Fast Electron Generation During High Intensity Laser-Solid Interactions In The Refluxing Limit

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Summary

K-shell spectroscopy has been used to infer the laser-electron conversion efficiency and study the heating of small mass targets

• the absolute $K_\alpha$ yield has been compared against a semi-analytical refluxing model that demonstrates laser-electron conversion efficiencies of around 10 - 20%

• the ratio of the number of emitted $K_\beta$ and $K_\alpha$ photons ($N_{K_\beta}/N_{K_\alpha}$) has been measured as a function of the target volume

• $N_{K_\beta}/N_{K_\alpha}$ variations diagnose the bulk electron temperature and has been used to infer the energy content of the fast electrons

• such a concomitant measurement provides a self-consistency check on the laser-electron conversion efficiency

• these results provide a comparison in preparation for future Omega EP studies
Collaborators

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Small mass targets are a good benchmark for studying fast electron conversion efficiency ($\eta_{L\rightarrow e}$), transport and volumetric heating.

- the principal aim is to study the energy content of the fast electrons
- the absolute $K_\alpha$ yield depends on the hot electron conversion efficiency
- $NK_\beta/NK_\alpha$ is sensitive to the bulk temperature of the target material

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The multiterrawatt (MTW) laser facility at LLE is the front end prototype for OMEGA EP.

- Typical laser characteristics: $E_{\text{max}} = 1-10 \text{ J}$, $1-10$ ps, $\lambda_0 = 1053\text{nm}$
- Pulse duration measurement: scanning second harmonic autocorrelator
- Contrast ratio: $10^8$

$R_{50} \approx 4\mu\text{m} \Rightarrow I_{50} \approx 2 \times 10^{19} \text{Wcm}^{-2}$
A single photon counting CCD\(^1\) diagnoses the absolute \(K_\alpha\) and \(K_\beta\) photon yields that are generated during the interaction.

- copper target: (500 x 500 x 20) \(\mu\)m
- laser: 1J, 1ps

Semi-analytic modelling\(^1\) has been used to study MTW experiments operating in the cold material limit.

- assume the classical slowing down approximation (CSDA)
- relativistic K-shell ionization cross-sections
- refluxing is included
- reabsorption is included
- fast electron energy spectrum is specified (via the Wilk’s scaling relationship)

\(^1\)Myatt et al, Physics of Plasmas 14, 056301 (2007)
MTW $K_\alpha$ yields are consistent with the refluxing electron model assuming that $\eta_{L\rightarrow e} \approx 10\text{ - }20\%$ for $I > 10^{18}$ Wcm$^{-2}$

- refluxing theory
- non-refluxing theory

- LLE MTW
- RAL PW$^1$

- copper target: 500 x 500 x 20 $\mu$m
- MTW laser pulse: 1 J, 1 ps
- Vulcan Petawatt: 500 J, 1 ps

$^1$Theobald et al, Physics of Plasmas 13, 043102 (2006)
Numerical calculations (LSP) of K-shell emission have been performed to account for spatio-temporal variations in the target heating

- fast electrons promoted from the cold background
- an isotropic Maxwellian energy spectrum is defined via the ponderomotive scaling
- inter- and intra-particle collisions
- the relative emission probability of $K_{\beta}$ is adjusted via Thomas-Fermi
- > 90% of the fast electron energy is converted into target thermal energy
For 20 x 20 x 3 µm Cu targets and $\eta_{L\rightarrow e} > 10\%$, both $K_\alpha$ and $K_\beta$ lines start to be depleted and $NK_\beta/NK_\alpha$ drops from 0.2 and tends to 0.1

<table>
<thead>
<tr>
<th>laser-electron conversion efficiency</th>
<th>$NK_\beta:NK_\alpha$</th>
<th>$K_\alpha:K_{\alpha,\text{cold}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.21</td>
<td>0.87</td>
</tr>
<tr>
<td>30%</td>
<td>0.08</td>
<td>0.35</td>
</tr>
<tr>
<td>50%</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table I: 20 x 20 x 3 µm copper target

- the ionization population is calculated using Prism SPECT
- this is used to weight the emission probability of $K_\alpha$ and $K_\beta$ for each ion
Present $NK_\beta/NK_\alpha$ Vulcan data\(^1\) exhibits large scatter and neither confirms nor denies $\eta_{L\rightarrow e}$ theoretical predictions

\(^1\)Theobald \textit{et al}, Physics of Plasmas 13, 043102 (2006)
The reduction in $\text{NK}_\beta/\text{NK}_\alpha$ due to target heating in small mass Cu targets is clearly observed on MTW.

Cu target: (500 x 500 x 50) µm laser: 5J, 1ps

Cu target: (20 x 20 x 3) µm laser: 5J, 1ps
20 x 20 x 2 µm Cu targets have been mounted using stalks or spider silks with no significant differences in the datasets.
The $K_{\alpha}$ and $K_{\beta}$ photon energies reduce over the range of target volumes studied in accordance with theoretical predictions. 

$\eta_{L\rightarrow e} = 10\%$ semi-analytic model in the cold material limit

$K_{\alpha}$ drop predicted for $\eta_{L\rightarrow e} = 10\%$ with 20 x 20 x 3 $\mu$m targets is consistent with the MTW experimental data
\( \text{NK}_\beta/\text{NK}_\alpha \) variations diagnose the bulk electron temperature and has been used to infer the energy content of the fast electrons.

- Heating calculations for 20 x 20 x 3 \( \mu \text{m} \) targets and \( \eta_{\text{L} \rightarrow \text{e}} = 10\% \) is consistent with the MTW dataset - \( \text{NK}_\beta/\text{NK}_\alpha = 0.21 \).
Summary

K-shell spectroscopy has been used to infer the laser-electron conversion efficiency and study the heating of small mass targets.

- The absolute $K_\alpha$ yield has been compared against a semi-analytical refluxing model that demonstrates laser-electron conversion efficiencies of around 10 - 20%.

- The ratio of the number of emitted $K_\beta$ and $K_\alpha$ photons ($N_{K_\beta}/N_{K_\alpha}$) has been measured as a function of the target volume.

- $N_{K_\beta}/N_{K_\alpha}$ variations diagnose the bulk electron temperature and have been used to infer the energy content of the fast electrons.

- Calculations are underway to make detailed comparisons between the experimental $N_{K_\beta}/N_{K_\alpha}$ curve and theoretical predictions.

- Such a concomitant measurement provides a self-consistency check on the laser-electron conversion efficiency.

- These results provide a comparison in preparation for future Omega EP studies.