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Fast electrons produced by the irradiation of plane-layered targets with 20-J, 100-ps, 10^{13}-W-cm^{-2}, neodymium-laser pulses have been diagnosed by the Kα emission associated with the light produced during the laser pulse. The fast-electron energy spectrum and absolute energy deposition (target preheat) are measured.

When high-intensity laser radiation is incident on a solid it is well known that the resulting plasma has both a thermal (cold) and a hot component in its electron distribution and that a large fraction of the absorbed laser energy couples into the hot electrons.1–3 Fast ions are accelerated by the hot electrons, and the temperature of the hot electrons \( T_H \) has been inferred from the ion-velocity spectrum.4 A substantial fraction of the hot-electron energy is transferred to the ions, and the remainder is deposited in the target causing preheating of the solid, \( \alpha \)-ray continuum emission and \( K \) line emission. The hard-\( \alpha \)-ray (5–50 keV) continuum slope has been widely used to estimate the hot-electron temperature.1,4,5 However, the experimental method is not amenable to spatial resolution, and the total energy inferred in the hot electrons is sensitive to the model electron distribution function.6

We report the first experiments using \( Kα \) radiation from laser-produced plasmas to measure the magnitude of preheating of the solid by hot electrons, with radiation-induced \( Kα \) emission and saturation of the \( Kα \) emission due to ionization eliminated. The range and degree of the preheating, and the form of the hot-electron velocity distribution are also measured. Direct measurement of this preheating has not previously been obtained and is of importance for laser-fusion target design.

Earlier work7,6 has attributed \( Kα \) emission to fast electrons and in a detailed study9 their range and effective temperature were deduced for 10.6-\( \mu \)m radiation at 3 \( \times \) 10^{13} W. cm^{-2}. Target preheating was estimated in Ref. 8, but consideration of ionization effects below suggest that the conclusions drawn from the experiment were invalid.

\( Kα \) radiation can arise from electron- or radiation-produced \( K \)-shell ionization. Radiative \( K \)-shell ionization is very efficient if the photon energy \( \hbar \nu \) is slightly greater than \( E_K \), the \( K \)-shell ionization potential. The low-energy \( x \)-ray recombination continuum from laser-produced plasmas has the form \( R(\nu) = I_{\chi \nu} \exp(-\hbar \nu/kT_e) \) where the cold-electron temperature \( T_e \) is \(~0.5 \) keV in the present experiment. Thus to reduce radiation pumping \( E_K \) must be much greater than \( kT_e \).

In contrast, electrons are inefficient in \( K \)-shell ionization. The instantaneous ratio\( ^{10} \) of \( K \)-shell ionization to total energy deposition by an electron of energy \( E \) may be written as

\[
R(E) \sim 3.0 \times 10^{-12} \ln(E/E_K)/\ln(4E/E) \]

for potassium, where the mean excitation energy \( \bar{E}_r \) is \( \bar{E}_r \sim 240 \) eV. For \( E > 15 \) keV, \( R(E) \) is nearly constant at \( R \sim 1 \% \). The \( Kα \) yield is then \( \omega \bar{E}_r U \) where \( U \) is the energy deposited by electrons, and \( \omega \) is the fluorescence yield times the \( Kα \) photon energy divided by \( E_K \) (0.15 for Ca).

As \( U \) increases, the ionization causes only a small shift in the wavelength of the \( Kα \) line until an electron is removed from the \( L \) shell, when

\[
U = U_K = N_a \left\{ \sum_{n=1}^{2} E_1^n \exp \left\{ 1.5k(\bar{Z} - 10)T_e + T_1 \right\} \right\}
\]

where \( E_1^n \) is the ionization potential of ionization stage \( n \) and \( N_a \) is the number of fluor atoms under the focal area. The saturation energy yield of the “unshifted” \( Kα \) line is simply \( U_K \bar{E}_r \).

Previous work with neon has ignored this saturation effect.12 We estimate the saturation energy yield of the electron-pumped neon \( Kα \) in Ref. 8 to be \( 5 \times 10^{-13} \) J (for \( 10^{14} \) atoms) compared with the reported observed yield of \( 2 \times 10^{-4} \) J.

The saturation and radiation pumping effects suggest using a fluor whose \( Z \) is appreciably larger than \( 10 \), but not so large that \( E_K \) is comparable with \( kT_e \). In the work below, Ca and K \( (E_K = 4.04 \) and 3.62 keV, respectively) were used and \( kT_H \) was 11 keV. A 20-J, 100-ps neodymium
laser was normally incident on various plane-layered targets. The targets were positioned 150 μm away from the optimum focus of a f/1 lens. X-ray pinhole pictures indicated a focal spot of 100 μm, which corresponds to photographic measurements of the equivalent image plane. The layers were 0.1-μm Al; 1.0-μm SiO; 3.0-μm KCl; 2.5-, 12.5-, 25-, or 50-μm variable-thickness Mylar; and 2.5-μm CaF₂. The laser was incident on the Al. The top two layers of Al and SiO isolated the Kα fluors from the ablation plasma, whose burnthrough depth for 100-ps pulse was only 0.1 μm. The Ca and K Kα radiation was excited by electrons: The Cl with lower E_k was appreciably pumped by soft x-ray radiation. Time-integrated x-ray spectra were recorded by two miniature flat pentaerythritol crystal spectrometers. The reflectivities of the crystals have been measured. All the Kα emission lines were recorded by a spectrometer behind the targets. A spectrometer in front of the target recorded the K and Cl Kα lines, the attenuated Ca Kα line, and the soft-x-ray plasma emission.

A typical microdensitometer trace from the front spectrometer is shown in Fig. 1. Three Kα lines, the plasma continuum, and the Si and Al plasma emission lines are shown. The Ca and K Kα intensities for different Mylar thicknesses are shown in Fig. 2. As expected, with increasing Mylar thickness the number of electrons energetic enough to penetrate to the activate the rear fluor decreases and thus the Kα yield decreases with increasing depth in target.

The saturation and radiation effects referred to above were experimentally demonstrated. Figure 3 shows the Kα line profile from the K at the front, in which the energy deposition is highest. The line clearly has shifted components. The energy in the "unshifted" component is (1.4 ± 0.1) x 10⁻⁵ J sr⁻¹, whereas the energy in the shifted components is (0.8 ± 0.3) x 10⁻⁵ J sr⁻¹. For K Kα U₀ = 1.0 x 10⁻⁵ J sr⁻¹ for the 100-μm-diam, 3-μm-deep emitting volume of KCl, in fair agreement with the experimental data.

To show the effect of radiation-induced Kα emission, a 25-μm Mylar target with KCl on the rear was irradiated with a larger focal spot and hence lower flux density. There was no K Kα yield observed, because the hot-electron temperature was too low. However, the Cl Kα yield was (1.3 ± 0.1) x 10⁻⁶ J sr⁻¹. The soft-x-ray recombination emission was the same as for the 100-μm focal spot, and was measured to have \( I_0 = (6.0 ± 1.0) x 10^{-6} \) J sr⁻¹ eV⁻¹ and \( kT_e = 0.5 ± 0.1 \) keV. The calculated Cl Kα yield induced by this recombination emission was 1.7 x 10⁻⁹ J sr⁻¹, again in fair agreement with experiment. In this calculation proper account was taken of target geometry and reabsorption. The predicted radia-
tion pumped K Kα yield is only $0.3 \times 10^{-6}$ J sr$^{-1}$ which is small compared with the lowest observed value of $2 \times 10^{-6}$ J sr$^{-1}$.

The energy spectrum of the fast electrons was obtained from calculations of the Kα yield of monoenergetic electrons using Ref. 14. To check this calculation, especially at low energy, an electron beam was used to calibrate duplicate targets. The beam supplied 0.1 μA at 15 to 50 kV into a 300-μm spot. The x-ray crystal spectrometer was used to record the various Kα yields, for a known deposited charge. From the calibration and calculation the Kα yields $Y(E)$ in J sr$^{-1}$ electron$^{-1}$ as a function of electron energy were obtained and are shown in Fig. 4. The agreement of the two adds confidence to our absolute measurement.

From the yields $Y(E)$ for monoenergetic electrons the yields for a distribution function $n(E)$ of electrons passing into the targets were predicted from $\int_{E_0}^{\infty} n(E)Y(E)dE$. With $n(E) = AE^{-N/2} \exp(-E/kT_N)$, yields for $N=0$ and $N=3$ were calculated.

FIG. 3. An expanded microdensitometer tracing of a K Kα line showing the short-wavelength shifted components. The indicated transitions from Ref. 11 should be compared with the observed peaks. "Unshifted" components are shaded.

FIG. 4. The Kα yield per electron as a function of incident electron energy for each of the different fluor layers. Curves 1, 2, and 3 refer to Mylar thicknesses of 2.5, 12.5, and 25.0 μm, respectively. The dotted line is the calculated yield for the front K layer and the points are from the electron-beam calibration. The good agreement should be noted. The solid lines are the yields used, derived from theory and the calibration.
and are shown in Fig. 2. The factors $A$ and $kT_H$ are determined by fitting the predicted yields to the experimental yields. The case $N = 3$ fits the data best with $kT_H = 11 \pm 2$ keV. The slope of the hard-x-ray continuum between 10 and 20 keV also indicates a temperature of $12 \pm 2$ keV, which is comparable with collected data at $2 \times 10^{15}$ W cm$^{-2}$.

Choosing $N = 3$, the fit to the experimental results gives $A = (9.4 \pm 2.0) \times 10^{11}$ electrons keV$^{-2.5}$, $kT_H = 11.0 \pm 2.0$ keV. The total energy in this distribution which is passing into the target is $\int_0^\infty n(E)E \, dE = 2.2 \pm 0.4$ J. However, the calculation of the energy deposited into the target is insensitive to the assumed distribution function, provided that the distribution is fitted to the observed yields. This is because $R(E)$ is almost constant and a simple division of the energy in the $K\alpha$ line by $\omega/R$ gives the total energy deposited in the fluor. A more accurate calculation of energy deposition has been made using the $N = 3$ distribution and the results are shown in Table I.

Finally, we remark that the fast-electron energy deposition that we observe is broadly consistent with the expected overall energy balance. Of the 20 J onto the target, about 7 J should be absorbed. 3 About 60% of the absorbed energy should reappear as fast ions. 2 We observe the bulk of the remainder as preheat. One might speculate that this observed 2.2-J deposition of energy by hot electrons suggests that any inhibition of the hot-electron transport is not very significant.

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**Table I. Total energy deposition in fluor compounds.**

<table>
<thead>
<tr>
<th>Fluor layer (Mylar thickness)</th>
<th>Depth in target (mg cm$^{-2}$)</th>
<th>Deposited energy (J)</th>
<th>Deposited energy density (J cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCl (top)</td>
<td>0.56</td>
<td>0.40</td>
<td>$1.4 \times 10^7$</td>
</tr>
<tr>
<td>CaF$_2$ (2.5 μm)</td>
<td>1.58</td>
<td>0.24</td>
<td>$1.0 \times 10^7$</td>
</tr>
<tr>
<td>CaF$_2$ (12.5 μm)</td>
<td>2.81</td>
<td>0.12</td>
<td>$5.1 \times 10^6$</td>
</tr>
<tr>
<td>CaF$_2$ (25 μm)</td>
<td>4.50</td>
<td>0.04</td>
<td>$1.7 \times 10^6$</td>
</tr>
</tbody>
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12. B. Yaakobi, private communication.
