 \times 10^{13}$ W/cm$^2$. We note from reference 25 that 2D rarefaction and disassembly of the target may allow enhanced x-ray transmission through them at times late in the laser pulse. Our interpretation and analysis of the PIN diode data should take this
into account. Better understanding of the effects which this late-time disassembly might have on the time-integrated x-ray flux through the targets requires time-resolved measurement of the front and rear x-ray signals.

4.2.2 Time-Resolved XRD Measurements

The time of shock breakout relative to the incident laser pulse has been determined using the optical diagnostics described in section 3.5. The results are presented in Figure 4-4. The circles are data from shock-induced luminous emission
observations averaged over several laser shots and the dashed curve is a least-squares fit to this data. The squares are data from reflectivity observations averaged over several laser shots and the dash-dotted curve is a least-squares fit to this data. Also shown are the isodensity trajectories corresponding to the shock front obtained from hydrodynamic simulations, indicated by the solid lines in the figure. The simulations correspond to a Gaussian laser pulse with a FWHM of 2.5 ns and an average absorbed irradiance of $2 \times 10^{13} \text{ W/cm}^2$. We see in Figure 4-4 that this yields the shock speed observed by the two diagnostics. However, the rear surface reflectivity measurements indicated shock breakout $\sim 200$ ps earlier than predicted, and the rear surface emission measurements indicated shock breakout $\sim 200$ ps later than predicted. This may be due to the reflectivity measurement’s greater sensitivity to minor disturbances at the foil rear surface, and the low emission signal levels at shock breakout as mentioned in Chapter 3.

However, the exact temporal correlation of the x-ray emission from the laser-produced plasma on target front side and the laser peak cannot be determined experimentally. In order to relate the x-ray signals obtained using the XRDs to the shock breakout determined with the optical diagnostic, we need to assume some relationship between the x-ray emission power and the laser pulse power. We made the very simple assumption that the x-ray power was some monotonically increasing function of the laser intensity, and there was no target disassembly during the laser pulse. Such a scaling would result in an x-ray emission peak coincident with the laser peak but not necessarily having a temporal profile with the same full width at half maximum.

In order to verify detector insensitivity to stray light within the target chamber, the entrance window filter was replaced with $\sim 100 \mu\text{m}$ thick glass. This was sufficient to eliminate the x-rays reaching the detector, but allowed visible light transmission. In this configuration there was no detectable signal above the noise level of a few millivolts when observing the laser-produced plasma, indicating that
Figure 4-4 Shock Trajectory. The circles are averaged data from rear surface emission observations, and the squares are averaged reflectivity observations. The dashed line is a least-squares fit to the raw reflectivity data, and the dotted line is a least-squares fit to the raw emission data. The solid lines are isodensity trajectories from a computer simulation\textsuperscript{36} for an absorbed irradiance of $2 \times 10^{13}$ W/cm\textsuperscript{2}.

The XRDs were insensitive to laser or plasma stray light. As well, charged particles reaching the detector casing from the plasma had velocities which were low enough that any signals due to their incidence on the detectors would be temporally separated from the x-ray signal. This required only a few centimetres of target-to-detector distance, allowing us to cover as large a solid angle as possible with the detector photocathodes.
Chapter 4: Experimental Results

The detectors and/or their signal cables were apparently sensitive to the electrical noise produced by the motion of the free charges in the laser-produced plasma, though. In order to obtain useful information from experiments using thick foil targets and filters, various precautions were taken to reduce the noise levels. As a first step, the detector casings were shielded from direct incidence of the expanding plasma by thick metallic sheets. The signal and bias cables had a second and then a third layer of braided wire shielding applied. Magnets were employed to control the motion of the charged particles in the plasma, being placed in such a manner that the magnetic field lines were parallel to the foil front surface with as great a field strength as we could obtain using readily available intrinsic magnets. Furthermore, the pressure of the residual gas within the chamber was allowed to reach as high a level as would allow the XRDs to hold their bias voltage without breakdown. We found all of these—the shielding, the magnets, and the high residual gas pressure—to be significant factors in reducing the noise. At a residual chamber pressure of \( \sim 100 \text{ mTorr} \) the maximum safe detector bias was \( \sim 500 \text{ V} \) and a noise level in the millivolt range was achieved.

The XRD detectors were arranged as shown in Figure 3-14, and were timed relative to one another using the peak of the x-ray pulse produced by high-intensity irradiation of thin aluminum foils while using relatively thick XRD entrance windows (~ 5 μm). Figure 4-5 shows typical x-ray pulses from laser shots on 2 μm aluminum foils. The peak of this x-ray pulse is seen to occur several hundred picoseconds prior to the peak of the x-ray pulse observed from irradiation of a thick foil target (≥ 20 μm) which would be at a time ~ 200 ps before the centre of the photograph. Thus, the peak of the x-ray signal occurred at a point where the laser intensity was still increasing. The termination of the emission would appear to be due to the rapid ablation and radial expansion of the thin foil: the ablation depth for our irradiation conditions is 2 ~ 3 μm\(^{26}\). Since x-rays which would be significantly absorbed within the plasma formed by the 2 μm foil would not penetrate the
~ 5 μm aluminum filter on the XRDs, we might assume that the x-ray emission of the laser-produced plasma was virtually identical both in front of and behind the target near the time of the x-ray signal peak. Thus, the time of the signal peak must also be the same at both the front and back side of the target.

• Figure 4-5 XRD Signals — (a) Front, (b) Back. These signals were produced by laser irradiation of a 2 μm aluminum foil. Each XRD had a 5 μm aluminum entrance window. The distance from the target to the front diode photocathode was 7.8 cm, and that to the rear diode was 10.4 cm.

Having identified the relative timing of the XRD signal, incident laser pulse and shock breakout, we made a series of x-ray measurements on aluminum foils of various thicknesses. This was repeated several times, using both emission and reflectivity measurements as shock diagnostics, and using a defocussed laser spot for some measurements.

For each foil thickness, we made certain that the target and equivalent filter foil (on the front XRD) were obtained from the same piece of material. If polishing the foils resulted in any significant thinning of the foil, this effect would be eliminated by the fact that both the target and the front-side filter were thinned.
The measured rear-to-front x-ray signal ratio would yield a comparison of x-ray transmission through a shock-compressed target with that through an identical uncompressed foil.

We have noted some deterioration of the exposed B-10 entrance window on the back-side XRD following a particularly lengthy series of preliminary XRD shots. In order to avoid modification of the measured signal ratios by an imbalance in the detector entrance windows, the B-10 foil on each detector was replaced at frequent intervals, before there was any visible deterioration of the aluminum layer on the filter.

The time-resolved front and rear x-ray signals $X(t)$ can be integrated up to any given time $\Delta \tau$ in order to obtain $I_x(\Delta \tau)$, the total x-ray flux up to that time:

$$I_x(\Delta \tau) = \int_0^{\Delta \tau} X(t) \, dt,$$  \hspace{1cm} (4.1)

where the onset of the laser pulse is at time $t = 0$. The value $I_x(\Delta \tau)$ has been evaluated for both the front and rear XRD signals obtained in x-ray measurements for the laser irradiation of two aluminum targets, and the results are presented in Figure 4-6. Results for the irradiation of a 25 \, \mu m thick aluminum target are presented in 4-6(a), and results for a 34 \, \mu m target are presented in 4-6(b).

For time-integrated measurements with $\Delta \tau \geq \tau_s$, the time of shock transit through the foil, the x-ray measurement at target rear side becomes dominated by enhanced transmission following shock breakout. This observation is true for all foil thicknesses used in the time-resolved XRD measurements, and we suggest that the results will also hold true for the thicker and denser targets used in the earlier experiments using the PIN diodes. It was not possible for us to observe x-rays through such targets employed in the PIN measurements, as the XRD sensitivity was much lower than that of the PIN diodes. Although the XRD signal ratios
- Figure 4-6 Time-Integrated XRD Signals. These data are for 25 \( \mu \text{m} \) (a) and 34 \( \mu \text{m} \) (b) aluminum foil thicknesses. The data in (a) are derived from the signals in Figure 3-9. \( \tau_s \) is the moment of shock breakout.
cannot be directly compared with the PIN measurements, which were intrinsically time-integrated, it should be noted from Figure 4-6 (a) and (b) that the rear-to-front ratios of the integrated signals decrease with increasing target thickness. The ratio for targets of 50 \( \mu \text{m} \) thickness at an irradiance of \( 2 \times 10^{13} \, \text{W/cm}^2 \) is seen to be 2 ~ 3, that for 34 \( \mu \text{m} \) is 4 ~ 6, and that for 25 \( \mu \text{m} \) is 10 ~ 20. Thus, the time-integrated XRD results are qualitatively consistent with the PIN diode data described in section 4.2.1.

We also note that the time-resolved back-to-front signal ratio at the moment of shock breakout is generally greater than one; this ratio was examined in detail for all of our measurements. Results from multiple shots on aluminum foils of identical thickness were averaged together to produce the data shown in Figures 4-7 and 4-8. Figure 4-7 shows the results obtained using a slightly defocussed laser beam and using target rear surface emission measurements as shock diagnostics (as described in section 3.5.1). Figure 4-8 shows the results obtained using rear surface reflectivity measurements as shock diagnostics (as described in section 3.5.2). In each case, the front-side x-ray signal plotted corresponds to the peak of the signal trace. The peak of the back-side signal is distorted by the expansion of the foil, so that the value plotted for the backside x-ray signal is the rear-to-front x-ray signal ratio at shock breakout multiplied by the frontside peak x-ray signal. This yields the normalized backside x-ray signals which can be compared with the frontside data and the calculated transmission at the same time.

The peak of the signal from the XRD for each shot was divided by the square of the signal from the Gentec laser energy monitor, in order to reduce x-ray signal variation due to shot-to-shot variations in laser pulse energy. The calorimeter results indicated a power scaling law of 1.4 for x-rays observed through B-10 filters (Figure 4-1) whereas the PIN diode signals (Figure 4-2) show a much stronger scaling with
Figure 4-7 Full-Irradiance XRD Signals. Points are x-ray signals observed at target rearside, and at target frontside through filters identical to the target material. Circles are frontside data, and squares are back-side data. The solid curves are predictions for shocked aluminum and the dashed curves are predictions for normal aluminum, with $f_t$ the percentage of x-ray power in the $He_{\alpha}$ and $IC$ lines and $\sigma$ the opacity.

the absorbed irradiance for x-rays observed through very thick aluminum filters. We assumed a quadratic scaling law simply as a compromise.

The point corresponding to zero target thickness, which was set to a value of 100 for normalization, was obtained by observing the x-rays emitted by an aluminum target foil of 25 $\mu$m thickness with only a B-10 entrance window on the front-side detector. In order to avoid the high signal levels involved in such a measurement the detector was removed to a more distant point, 24.2 cm from the target, and
Figure 4-8 Reduced-Irradiance XRD Signals. The data are similar to those in Figure 4-7, but are for the luminous emission shock diagnostic, and were obtained with a reduced laser irradiance.

The signal was scaled for this change of distance using the inverse square law. The point at 1.35 mg/cm² was obtained by observing x-ray emission from the same thick target through a 5 μm aluminum entrance window (in addition to the B-10). All other points were obtained with targets identical to the frontside XRD filters.

The curves in these figures were produced by the computer program in Appendix A using the indicated percentage $f_i$ of x-ray power in the He$\alpha$ and IC lines and the indicated mass absorption coefficients $\frac{\sigma}{\rho}$ for these lines. It is clear that the frontside x-ray signals in Figures 4-7 and 4-8 (indicated by the circles) agree well with the predictions based on the continuum spectrum calculated by Duston et al.
The simulations by Duston et al\textsuperscript{1} predict $f_i \approx 11\%$, but a range of values has been used in our calculations to assess its effect on the predicted x-ray transmission. The value of $\frac{\mu}{\rho} = 4200 \text{ cm}^2/\text{g}$ is obtained from reference 8 for ordinary aluminum. The values of $\frac{\mu}{\rho}$ for the solid curves shown are simply chosen to indicate the range which yields reasonable agreement with the backside data (indicated by the squares). The calculations performed using the program in Appendix A have been discussed in Chapter 3, and the lowering of $\frac{\mu}{\rho}$ for these lines has been discussed in Chapter 2.

As well, the back-to-front ratios of the x-ray signals for the two irradiation conditions and different shock diagnostics are presented in Figure 4-9. For each foil thickness the data represents an average over five or more measurements, and the statistical uncertainty in the mean is indicated by the error bar. Figure 4-9(a) shows results of measurements made at reduced irradiance and using the rear surface emission measurements as the shock diagnostic. Figure 4-9(b) shows results of measurements made using rear surface reflectivity as the shock diagnostic.

The curves in Figure 4-9 were calculated using the program in Appendix A, assuming 10\% of the x-ray power resided in the He\textsubscript{a} and intercombination lines and with the calculated x-ray continuum spectrum of Duston et. al, as discussed in Chapter 3. The mass absorption coefficients taken for the lines were 530 mg/cm\textsuperscript{2} for Figure 4-9(a) and 460 mg/cm\textsuperscript{2} for Figure 4-9(b). These values are chosen simply to present curves which visually fit the data, and are not statistically fitted. It appears that the signal ratios measured for the case of lower laser irradiance are lower than those found with the target at the best focus of the incident laser beam.

### 4.2.3 Magnesium Experiments

Having noted the consistency between the K-edge shift model of the opacity of the shock-compressed aluminum and the experimental results, we wished to extend
We irradiated several 25 μm magnesium targets using the laser beam at best focus and using target rear surface reflectivity measurements as shock diagnostics. This was the only available magnesium foil which was thick enough that a shock wave would develop, but thin enough that the signal-to-noise ratio in the XRD measurements was not overly high. It was difficult to produce a high-quality reflecting surface on the magnesium foils, but a suitable surface was achieved.
Chapter 4: Experimental Results

For this one foil thickness the mean shock arrival time was \( (T_s) = -1.01 \pm 0.03 \text{ ns} \) with time zero corresponding to the time of peak laser intensity. Averaging the ratios of the instantaneous backside-to-frontside x-ray signals at shock breakout for each shot, we obtain a mean ratio of \( \langle R \rangle = 7.3 \pm 0.4 \). The ratio is clearly greater than the ratios measured for any of the aluminum targets at the same irradiance. The x-ray pulse signals observed at the front and at the back of the magnesium target were otherwise qualitatively the same as those for aluminum.

4.2.4 Copper-Coated Aluminum Experiments.

To determine whether the observed ratio was due to a general lowering of the L-shell x-ray absorption cross-section or due to a shift of the K-edge, we employed a layer of copper evaporated onto our aluminum targets as a source of strong x-ray radiation in a wide spectral band below the aluminum K-edge. The experimental facilities and procedures were otherwise similar to those used for the measurements on the pure aluminum targets described in section 4.2.3.

All aluminum foils used in the copper-coated target measurements were of 25 \( \mu \text{m} \) thickness and had been polished on the rear surface to facilitate reflectivity measurements. Only the reflectivity shock diagnostic was employed in this experiment. The front surface of the aluminum was cleaned and coated with the evaporated copper. The cleaning process was found to be necessary in order to ensure proper bonding of the copper layer to the aluminum substrate. It involved the use of a commercially available aluminum cleanser\(^{54}\), which might result in reduction of the foil thickness. All foils were therefore put through this cleaning process, including the uncoated targets which were irradiated as control targets and the aluminum filters which were used as the entrance window of the front-side XRD. The thickness of the aluminum substrates was checked following the polishing and cleaning processes, and this thickness was found to be 24 \( \pm 1 \mu \text{m} \). The thickness
of the evaporated copper layer was determined by the use of a deposition thickness probe in the evaporation chamber.

The photograph in Figure 4-10 is an oscilloscope trace of an x-ray signal obtained from the frontside XRD, for a copper layer thickness of 0.2 \( \mu m \). The ablation of the copper layer on the target frontside distorted the x-ray emission pulse shape. The x-ray emission showed two peaks. The first peak corresponded to emission from the copper layer and the second peak corresponded to emission from the aluminum substrate at the peak of the laser irradiance. As the copper coating thickness was increased the first peak lengthened in time and grew in amplitude until it merged with the second peak, yielding only one large peak for the thickest copper layers. This peak was at the position of the peak observed for irradiation of solid copper targets, which is \( \sim 200 \text{ ps} \) after the centre of the photograph in Figure 4-10.

- Figure 4-10 Frontside X-Ray Signal for a Copper-Coated Aluminum Target. This is example of the distorted x-ray pulse shape observed on the front side of copper-coated aluminum targets. The copper layer thickness for this shot was 0.2 \( \mu m \).
In order to determine the timing of the x-ray signals relative to the laser pulse peak, we fired several shots on a target of solid copper and noted where the peak occurred on the oscilloscope screen. As the oscilloscope was triggered by the 0.532 \( \mu m \) laser light, it was found that the position of the peak on the screen was reasonably stable—within \( \pm 100 \text{ ps} \). Again, the location on the oscilloscope screen of the front-side peaks observed for solid copper was assumed to be coincident with the peak of the laser pulse, and was used as our time zero. The method of using the peak of the frontside x-ray signal peak for each shot as the time zero is clearly preferable, but is only applicable to uncoated target shots.

It was suggested that the copper plasma might emit strongly at photon energies of roughly 9 keV, due to K-shell x-ray processes. In order to verify that there was no high-energy x-ray component in the x-ray spectrum, a few shots were performed with a copper layer on the frontside XRD aluminum filter, and a copper layer thickness of 1.0 \( \mu m \) on the target. The additional attenuation factor of 10 for 0.5 \( \mu m \) copper and 80 for 1.0 \( \mu m \) copper on the aluminum filter was consistent with the assumption that the x-rays which we observed penetrating the aluminum filters were between photon energies of 1.2 keV and 1.5 keV. Clearly, less than one percent of the observed signal is due to copper K-shell x-rays.

As in the case of the aluminum experiments in section 4.2.3 the signals were normalized to the square of the laser energy, reducing the effects of shot-to-shot variations in the laser pulse energy. Figure 4-11 shows the XRD frontside signal (the squares) and the XRD backside signal (the circles) at the time of shock breakout. The frontside x-rays were attenuated by a filter identical to the aluminum substrate in the layered target, and both XRDs had B-10 entrance windows. For each copper layer thickness, the data points represent the average of five or more measurements, and the uncertainties in the sample means are indicated by the error bars. The curves in Figure 4-11 are not fitted analytic functions, but are simply smooth lines following the general features of the two sets of data points. Clearly, the backside
x-ray signals are greater than the frontside signals in these measurements. The frontside signals level off to a limiting value as the copper thickness approaches 0.8 μm thickness. The back-side signal also levels off near copper layer thicknesses of 1.0 μm, but then decreases for copper thicknesses greater than ~ 1.4 μm.

Figure 4-12 shows the averages of the ratios of the signals from the backside to front-side XRDs at the time of shock breakout, for various copper layer thicknesses. We collected the data from measurements made in three separate days, and shots from each day covered points ranging over a broad range of copper coating thicknesses including the dip at 0.3 ~ 0.7 μm.

The ratio rapidly drops as copper is added to the bare aluminum target (indicated by zero coating thickness) and the copper x-ray signals dominate the aluminum x-ray signals. The region of interest is that for which effectively all of the signal is due to copper x-rays, but the unablated copper layer is insufficient to significantly affect the x-ray transmission through the target. This occurs when the copper layer thickness is about equal to that which would be ablated at the time of shock breakout. According to 1-dimensional simulations\textsuperscript{26} this corresponds to copper thicknesses in the range of ~ 0.4 μm up to ~ 0.6 μm, and the back/front signal ratio in this region is 1.3 ~ 1.5.
**Figure 4-11** X-Ray Signals for Copper-Coated Aluminum Targets. Circles are signals from the XRD behind the coated target. Squares are signals from the XRD in front of the target, with a filter identical to the aluminum substrate.
Figure 4-12 Back/Front X-Ray Signal Ratio for Copper-Coated Aluminum Targets. 

These are the averages of the back/front x-ray signal ratios for the copper-coated aluminum targets. The frontside has a filter identical to the aluminum target substrate.
5.1 X-Ray Production

Conversion of laser energy into x-ray energy has been studied elsewhere;\textsuperscript{27,30} the conversion efficiency depends on the x-ray photon energy range being considered. The B-10 foil which we used had a 1/e cut-off energy of \( \sim 800 \text{ eV} \). This is the x-ray transmission band which we are considering in the x-ray energy emission measurements of Figure 4-1.

The strong x-ray radiation from the recombination of aluminum ions to lithium-like states above the L-shell recombination edge (at 440 eV helium-like ions) does not penetrate the filter well. As is evident from Figure 2-3, the radiation at energies over 1500 eV is not energetically important\textsuperscript{1}. There is also a gap in the aluminum emission spectrum below this energy of 1500 eV. Clearly, the aluminum emission spectrum is poorly matched to the transmission band of the B-10 filter, and this results in aluminum being the weakest source of x-ray emission shown in Figure 4-1.

The copper edge energy for recombination to the sodium-like state is \( \sim 660 \text{ eV} \), while the many available valence orbitals will result in a high cross-section for this recombination\textsuperscript{7}. Thus, there will be strong emission at photon energies
above this level, which is well matched to the transmission characteristics of the B-10 foil. In addition, the neon-like state has a 3S–2P transition producing \( \sim 1000 \text{eV} \) photons, and higher ionization states should yield similar 3S–2P line energies. Spectroscopic measurements of x-rays from exploding-wire plasmas have revealed the presence of a large number of energetically important lines in the x-ray emission spectrum over 1000 eV, including the 3S–2P lines from neon-like and sodium-like copper. All of these lines would be almost entirely transmitted by the B-10 filter. Indeed, copper is a much more powerful source of x-rays in the B-10 transmission band than either aluminum or molybdenum (as seen in Figure 4-1).

The molybdenum M-shell absorption edge energy is 228 eV, and we would expect to see recombination radiation from molybdenum at energies above this. For high ionization states in molybdenum, \( Z \geq 7 \), the recombination edge energy will shift upward. As the absorbed laser irradiance increases, the average ionization of the molybdenum will increase to a point where the M-shell recombination energy is roughly equal to or greater than the electron thermal energy, and the plasma will emit x-rays above this energy. We would observe this as a radiation edge near or above 400 eV for our laser-produced plasmas, near the aluminum lithium-like recombination edge energy mentioned above. Thus, the molybdenum M-shell recombination radiation will similarly fail to penetrate the B-10 filter well. On comparing the emissions of the materials as shown in Figure 4-1, we see that the molybdenum x-ray emission observed is less than the copper emission, but that it is greater than that of aluminum. This is understandable, as the molybdenum plasma may be collisionally excited to an ionization state having a higher recombination energy, one which is better matched to the B-10 transmission characteristics than the recombination energy of the helium-like aluminum ions.

For the aluminum measurements, a more quantitative comparison can be made with theoretical calculations. If the angular distribution of the emission on target frontside is isotropic, the total radiated x-ray energy detected through
Chapter 5: Interpretation of Results

a B-10 filter would be the measured energy per steradian multiplied by $2\pi$. For a Lambertian distribution, where the intensity is proportional to the cosine of the angle between the line of observation and the target normal, the total radiated x-ray energy detected through a B-10 filter would be the measured energy per steradian multiplied by $\pi$. As the calculations in reference 1 were performed in only one dimension, without accounting for the x-ray emission in the radial direction, it is not clear which angular distribution the calculations should be compared with. Using the x-ray continuum and line emission spectrum of Duston et al.1 in the program in Appendix A, we find that the overall energy transmission through a B-10 filter will be $20 \sim 25\%$. Thus, the total x-ray energy emitted by the laser-produced plasma will be $4 \sim 5$ times what is indicated in Figure 4-1, for this spectrum. The highest x-ray conversion efficiency which we could infer from Figure 4-1 would be $\sim 5 \times 2\pi \times 1.45\text{mJ}/0.56\text{J}$ at an absorbed irradiance of $10^{13} \text{W/cm}^2$, or $\sim 8\%$, assuming an isotropic angular distribution of the x-ray emission. This is less than the 26.4% conversion predicted by Duston et al for an absorbed irradiance of $10^{13} \text{W/cm}^2$ of 1.06 m laser light. We have no similar calculations to compare with the copper and molybdenum measurements.

5.2 X-Ray Transmission Following Shock Breakout

In Figure 4-2 we note that the x-ray signals detected directly behind the targets are greater than the signals detected at some angle away from target normal. This feature may be explained by the fact that the detector at an angle is looking through a greater thickness of target material when observing the x-rays emitted by the hot plasma on the target front-side. The factor of increase in thickness will be equal to the secant of the angle of observation, and $\sec(35)\degree = 1.22$. Thus, in
order to explain the attenuation factor of ~ 4 times at an angle of 35° relative to x-rays penetrating straight through the target, we require

\[ e^{-\left[\sec(35°) - 1\right]\frac{\sigma}{\rho}d} \approx \frac{1}{4}, \]  

which means that we require

\[ 1.4 \approx \left[\sec(35°) - 1\right]\frac{\sigma}{\rho}d \]

\[ \approx 0.22\frac{\sigma}{\rho}d, \]  

For the various target areal densities stated above, this corresponds to opacities \( \frac{\sigma}{\rho} \) which are of the order of the minimum opacities of the target materials in the keV photon energy range\(^{28} \). It is at these minima of \( \frac{\sigma}{\rho} \) that we get the greatest x-ray transmission through thick foils. Thus, the decrease in the x-ray signal observed at a line of sight 35° from target normal is roughly equal to the extra attenuation for the x-rays which we would expect to shine through the target.

Measurable signals were observed from the aluminum and copper targets through the respective aluminum and copper filters which were identical to the targets, as shown in Figure 4-3. There was no x-ray signal detected from the molybdenum target through an identical molybdenum filter. This is because the areal density of the molybdenum targets was 25.6 mg/cm\(^2\), much higher than that of the copper (17.9 mg/cm\(^2\)) or aluminum (13.5 mg/cm\(^2\)). The transmissions of the x-rays from the laser-produced plasmas on the various targets through the various filters are clearly different.

It is clear from comparison of Figures 4-2 and 4-3 that the irradiated targets allow a greater transmission of x-rays than an equivalent unperturbed filter. As the backside x-ray signal increases more rapidly with absorbed irradiance than the frontside signal (Figures 4-2 and 4-3 respectively) the ratio of x-ray transmission
Chapter 5: Interpretation of Results

through an irradiated target to that through the equivalent cold filter also increases with laser irradiance.

Such enhanced x-ray transmission through the irradiated target is also found in the time-resolved measurements made using the XRDs. As discussed earlier, to allow a comparison of the XRD and PIN results, we have plotted the time-integrated XRD signal as a function of the integration time in Figure 4-6. Note the high back/front time-integrated signal ratios associated with the XRD measurements on the aluminum foils of 25 and 34 $\mu$m thickness (Figures 4-6(a) and 4-6(b) respectively) and the decrease of this ratio as we move to thicker targets. It is also clear from Figure 4-6 that the back/front time-integrated signal ratio is much lower when the integration is performed up to the time of shock breakout than when it is performed for the entire x-ray pulse. This observation is true for all foil thicknesses used in the time-resolved XRD measurements, and it is reasonable to suggest that it will also hold true for the thicker and denser targets used in the time-integrated PIN diode experiments. Thus, the high back/front x-ray signal ratios observed from the PIN measurements would be largely due to the increased transmission of x-rays through the target following shock breakout.

This observed enhanced x-ray transmission can be attributed to target rarefaction due to the release of the target rear side material by the shock wave. It has been observed that the target expands outwards into the surrounding vacuum following shock breakout, allowing transmission of laser light and possible transmission of x-rays. Thus, the greater part of the x-ray signal which we detect behind the foil may arise from x-rays penetrating the target after shock breakout, as the effective foil areal density decreases.

Examining earlier experimental data on the transmission of the incident laser light through the target, we note that the average density of the target material drops below the critical density of the 0.532 $\mu$m laser light shortly after shock
breakout. This has been explained as an effect of the radial and axial expansion of the target material into the surrounding vacuum, or 2D rarefaction of the foil\textsuperscript{25}.

Purely axial expansion of the foil into the vacuum behind the target would result in a lowering of the average material density \( \langle \rho \rangle = \rho_0 / X(t) \), where \( \rho_0 \) is the initial target material density and \( t \) is time. \( X(t) \) is the axial average expansion factor, which is assumed to be some simple function of time. The average areal density \( \langle d \rangle \) will remain equal to its initial value \( \rho_0 d_0 \), since conservation of mass implies conservation of areal density in the absence of any radial expansion. Thus, we also have \( \langle d \rangle = d_0 X(t) \). When we combine radial expansion with axial expansion the areal density is no longer conserved. Such 2D rarefaction would lead to the greater density change

\[
\rho \approx \frac{\rho_0}{X(t)} \left[ \frac{1}{\kappa X(t)} \right]^2,
\]

but we would still have \( \langle d \rangle = d_0 X(t) \). \( X(t) \) is again the axial average expansion factor and we assume that the radial average expansion factor can be expressed as a constant multiple \( \kappa \) of \( X(t) \).

Note in reference \textsuperscript{25} that the material from the target backside detected far from the target is ejected in a cone \( \sim 30^\circ \) from the target perpendicular, so that the assumption appears valid with \( \kappa \approx 0.5 \). Purely axial expansion will have no effect on the attenuation of the x-rays power penetrating the foil, assuming that the mass absorption coefficient remains constant. Given that the mass density at the critical electron density required for laser transmission through the target is \( \rho_c \) and assuming an aluminum plasma with an average ionization of \( \langle Z \rangle \approx 4 \), we find \( \frac{\rho_c}{\rho_0} \approx 0.016 \). Taking \( \langle \rho \rangle = \rho_c \), we find that the value of \( X \) corresponding to \( \langle \rho \rangle = \rho_c \) will be given by

\[
X \approx \left[ \frac{\rho_0 \kappa^2}{\rho_c} \right]^{1/3}
\]

\( \approx 6.3 \),
Chapter 5: Interpretation of Results

The factor which affects x-ray attenuation will be the average value of the areal density, \( \langle \rho d \rangle \), and the value of \( \langle \rho d \rangle \) corresponding to \( X \approx 6.3 \) will be

\[
\langle \rho d \rangle \approx \frac{\rho_0}{X(t)} \left[ \frac{1}{\kappa X(t)} \right]^2 d_0 X(t)
\]

\[
= 0.1\rho_0 d_0.
\]

Accordingly, the x-rays will be attenuated by roughly a factor of ten less material at the time that the laser light begins to penetrate the target.

Since laser light transmission occurs during the laser pulse, it is clear that the target will thin out sufficiently to allow greatly enhanced x-ray transmission at times while there is still a significant x-ray source on the target front-side. From Figure 3-13, we would expect to have a time-resolved, back-to-front x-ray signal ratio of roughly 100 for a thickness decrease of roughly 10-fold. Such a ratio is seen at a time roughly one nanosecond after the peak of the front-side x-ray signal in Figure 5-1(b), in rough agreement with the onset of laser-light transmission observed in reference 25.

The late-time transmission enhancement factor for the 34 \( \mu m \) targets (Figure 5-2(b)) is not as great as would be expected from our rough analysis of the target breakup. The shock breakout will occur at later times for these thicker targets, as seen in Figure 4-4. The front-side plasma will also be cooler at these times, so that the x-ray emission spectrum of the plasma will not necessarily yield the same enhancement factor as expected on the basis of Figure 3-13.

5.3 X-Ray Transmission Through the Shocked Targets

As shown in Figure 4-6(a) and (b), enhanced x-ray transmission was observed prior to shock breakout. However, the model of 2D rarefaction presented above
- Figure 5-1 XRD Measurements for a 25 μm aluminum target.

(a) Frontside x-ray signal. The circles correspond to data shown in Figure 3-9(a). The solid line is a fitted Gaussian profile. (b) Back-to-front x-ray signal ratio. The circles correspond to data derived from Figure 3-9(a) and (b). The solid line represents a model calculation.
Figure 5-2 XRD measurements for a 34 μm aluminum target. (a) Frontside x-ray signal. The circles correspond to data also used to produce Figure 4-6(b). The solid line is a fitted Gaussian profile. (b) Back-to-front x-ray signal ratio. The circles correspond to ratios derived from the same data. The solid line represents a model calculation.
does not apply to these earlier times. Now, we shall address the instantaneous enhanced x-ray transmission detected by the XRD through the irradiated target at the time of shock breakout, as presented in Figures 4-7, 4-8 and 4-9. We will consider various processes which may increase x-ray transmission before the time of shock breakout. Three possible effects are discussed below in sections 5.3.1, 5.3.2, and 5.3.3. Section 5.3.4 examines the effects which the finite temporal resolution of the XRD might have on the observation, and section 5.3.5 is a detailed study of the copper/aluminum layered-target experiments for clarification of the uncoated aluminum target results.

5.3.1 Ablation and Hydrodynamic Effects

Firstly, let us consider the ablation of the aluminum target material. It has been determined from computer simulations that the aluminum ablation depth for our irradiation conditions will be $2 \sim 3 \, \mu\text{m}$ at the end of the laser pulse, or $1 \sim 2 \, \mu\text{m}$ at the time of shock shock breakout$^{26}$. This reduction in the thickness of the irradiated target will increase the x-ray transmission by $\leq 20\%$, which is small compared with the observed enhanced transmission in Figure 4-9. Conversely, the XRD on the target rear side observes the foil at an angle of $18^\circ$ from the target normal. The foil thickness along the line-of-sight of the detector is thus greater than the target material thickness by a factor equal to the secant of the angle of observation, or 5% greater thickness. For the 20 to $34 \, \mu\text{m}$ targets used in our experiments this extra 5% will be approximately equal to the ablation depth. Since the filter on the frontside XRD is identical to the unperturbed aluminum target and is perpendicular to the line-of-sight of the detector, the total filter material thickness viewed by the front and rear XRDs will be approximately the same. In Figures 4-7 and 4-8 we have simply ignored the combined effects of ablation and parallax.
Chapter 5: Interpretation of Results

An effect which is similar to ablation is the deformation and radial expansion of the target material prior to shock breakout, similar to that which is observed to occur following shock breakout. As the shock wave propagates through the irradiated target, the compressed aluminum would expand into the surrounding uncompressed material, driving a pressure wave radially outward inside the target.

Furthermore, there may be small local regions of high intensity in the focussed laser beam, or hot spots. The ablation pressure in a hot spot would be greater than the ablation pressure of the surrounding region, as ablation pressure scales with the irradiance to the power 0.84. This high local pressure would cause sharp radial pressure gradients in the material of the target, which might result in spherical pressure waves being driven into the target from the hot spot. These spherical pressure waves would induce radial flow within the target, reducing the average areal density \( \langle \rho d \rangle \) in the region of the laser focal spot prior to shock breakout. On the other hand, the mass ablation rate (and hence the ablation depth) scale with irradiance to the power 0.55. We have already noted that the ablation depth is small relative to the target thickness, and it would not increase greatly in a hot spot. However, the greater ablation in a hot spot would still contribute to the enhancement of the x-ray transmission.

We must consider whether or not the required thinning of the target due to shock hydrodynamic effects and increased ablation in hot spots is greater than could reasonably be expected. The radial pressure wave front will not propagate faster than the shock front which we observe reaching the foil back-side, as both of the waves will be driven by the same pressure within the shocked material. From Figure 3-13, we must have \( \langle \rho d \rangle \approx 0.6\rho_0 d_0 \) (where \( \rho_0 d_0 \) is the areal density of the unperturbed foil) in order to produce the observed enhanced transmission. Ablation effects will not contribute significantly to this. If we assume that the entire shocked region expands uniformly, this requires that the area of the material within the compressed region increases by a factor of \( \sim 1.7 \). Thus, it requires that the
material within this region expands to a radius ~ 30% greater than its initial value of ~ 20 μm in the time required for the shock to travel to the foil rear surface, over a distance of the order of 20 μm or more, the thickness of the target. Clearly, the radial motion required would only have to be 30% as fast as the axial shock wave in order for the resultant foil thinning to produce the enhanced transmission presented in Figure 4-11, and this is not at first sight unreasonable.

However, a radial expansion would weaken the shock wave as some of the absorbed laser energy went into the radial compression of the aluminum around the laser focal spot. This weakening would be greatest at the edges of the spot, where the radial pressure gradients are greatest, and the shock would first reach the rear surface of the target at the centre of the spot. Experimental studies of the breakout of the shock wave at the back of the target\(^{44}\) indicate that the shock wave reaches the rear surface simultaneously over the entire 40 μm spot area, at a speed consistent with one-dimensional hydrodynamic simulations for the absorbed laser irradiance\(^{26}\). These results are seen to be inconsistent with hot spots in the laser irradiation pattern or with two-dimensional flow within the target material prior to shock breakout.

### 5.3.2 L-Shell and K-Shell Opacity Lowering

It is to be expected that the ionization of the aluminum within the compressed region will produce some drop in the x-ray absorption cross-section by simply decreasing the total number of atomic electrons to be photoionized\(^{9}\). Above the K-edge the K-shell photo-ionization cross-section is more important, being roughly 13 times greater than the L-shell photo-ionization cross-section\(^{8}\). As we expect no significant K-shell ionization in the shocked target at temperatures of only 1 ~ 1.5 eV, ionization in the target will only affect transmission of those aluminum x-rays which
are below the K-edge and will not result in enhancement of x-ray transmission for photon energies above the K-edge.

Given that an ionization of approximately four is achieved in the shock compressed aluminum in this experiment the aluminum atoms would have seven L-shell electrons rather than the eight present in normal aluminum. The consequent lowering of the atomic L-shell cross-section may lead to increased x-ray transmission below the K-edge.

However, if such a L-shell opacity lowering effect were dominant, it would also give rise to strongly enhanced transmission of copper x-rays through the shocked aluminum substrate in the layered target experiments. As we will see in section 5.3.5, the observed enhanced transmission of the copper x-rays is much too low to corroborate the effect of L-shell opacity lowering.

5.3.3 K-Edge Shift

The model of primary interest is one which involves the shift of the K-edge to higher energies, allowing the strongly-emitting He\textsubscript{α} and IC lines to penetrate the foil and be detected as enhanced transmission of x-rays through the foil. This model has been discussed earlier in some detail in section 2.3, and its agreement with the experimental results is shown in Figures 4-7 and 4-8.

The curves in these Figures were calculated using the computer program discussed in Appendix B; the differences between the various curves are the percentages of x-ray power assumed to be radiated in the He\textsubscript{α} and IC lines, and the opacity of aluminum for these lines. We find that the attenuation of the frontside x-ray signal due to increased aluminum foil thickness closely follows that which would be expected on the basis of the spectrum published by Duston et. al. The attenuation of the target back-side signal by increasing the target thickness is well approximated
by calculations using line opacities much lower than that for normal aluminum. In Figures 4-7 and 4-8, the line opacities $\frac{\sigma}{\rho}$ indicated for the upper and lower limits of the curves which fit the backside data points are close to the opacity just below the aluminum K-edge.

Let us assume a K-edge shift to photon energies above the He\(\alpha\) and IC lines for an atom of ionization state 4, and assume that the foil contains no atoms remaining in an ionization state of 3. On the basis of an L-shell mass absorption coefficient \(^\text{8}\) (just below the aluminum K-edge) of $\frac{\sigma}{\rho} \approx 300 \ \text{cm}^2/\text{g}$ we would expect to observe higher back/front x-ray signal ratios than we actually observed in Figures 4-9(a) 4-9(b), and a lower rate of attenuation with increasing target thickness than we actually found in Figures 4-7 and 4-8. On the other hand, if a small percentage of the aluminum atoms in the shock-compressed foil were to remain in an ionization state of 3, they would increase the overall mass absorption coefficient for the He\(\alpha\) and IC lines in the shocked material. The simplest approach to this scenario is to assume a weighted average of the two mass absorption coefficients, resulting in an absorption coefficient for the shock-compressed material of

$$\frac{\sigma}{\rho} \approx 300(1 - W_3) + 4200W_3 \ \text{cm}^2/\text{g}, \quad (5.6)$$

with $W_3$ being the fraction of the aluminum atoms which are triply ionized, and 4200 cm\(^2\)/g being the mass absorption coefficient just above the unshifted K-edge. We see in Figures 4-7 and 4-8 that the mass absorption coefficients which match our observations well are given by values of $W_3$ on the order of a few percent.

The ionization predicted for shocked aluminum\(^\text{22}\) as shown in Figure 2-8 gives $W \approx 30\%$, but the effects of radiation heating have not been included in those calculations. Such heating might lower $W$ to a few percent. There are no other experimental results or calculations which invalidate the model of K-edge shift in shock-compressed aluminum as a plausible explanation of our experimental results.
The observations described in section 4.2.3 are evidently consistent with the model of the K-edge energy shifting to photon energies higher than the He\textsubscript{a} and IC line energies, allowing these x-ray lines to be transmitted through the target at the time of the shock arrival at the rear surface.

A similar effect is observed in the irradiation of magnesium foils of 25 μm thickness, as described in section 4.2.4. Generally, we would expect to see such an effect whenever a major x-ray absorption edge in a material shifted from energies lower than that of a strongly emitting line to energies greater than that of the line. For magnesium, the He\textsubscript{a} and IC lines are at \(\sim 1.35 \text{ keV}\), while the absorption K-edge is at 1.305 keV. Thus, the required shift in the K-edge energy would be \(\sim 50 \text{ eV}\). The significance of this effect on x-ray transmission through the irradiated target will depend on the strength of the line or lines transmitted following the edge shift, relative to the overall strength of the continuum radiation which is transmitted through the target regardless of its state.

The back/front x-ray signal ratio is best examined in Figure 4-9, where we note that the ratio is approximately constant for the two laser irradiances, with some random scatter of the data points. The ratios seen using the defocussed laser beam appear lower than those found with the target at the best focus of the incident laser beam. However, it is found in Figure 4-4 that the shock breakout time determined from rear surface emission measurements lags behind that obtained from rear surface reflectivity measurements by \(\sim 400 \text{ ps}\). Although the shock compression ratio scales weakly with the laser irradiance, variations in the timing of the shock breakout might greatly affect the observed signal ratio, as evident from Figures 5-1 and 5-2. Hence, we question whether the difference in the back-to-front x-ray signal ratios results from this timing difference rather than any difference in the conditions of the compressed aluminum. The timing difference argument, however, would lead us to expect a lower ratio for the full irradiance shots where
reflectivity measurements were used as a shock diagnostic. This is because of the observed earlier shock breakout time (~ 400 ps earlier).

5.3.4 Effect of Finite Temporal Response of the XRD

If the observed enhanced x-ray transmission were due to the shifting of the aluminum K-shell absorption edge under shock compression, one would expect the rearside XRD signal to show a fast turn-on at the time of shock breakout. The rise-time \( \tau \) of the signal should correspond to \( \lambda_z/u_s \), where \( \lambda_z \) is the mean free path length of the He\( \alpha \) and IC line radiation photons in the unperturbed aluminum ahead of the shock front and \( u_s \) is the shock propagation speed.

Given that \( u_s = 1.5 \times 10^6 \text{ cm/s} \) and that the aluminum opacity to these lines is \( \sigma/\rho = 4200 \text{ cm}^2/\text{g} \), we have

\[
\tau = \lambda_z/u_s = \frac{1}{\sigma/\rho u_s} \approx 59 \text{ ps}. \tag{5.7}
\]

If we normalize the x-ray signal to a value of one for the x-rays whose transmission through the foil is unaffected by the shock, then the x-ray signal at the time of shock breakout will be \( T_s \geq 1 \), with a contribution \( T_s - 1 \) due to the He\( \alpha \) and IC line radiation. Given the value for \( \tau \) above, the normalized x-ray signal \( T(t) \) at any time \( t \) before shock breakout will be given by

\[
T(t) \approx 1 + (T_s - 1)e^{(t-t_s)/\tau}, \tag{5.8}
\]

where \( t \) is the time and \( t_s \) is the time of shock breakout. This provides a model for the temporal increase in the enhanced x-ray transmission through the target prior to shock breakout. However, such a fast on-set will be modified by the finite temporal response of the XRD.
The computer program used to model this effect is given in Appendix B. It was used to produce the curves in Figures 5-1 and 5-2. Note that the experimental frontside signals indicated by the open circles in Figures 5-1 (a) and 5-2 (a) are well approximated by normalized Gaussian curves. These curves are fitted not by using a least-squares method, but by assuming a Gaussian shape for the experimental data and setting the same FWHM.

In calculating the back/front signal ratios (Figures 5-1(b) and 5-2(b)), x-ray transmission through the target for times prior to shock breakout was based on the K-shift model presented in section 2-3, assuming a sharp reduction in the mass absorption coefficient for the He\textsubscript{a} and intercombination lines across the shock front. The late-time transmission used was not a theoretically derived function, but was simply constructed to make the prediction of the detected signal ratios at late times fit the experimental results. It was found that the x-ray transmission through the target rose in an approximately exponential manner with time, up to some limiting back/front signal ratio. A function of this form was therefore used, with the time constant and the limiting value varied until the calculations provided a reasonable approximation to the data at late times. This can be clearly seen in the program listing in Appendix B.

The two interesting regions of the Figures are therefore the moment of shock breakout, and the period prior to shock breakout during which the observed back/front signal ratio is rising. Given the temporal response of our detection system, it is clear that the initial rise time of the detected signal is slower than would be expected. It was also found that the calculated x-ray signal ratio at the time of shock breakout was approximately 10% lower than the idealized ratio initially assumed in the calculations. Thus, the finite response time of the XRDs would appear to yield a signal ratio at shock breakout which is 10% lower than that of an ideal detector. This has not been taken into account in Chapter 4, because the onset of the measured x-ray signal in 5-1(b) and 5-2(b) appears to occur earlier
than would be expected on the basis of the theoretical model. It may be that the assumption that the mass absorption coefficient changes sharply across the shock front is not entirely valid.

The shots indicated in Figure 5-1 and 5-2 are the only ones for which such a detailed analysis was performed.

5.3.5 Copper-Aluminum Layered Target Experiment

Direct, temporally-resolved spectroscopic observations of the shift of the aluminum K-edge to higher energies have not been made. On the other hand, an indirect way to distinguish experimentally between the effects of the K-edge shift and the effects of L-shell opacity lowering or foil thinning is by means of measurements using copper as an ablation layer on the aluminum target. The copper acts as an x-ray source whose spectrum, as noted in section 5.1, shows strong emission for photon energies just below the aluminum K-edge. In such copper-coated aluminum target experiments, the back-to-front x-ray signal ratio rapidly drops as copper is added to the bare aluminum target (indicated by zero coating thickness) and the copper x-ray signals begin to dominate the aluminum x-ray signals. Since the transmission of the copper x-rays through the aluminum substrate will not be significantly affected by small shifts in the aluminum K-edge energy, this corroborates the assertion of a shift to higher photon energies for the aluminum K-shell photoabsorption edge discussed in 5.3.3.

On the other hand, we have not yet given detailed consideration to the transmission of the copper x-rays, but simply noted that the measured enhanced transmission through the shocked aluminum is lower than that of the aluminum x-rays through the shocked aluminum. The transmission of the copper x-rays in the copper layered target can be understood as follows.
Let us assume an approximately constant x-ray emission power per keV of photon energy in the spectrum below the K-edge, as suggested by the observations of reference 29. The aluminum opacity in the region just below the K-edge can be approximated linearly by the equation

$$\frac{\sigma}{\rho}(E) \approx \left[ \frac{\sigma}{\rho}(1560) \right] + \left[ E - 1560 \right] \times \left[ \frac{\delta}{\rho}(1560) \right] \text{cm}^2/\text{g},$$

(5.9)

where $E$ is the photon energy, $\frac{\sigma}{\rho}(E)$ is the mass absorption coefficient at photon energy $E$, and $\frac{\delta}{\rho}(E)$ is the first derivative of the mass absorption coefficient with respect to photon energy, at photon energy $E$. From reference 8, we see that $\frac{\sigma}{\rho}(1560) = 353 \text{ cm}^2/\text{g}$ and $\frac{\delta}{\rho}(1560) \approx -1 \text{ cm}^2\text{g}^{-1}/\text{eV}$. Note that we will simply ignore all copper x-rays above the aluminum K-edge, as these will be completely absorbed by the aluminum. Since we have assumed that the incident x-ray power of interest is independent of the photon energy, we can express the power per eV of photon energy as a constant $P_0$ for all photon energies up to 1560 eV. The absolute value of this constant is unimportant to us, as we are concerned only with the relative transmission of this spectrum through various thicknesses of aluminum. The transmission factor $T$ for photons of energy $E$ incident on a foil of density $\rho$ and thickness $d$ is simply

$$T = e^{-\rho d [353 - 1 \times (1560 - E)]}.$$  

(5.10)

Thus, by dividing the x-ray power $P_d$ transmitted through a foil of thickness $d$ by the x-ray power $P_{25}$ transmitted through a foil of 0.0025 cm thickness, the constant $P_0$ can be eliminated.
For aluminum foil thicknesses \( d \) of the order of 0.0025 cm, and with aluminum density \( \rho = 2.7 \text{ g/cm}^3 \), the total transmitted x-ray power will be given by

\[
P_d \approx P_0 \int_0^{1560} e^{-2.7d(1913-E)} dE, \tag{5.11}
\]

so that we have

\[
\frac{P_d}{P_{25}} \approx \left( \frac{0.0025}{d} \right) e^{-953(d-0.0025)}, \tag{5.12}
\]

where \( d \) is measured in cm. Accordingly, the thinning of the aluminum substrate required to produce the observed back-to-front x-ray signal ratio of 1.3 ~ 1.5 in Figure 4-12 is only 2 ~ 3 \( \mu \text{m} \), or only 8 ~ 12% of the aluminum substrate thickness.

On the other hand, we have not considered the effect of ionization in the aluminum substrate. In section 5.3.3 we noted that the average ionization of the dense aluminum plasma in the shocked target will be roughly four. X-rays are attenuated according to the exponent of the factor \( \frac{\varepsilon}{\rho d} \), so that an 8 ~ 12% reduction in \( \frac{\varepsilon}{\rho} \) is equivalent to an 8 ~ 12% reduction in \( \rho d \). Thus, given that the L-shell absorption cross-section of an atom is roughly proportional to the number of L-shell electrons in the atom, the removal of only one L-shell electron from each atom within the volume of the shocked target is sufficient to reduce \( \frac{\varepsilon}{\rho} \) for the copper x-rays in the aluminum by ~ 12.5%. However, the photoabsorption cross-section per L-shell electron in an atom will actually increase as the electrons are removed, so that the total atomic photoabsorption cross-section will not decrease quite linearly with the number of L-shell electrons in the atom and this figure of 12.5% represents an upper limit. The average ionization state of four expected in the shocked aluminum might still be enough to yield the observed transmission enhancement of 1.3 ~ 1.5 for the copper x-rays through the aluminum (Figure 4-12) even in the absence of
hydrodynamic thinning of the target, given that the reduction in the total atomic L-shell photoabsorption cross-section decrease is $\geq 8\%$ for an average ionization $(Z) = 4$.

Furthermore, radiation heating by the intense copper x-ray flux may also increase the ionization within the aluminum substrate, and hence cause lowering of the L-shell photoabsorption cross-sections of the atoms in the aluminum. This x-ray heating will be greatest at the highest copper x-ray intensity, so that the enhanced transmission will be seen to increase to some limit as the copper coating thickness is increased and the production of the copper x-rays approaches its corresponding limit. Such an increase is clearly seen for an increase of the copper coating thicknesses from 0.5 to $1.0 \mu m$. Over this same range the frontside x-ray signal showed an increase of a factor of more than 5.

If we assume that the enhancement of the transmission of the copper x-rays through the aluminum substrate by a factor of $1.3 \sim 1.5$ as seen in Figure 4-12 was due to thinning of the aluminum substrate by $2 \sim 3 \mu m$ as derived above, then thinning of a bare aluminum target by the same amount will result in similar enhanced transmission of the aluminum x-rays through the target; that is, a factor of $1.3 \sim 1.5$. On the other hand, a lowering of the L-shell absorption coefficient will affect only those aluminum x-rays which lie below the K-edge. Therefore, if we assume that the observed enhanced transmission of copper x-rays through shocked aluminum is due to L-shell opacity lowering, this will have a smaller effect on the transmission of aluminum x-rays through a shocked aluminum target. In any case, the combined effect of hydrodynamic thinning and L-shell ionization would account for an enhancement ratio of $< 1.3 \sim 1.5$ in Figure 4-9. The remaining enhancement factors of 2 to 4.5 would then still be inexplicable except by means of the shift in the aluminum K-edge.
CHAPTER 6

DISCUSSIONS AND CONCLUSIONS

6.1 X-Ray Emission Studies

The results of the x-ray emission energy measurements are summarized in Figure 4-1. We conclude that the best source of x-rays of spectral distribution suitable for high transmission through a B-10 foil is copper, producing roughly 3.5 times the x-ray energy emission of aluminum and 1.75 times the x-ray emission of molybdenum at an absorbed irradiance of $2 \times 10^{13}$ W/cm$^2$. The emission scales with irradiance approximately as a power law, with the exponent for the aluminum being 1.4, and the exponent for the copper and molybdenum being 1.3.

6.2 X-Ray Transmission Studies

The intrinsically time-integrated PIN diode results and the time-integrated XRD results reveal that the transmission of x-rays from the frontside through the aluminum target foil is enhanced from that which would be expected on the basis of observation of the target frontside through a filter which is identical to the unperurbed target material. After shock breakout, we observe greatly enhanced x-ray transmission through aluminum targets which are consistent with previous
observations of 2D rarefaction effects in the target foils. This late-time enhanced transmission will lead to x-ray heating of the foil backside much stronger than that which would be expected on the basis of 1-dimensional simulations. Thus, the result corroborates earlier observations of delayed x-ray heating of the target rear surface. Moreover, the results indicate that time-integrated soft x-ray pyrometry on the target rear surface will be affected both by this late-time heating of the foil backside and by the enhanced flux of soft x-rays penetrating the disassembling foil.

The results of the time-resolved XRD measurements on the foil backside show that the x-ray transmission is strongly time-dependent. At the moment of shock breakout, enhanced x-ray transmission through the target was clearly observed. The results of the copper-coated target experiments show that the shock enhanced transmission cannot be explained by the lowering of the L-shell contribution to the mass absorption coefficient, or by hydrodynamic processes giving rise to a decrease in the effective target thickness at the time of shock arrival at the target rear surface. It is seen that the enhanced x-ray transmission described in section 4.2.4 is consistent with the model of the K-edge energy shifting to photon energies higher than the He\textsubscript{a} and IC line energies, as discussed in section 2.3. This would allow these x-ray lines to be transmitted through the foil at the time of shock arrival at the rear surface of the target. A similar effect is observed in the irradiation of magnesium foils of 25 µm thickness.

6.3 Future Research

The most significant finding of this work is the first experimental evidence of substantial increase in x-ray transport due to a shift of the K-shell photoabsorption edge induced by shock-compression of a dense plasma. The most important future contribution which can be made to the study of the K-shell x-ray processes in
shocked materials is the direct observation of the K-edge shift using time-resolved x-ray spectroscopy. This would be best accomplished through the use of an x-ray crystal spectrometer, employing a diffracting element such as KAP, in conjunction with an x-ray streak camera.

With regard to enhanced x-ray transmission due to a shift in the absorption edge, we would expect to see such an effect whenever a major x-ray absorption edge in a material is shifted from energies lower than that of a strongly-emitting line to energies greater than that of the line. The significance of the effect will depend on the strength of the line or lines transmitted following the edge shift, relative to that of other x-rays transmitted through the target. On this basis, a further study of magnesium, silicon and silica targets should be undertaken. Silica, although not a pure element, would be interesting in light of its common use as a shell material in fusion targets. Such an edge shift would yield anomalously high x-ray transmission from the pellet surface to the fusion fuel in the core.

Enhanced x-ray transmission similar to that already observed in aluminum and magnesium should also be observed in silicon, as the He$\alpha$ and IC lines in silicon are much closer to the silicon absorption K-edge$^{29}$. For heavier elements, the He$\alpha$ line lies below the K-edge$^{29}$, and a shift in the K-edge will have no effect on the transmission of the line. For lighter elements, the K-edge shift required to effect enhanced transmission of the He$\alpha$ line grows increasingly larger$^{7,45}$, although it may be easier to produce a large K-edge shift for such light elements.
BIBLIOGRAPHY


4 D. Mosher, Phys. Rev. A 10, 2330 (1974);
   N. Nakano and H. Kuroda, Phys. Rev. A 27, 2168 (1983);

5 K. G. Whitney and J. Davis, J. Appl. Phys. 45, 5294 (1974);
   M. H. Key et al., Phys. Rev. Lett. 44, 1669 (1980);
   D. L. Matthews et al., J. Appl. Phys. 54, 4260 (1983);


11 M. H. Key and R. J. Hutcheon, Adv. At. Molec. Phys. 16, 208–211 (1980);
   S. Skupsky, Phys. Rev. A 21, 1316 (1980);

12 Peter Celliers, “Hydrodynamics of Laser-Driven Ablation in Planar Targets,”


15 100-PIN-250 X-Ray Diodes, Quantrad Corporation, 19900 S. Normandie Ave.
   Torrance CA, 90502, U. S. A.


   Livermore National Laboratory, 5-2 (1979) URCL – 50021-79.

   Soc. 25, 962 (1980).


20 ~ 150 $\mu$g/cm$^2$ polycarbonate with ~ 50 $\mu$g/cm$^2$ aluminum, supplied by
   Alexander Vacuum Research, Greenfield Mass. U. S. A.


22 Y. Lee and D. More, (private communication).

   Press, 78 (1972).


26 P. Celliers, Modified MEDUSA code, (unpublished).


38 Model ED-200 energy meter, *Gentec Inc.*


41 #380401 laser energy/power meter, *Scientific Corp.*, Boulder, Col., U. S. A.


55 P. Celliers, "Hydrodynamics of Laser-Driven Ablation of Planar Targets,"

APPENDIX A

X-RAY TRANSMISSION AND DETECTION CALCULATIONS

The basis of the calculation in this program is discussed in Chapter 2 in conjunction with the discussions on x-ray emission and absorption. By specifying an incident x-ray power spectrum including the fractions of the total x-ray power in each of the various lines, the mass absorption coefficients of the filter material for the same spectrum, and by specifying the relative sensitivity of the detector to photons of the same spectrum, the overall signal response of the detector is obtained, relative to that which would be obtained with no filter material. Absolute signal calculations are not included.

To use the program, a file containing these spectra must be created for read-in by the program. The mass density and thickness of the filter material are then given in response to the program's prompts.
Appendix A: X-Ray Transmission and Detection Calculations

This program accepts a coarsely-defined input spectrum, opacity spectrum and various line data, and simulates the transmission of that spectrum through a filter of the given opacity and of some given thickness. The program then calculates the response of a detector of given sensitivity. It then integrates and sums the transmitted spectrum and lines in order to obtain the net signal due to transmitted x-rays.

REAL*4 ENCN(500),INCN(500),ENLN(50),PWRLN(50),NWPWR
REAL*4 DECN(500),RECN(500),DELN(50),INSIG,LNSIG
REAL*4 OPCN(500),OPLN(50),LNPWR,NWCN(500)
REAL*4 LNSIG,NWSIG,NWLN(50),RELN(50)
INTEGER*4 LIST(1)/'*'/

C Obtain data...
CALL SPTMCN(ENCN,INCN,OPCN,DECN,NSTOP)
CALL SPTMLN(ENLN,PWRLN,OPLN,DELN,NLINE)

C Integrate the incident spectrum to obtain the normalization constant...
CALL INTGL(INCN,ENCN,NSTOP,SPPWR)

C Sum the incident lines to obtain the normalization constant...
CALL SUMLN(PWRLN,NLINE,LNPWR)

C Calculate the normalization constant...
PWRCN=1.0-LNPWR
RNORM=PWRCN/SPPWR

C Calculate the initial detector response for continuum and lines...
CALL SPDET(INCN,DECN,RECN,NSTOP)
CALL SPDET(PWRLN,DELN,RELN,NLINE)

C Integrate the continuum response to obtain the signal...
CALL INTGL(RECN,ENCN,NSTOP,CNSIG)

C Sum the line response to obtain the signal...
CALL SUMLN(RELN,NLINE,LNSIG)
INSIG=LNSIG+RNORM*CNSIG

C Obtain transmission simulation parameters...
WRITE(6,200)
200 FORMAT('Enter Density (g/cm3) and Target thickness (cm)',//)
READ(6,LIST) RHO,T

C Calculate the transmission of the continuum x-rays...
CALL SPTRNS(INCN,NWCN,OPCN,RHO,T,NSTOP)

C Calculate the transmission of the line x-rays...
CALL SPTRNS(PWRLN,NWLN,OPLN,RHO,T,NLINE)

C Integrate the transmitted spectrum to obtain the transmittance...
CALL INTGL(NWCN,ENCN,NSTOP,SPPWR)

C Sum the transmitted lines to obtain the transmittance...
CALL SUMLN(NWLN,NLINE,NWPWR)

C Output the transmittance...
SPPWR=SPPWR*RNORM
WRITE(6,400) PWRCN,LNPWR
Appendix A: X-Ray Transmission and Detection Calculations

400 FORMAT(' Continuum in:',G14.6,', Line in:',G14.6,//)
WRITE(6,500) SPPWR,NWPWR
500 FORMAT(' Continuum out:',G14.6,', Line out:',G14.6,//)
C Output the initial x-ray continuum spectrum...
WRITE(7,600)(ENCN(I),INCN(I),I=1,NSTOP,5)
600 FORMAT(2G14.6)
C Calculate detector response for transmitted continuum and lines...
CALL SPDET(NWCN,DECN,RECN,NSTOP)
CALL SPDET(NWLN,DELN,RELN,NLINE)
C Output the detected continuum x-ray spectrum...
WRITE(7,601)(ENCN(I),RECN(I),I=1,NSTOP,5)
601 FORMAT(2G14.6)
C Integrate the continuum response to obtain the signal...
CALL INTGL(RECN,ENCN,NSTOP,CNSIG)
C Sum the lines to obtain the signal...
CALL SUMLN(RELN,NLINE,LNSIG)
NWSIG=LNSIG+RNORM*CNSIG
C Normalize output response to initial response...
SIGNM=NWSIG/INSIG
C Output the detector signals...
WRITE(6,800) INSIG, NWSIG
800 FORMAT(//' INPUT SIGNAL',G14.6,' OUTPUT SIGNAL',G14.6)
WRITE(6,700) SIGNM
700 FORMAT(//' NORMALIZED SIGNAL ',G14.6)
WRITE(6,750) LNSIG
750 FORMAT(//' NORMALIZED LINES ',G14.6)
STOP
END

C This subroutine calculates the transmission of the x-rays
C through the filter material...
SUBROUTINE SPTRNS(INCN,NWCN,OPCN,RHO,T,NSTOP)
REAL*4 INCN(1),NWCN(1),OPCN(1)
C DO 100 I=1,NSTOP
NWCN(I)=INCN(I)*EXP(-RHO*T*OPCN(I))
100 CONTINUE
C RETURN
END

C This subroutine adds up the fractional power in each line,
C giving the total fraction of incident energy presently in the
C lines...
SUBROUTINE SUMLN(PWRLN,NLINE,LNPWR)
REAL*4 PWRLN(50), LNPWR
INTEGER*4 NLINE
LNPWR= 0.0
DO 100 I= 1, NLINE
LNPWR= LNPWR + PWRLN(I)
100 CONTINUE
RETURN
END
Appendix A: X-Ray Transmission and Detection Calculations

This subroutine reads incident spectrum and opacity spectrum data and does a log-log interpolation, preparatory to detailed calculations...

```
SUBROUTINE SPTMCN(ENCN, INCN, OPCN, DECN, NSTOP)
REAL*4 ENCN(500), INCN(500), X(50), Y(50), Z(50), OPCN(500)
INTEGER*4 LIST(1)/**/
REAL*4 DECN(500), W(50)

SET number of points to be inserted by interpolator...
NINT=9

READ data to be interpolated from...
READ(1, LIST) N
NSTOP = N + NINT*(N-1)
READ(1, LIST)(X(I), Y(I), Z(I), W(I), I=1,N)

Interpolate the data in the arrays...
This is the detector response function at some point in the x-ray continuum...
CALL INTP(DECN, W, NINT, N)

This is the photon energy of this point in the continuum...
CALL INTP(ENCN, X, NINT, N)

This is the relative intensity (per unit of photon energy) at this point in the continuum...
CALL INTP(INCN, Y, NINT, N)

This is the mass absorption coefficient of the filter material...
CALL INTP(OPCN, Z, NINT, N)
RETURN
END
```

This subroutine interpolates scattered data points, on a logarithmic basis. Thus, a power-law scaling is obtained between points on a graph when both ordinates and abscissae are interpolated...

```
SUBROUTINE INTP(ARRL, ARRS, NINT, N)
REAL*4 ARRL(500), ARRS(50)

SET up parameters for interpolation...
NST=N-1
NINTP=NINT+1

Scan through input data file and interpolated output file...
DO 100 I=1, NST
DO 200 J=1, NINTP
```

This subroutine reads incident line and line opacity data, preparatory to detailed calculations...

```
SUBROUTINE SPTMLN(ENLN, PWRLN, OPLN, DELN, NLINE)
REAL*4 ENLN(50), PWRLN(50), OPLN(50), DELN(50)
INTEGER*4 LIST(1)/**/

READ(2, LIST) NLINE
READ(2, LIST)(ENLN(I), PWRLN(I), OPLN(I), DELN(I), I=1,NLINE)
RETURN
END
```
Appendix A: X-Ray Transmission and Detection Calculations

C Interpolate logarithmically...
   K=(I-1)*NINTP + J
   ARRL(K) = ALOG(ARRS(I)) + (ALOG(ARRS(I+1)) - ALOG(ARRS(I)))
   &*(J-1)/(NINTP)
   ARRL(K) = EXP(ARRL(K))
200 CONTINUE
100 CONTINUE
   ARRL(K+1) = ARRS(N)
   RETURN
END

C This subroutine performs numerical integrations...
SUBROUTINE INTGL(Y,X,NSTOP,RESULT)
REAL*4 Y(500),X(500)
C
   RESULT=0.0
   NST=NSTOP-1
   DO 100 I=1,NST
       RESULT=RESULT + (Y(I) + Y(I+1))/2.0*(X(I+1)-X(I))
100 CONTINUE
   RETURN
END

C This subroutine calculates the effect of the detector photocathode...
SUBROUTINE SPDET(INLST,DELST,RELST,N)
REAL*4 INLST(1),DELST(1),RELST(1)
C
   DO 100 I=1,N
       RELST(I) = INLST(I)*DELST(I)
100 CONTINUE
   RETURN
END
This program is discussed in Chapter 4 in conjunction with the interpretation of the time-resolved XRD signals. The program prompts the user for various parameters describing the x-ray frontside and backside x-ray powers assumed for an aluminum target shot. It then generates the XRD-detected frontside and backside signals which would be expected on this basis, along with the signal ratio which would be found from these signals.
This program produces simulated temporally-resolved front- and back-side XRD signals. These signals are then convolved with the detector temporal response function, assumed to be Gaussian. The ratio of these signals is then obtained and output.

REAL*4 IDEAL(500), BACK(500), FRONT(500), DETEC(100)
REAL*4 BSIG(500), FSIG(500), RATIO(500), DFWHM, FTEMP(500)
REAL*4 FFWHM, RASHK, TMSHK, TAU, ELECT(100), BTEMP(500)
INTEGER*4 LIST(1)/*/"

Obtain necessary parameters...
WRITE(6,100)
100 FORMAT(/'Enter the idealized frontside signal FWHM...')
READ(6,LIST) FFWHM
WRITE(6,200)
200 FORMAT(/'Enter the detector system response FWHM...')
READ(6,LIST) DFWHM
WRITE(6,300)
300 FORMAT(/'Enter the shock arrival time...')
READ(6,LIST) TMSHK
WRITE(6,400)
400 FORMAT(/'Enter the idealized x-ray ratio at shock arrival...')
READ(6,LIST) RASHK

Generate the idealized Gaussian front side signal...
CALL GAUSS(FRONT,FFWHM,500)

Generate the Gaussian system response function...
CALL GAUSS(DETEC,DFWHM,100)

Generate the idealized ratio...
CALL SIMIT(IDEAL,TMSHK,RASHK)

Generate the idealized backside signal...
CALL TIMIT(BACK,FRONT,IDEAL)

Convolve the signals with the system response function...
CALL CONIT(BACK,DETEC,BSIG)
CALL CONIT(FRONT,DETEC,FSIG)

Determine the ratio seen by the parametrized detector...
CALL OVRIT(BSIG,FSIG,RATIO)

Prepare to output the various signals to various files...
WRITE(1,10)
10 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "IDEAL FRONT"')
WRITE(2,20)
20 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "IDEAL BACK"')
WRITE(3,30)
30 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "IDEAL RATIO"')
WRITE(4,40)
40 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "FRONT SIGNAL"')
WRITE(7,50)
50 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "BACK SIGNAL"')
WRITE(8,60)
60 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "SIGNAL RATIO"')
WRITE(9,70)
70 FORMAT( 'GENERATE A PLOT.'/' INPUT DATA.'/' "DETECTOR"')
Appendix B: Detector Response-Time Effect Calculations

C Output the numbers in the arrays...

600 FORMAT(2G14.6)
   DO 500 I=125,375,5
      WRITE(1,600) I, FRONT(I)
      WRITE(2,600) I, BACK(I)
      WRITE(3,600) I, IDEAL(I)
      WRITE(4,600) I, FSIG(I)
      WRITE(7,600) I, BSIG(I)
      WRITE(8,600) I, RATIO(I)
   500 CONTINUE
   DO 700 I=1,100
      WRITE(9,600) I, ELECT(I)
   700 CONTINUE
   STOP
   END

C This subroutine multiplies elements of FRONT by elements
C of IDEAL on a one-to-one basis to produce BACK...
SUBROUTINE TIMIT(BACK,FRONT,IDEAL)
   REAL*4 BACK(500), FRONT(500), IDEAL(500)
   DO 100 I=1,500
      BACK(I)=FRONT(I)*IDEAL(I)
   100 CONTINUE
   RETURN
   END

C This subroutine produces an array approximating a Gaussian
C distribution in BELLC, with FWHM being the full-width-at-half-
C maximum in units of 50 elements...
SUBROUTINE GAUSS(BELLC,FWHM,NSTOP)
   REAL*4 BELLC(500), FWHM, BELLT, CENT, SIGM
   CENT=NSTOP/2.
   SIGM=FWHM*50.*0.42466
   BELLT=0.
   DO 100 I=1,NSTOP
      BELLC(I)=1./EXP((I-CENT)/SIGM*(I-CENT)/SIGM/2.)
      BELLT=BELLT+BELLC(I)
   100 CONTINUE
   DO 200 I=1,NSTOP
      BELLC(I)=BELLC(I)/BELLT
   200 CONTINUE
   RETURN
   END

C This subroutine divides the elements of array BACK by the
C elements of array FRONT on a one-to-one basis, to produce
C array RATIO...
SUBROUTINE OVRIT(BSIG,FSIG,RATIO)
   REAL*4 BSIG(500), FSIG(500), RATIO(500)
   DO 100 I=1,500
      FMIN=BSIG(I)/1000.
      RATIO(I)=1000.
      IF(FSIG(I).LT.FMIN) GOTO 100
      IF(FSIG(I).LT.1.E-30) GOTO 100
      RATIO(I)=BSIG(I)/FSIG(I)
   100 CONTINUE
   RETURN
   END

C This subroutine convolves array XRAYS with array RSPNS to
SUBROUTINE CONIT(XRAYS, RSPNS, SIGNL)
REAL*4 XRAYS(500), RSPNS(100), SIGNL(500)
DO 100 I=1,500
   SIGNL(I)=0.
100 CONTINUE
DO 200 I=1,500
   DO 300 J=1,100
      K=I+J-50
      IF(K.LT.1.OR.K.GT.500) GOTO 300
      SIGNL(K)=SIGNL(K)+XRAYS(I)*RSPNS(J)
300 CONTINUE
200 CONTINUE
RETURN
END

C
C This subroutine calculates an idealized time-dependant back/front
C x-ray signal ratio from a K-shift model. The time of shock
C breakout, TIME, corresponds to array element N1...
SUBROUTINE SIMIT(IDEAL, TIME, RATIO)
REAL*4 IDEAL(500), TIME, RATIO
N1=250+TIME*50.
ECON=0.0225
NCON=35
DO 100 I=1,N1
   IDEAL(I)=1.+(RATIO-1.)*EXP(0.28*(I-N1))
100 CONTINUE
N2=N1+1
DO 200 I=N2,500
   IDEAL(I)=RATIO*EXP(ECON*(I-N1))
   IF(IDEAL(I).LT.NCON) GOTO 200
   IDEAL(I)=NCON
200 CONTINUE
RETURN
END