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K_α-radiation from relativistic laser-produced plasmas

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Abstract. – We present systematic investigations on the generation of titanium K_α-radiation ($E = 4.5\,\text{keV}$) from plasmas produced with ultrashort, high-intensity laser pulses. A maximum K_α-yield appears at a laser intensity of about $3 \cdot 10^{17}\,\text{W/cm}^2$, corresponding to a plasma electron temperature of a few times the K_α photon energy. We observe a second increase in the K_α-emission yield at intensities higher than a few times $10^{18}\,\text{W/cm}^2$, due to the increase in the K-shell ionization cross-section for relativistic electrons. The intensity dependence of the K_α-yield is modeled by an analytical expression, only including cross-section, pathlength and electron energy distribution.

Introduction. – Plasmas which are generated by the interaction of ultrashort and ultraintense laser pulses with solid matter are efficient sources of relativistic electrons and of X-ray radiation with exceptional brightness. The primary process which leads to X-ray generation is the acceleration of plasma electrons in the ponderomotive potential of the intense light field. At intensities of $\geq 10^{19}\,\text{W/cm}^2$ which are now accessible by state-of-the-art tabletop laser systems, the characteristic temperature of the electron distribution is in the order of several MeV [1,2]. The duration of this electron pulse is in the order of the laser pulse duration, *i.e.* typically less than 100 fs. These laser-accelerated electrons penetrate the solid target material where they generate bremsstrahlung with photon energies up to many MeV as well as line radiation from atoms. Inner shell recombination takes place on a time scale of femtoseconds or even attoseconds. Consequently, the duration of inner shell radiation, namely K_α-radiation, is limited by the laser pulse duration and propagation effects [3]. Due to the small source size of about $50\,\mu$m in diameter [4] these laser-produced K_α-sources can be as bright as the largest undulators at photon energies of several keV despite the isotropic emission. This qualifies them as light sources for femtosecond time-resolved X-ray diffraction experiments and for first experiments towards nonlinear X-ray optics.

Measurements of K_α-radiation from ps-laser–produced plasmas were presented as early as 1979 by Hares *et al.* [5], and an efficient K_α X-ray source from fs-laser–produced plasmas is described by Rousse *et al.* [6]. A systematic investigation of the intensity dependence of the K_α-yield has recently been performed by Eder *et al.* [4]. It turned out that the yield peaks at a cer-

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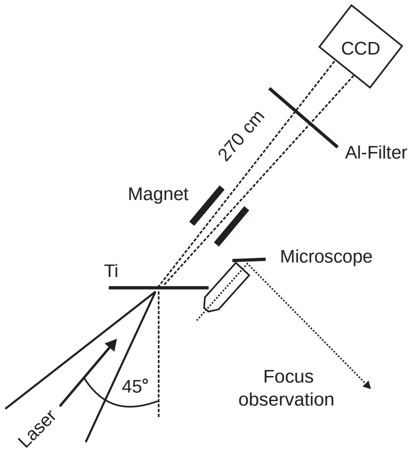

Fig. 1

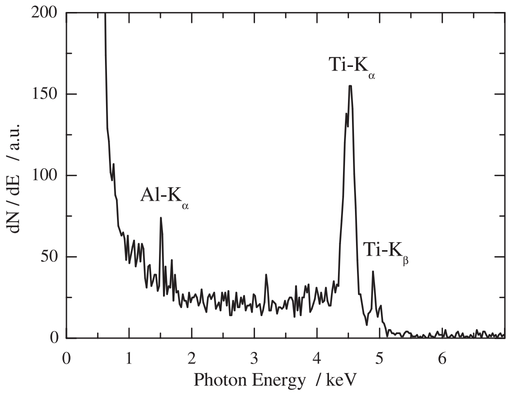

Fig. 2

Fig. 1 – Experimental setup: A 12 μm thick titanium foil is irradiated by the intense laser pulse under an angle of incidence of 45°. The intensity is determined by measuring the beam size on the target by means of a microscope. The K_α-yield is measured with a CCD camera in the single-photon counting mode, located 270 cm apart from the target. The camera is protected from charged particles by a magnet and from visible light by a thin metal filter.

Fig. 2 – Spectrum of the laser-produced K-shell emission of titanium. The background signal on the low-energy side of the K_α-line originates from multipixel events on the CCD camera and is taken into account in the analysis.

tain laser intensity, corresponding to an optimum electron temperature. From classical cross-section arguments it follows that this optimum electron temperature should be a few times the K_α absorption edge. Even though no absolute laser intensities are given in ref. [4], the experimental data support this simple model. Reich *et al.* [7] calculate the yield of short-pulse laser-generated K_α-pulses by means of Monte Carlo and particle-in-cell simulations. They explain the existence of an optimum laser intensity for the K_α-yield as equilibrium between K_α-production and reabsorption in bulk targets. This approach does not include electron energies above $U_0 = E_0/E_K \approx 20$ in the calculation of the K_α-yield (with E_0 the incident electron energy, E_K the ionization energy of the K-shell, $E_K = 4.96\,\text{keV}$ for titanium), since faster electrons deposit their energy deeper in the target than the absorption length of K_α-radiation.

However, it is known since the early seventies that the cross-section for K-shell ionization by electrons increases at relativistic electron energies [8, 9]. Since cross-section data for many medium-Z elements are well known between ionization energy and hundreds of MeV [10], the dependence of the laser-produced K_α-yield on the laser intensity may be a test of the electron energy distribution in the relativistic laser-produced plasma.

In this work we investigate the generation of titanium K_α-radiation from a relativistic laser-produced plasma. The radiation yield is measured as it depends on the laser intensity. An analytical expression is presented, which models the experimental results with regard to the interaction of relativistic electrons with the solid target.

Experiment. – For these measurements the 10 Hz Ti:sapphire laser system in Jena was operated with 300 mJ pulses of 80 fs duration at a center wavelength of 800 nm. The laser beam was focused with a $f/2$ parabola onto a 12 μm thick titanium foil with an angle of incidence of 45° and parallel polarization (fig. 1). One prepulse at 600 fs with a contrast ratio of $5 \cdot 10^{-4}$ with

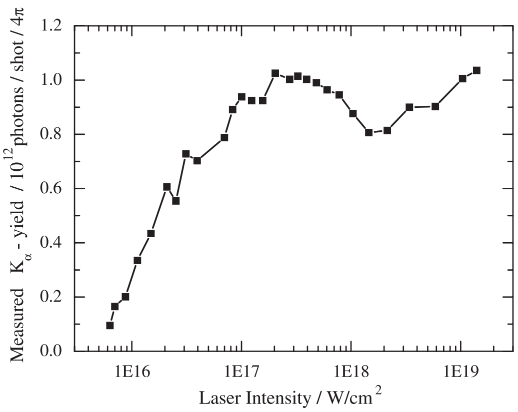

Fig. 3

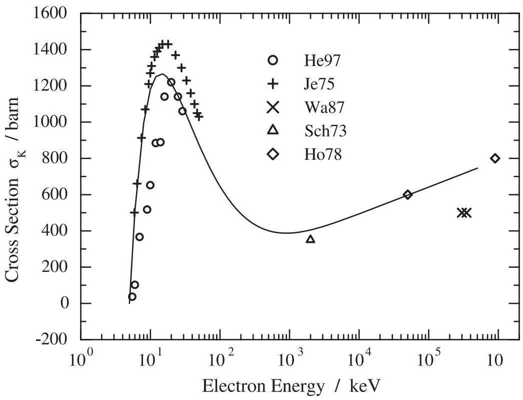

Fig. 4

Fig. 3 – Experimental Ti K_α-yield from a laser-generated plasma as it depends on the laser intensity.

Fig. 4 – Cross-section σ_K for the K-shell ionization of titanium by electron impact. The data points are experimental values from different sources, collected in [10]. The solid line represents the theoretical cross-section given by eq. (3).

respect to the main laser pulse is known. No further prepulses at other times are measurable within a relative intensity of 10^{-5}. The laser intensity on the target was changed by moving the foil along the beam direction, while the beam size on the target could be controlled by means of a microscope combined with a CCD camera. Thus the intensity could be varied between $2 \cdot 10^{16}\,\mathrm{W/cm^2}$ and $2 \cdot 10^{19}\,\mathrm{W/cm^2}$ by adjusting the focal beam size and keeping the total amount of energy constant. The highest intensity reached was $2 \cdot 10^{19}\,\mathrm{W/cm^2}$, within the 1/e-area ($7\,\mu\mathrm{m}^2$) of the best focus. The error of the measured laser intensity was within 15% for the best focus, *i.e.* the highest intensity; for lower intensities the error increased up to 50% because the beam profile becomes slightly worse at far distances from the focus position.

The X-ray radiation was detected with appropriate energy resolution using a CCD camera in the single photon counting mode. The CCD array consists of 256×1024 pixels. Each of these pixels represents a small Si-detector with its signal being proportional to the deposited photon energy. If at maximum one photon per pixel is detected, a histogram of the energy deposited in all pixels represents the incident spectrum. To avoid any pile-up problems due to summation of the energy of more than one photon within one pixel, we reduced the flux to less than about one photon per 10 pixels. Therefore the camera was located 270 cm apart from the X-ray source and aluminium filters were used to protect the CCD from low-energy bremsstrahlung and from visible light. Strong magnets prevented charged particles from hitting the detector (fig. 1). After subtraction of a bremsstrahlung background, one obtains single-shot spectra as shown in fig. 2 with the well-resolved K_α- and K_β-lines at 4510 eV and 4930 eV, respectively. The line at 1487 eV is due to aluminium K_α-radiation, generated in the Al-filter by bremsstrahlung photons. The absolute Ti K_α-emission yield was derived by integrating the number of K_α-photons registered by the CCD and calculating the total yield per laser shot in 4π, considering filter transmission and quantum efficiency of the CCD. The quantum yield of the CCD was measured seperately with titanium K_α-fluorescence excited by a conventional tungsten X-ray tube.

Results. – Figure 3 shows the K_α-emission from a laser-produced titanium plasma as it depends on the laser intensity. The K_α-yield is plotted in number of photons per laser shot into full solid angle. Beginning with low intensities, the K_α-emission increases steadily with laser intensity and shows a maximum at $3{\cdot}10^{17}\,\mathrm{W/cm^2}$. The maximum K_α-yield is 10^{12} photons per shot. With still rising laser intensity the K_α-signal decreases again and reaches a minimum at about $10^{18}\,\mathrm{W/cm^2}$. This behaviour is already known and has been presented for laser-produced Cu-K_α-radiation, but without an absolute intensity scaling [4]. At intensities above $10^{18}\,\mathrm{W/cm^2}$ however, a second increase up to the maximum yield of K_α-photons of, again, 10^{12} photons per laser shot at $2\cdot 10^{19}\,\mathrm{W/cm^2}$ is found, which has not been observed earlier.

The experimental accuracy is mainly determined by the error of the CCD sensitivity and the shot-to-shot variations in laser intensity. The statistical and absolute errors in the K_α-yield are determined to be $< 10\%$ and 50%, respectively.

For different emission angles, the intensity dependence has been measured and no anisotropy in the K_α-signal was observed. Between all four directions examined, target normal (0°), specular (−45° with respect to target normal), in laser direction (225°) and 135°, no significant deviations either in the qualitative behaviour of the characteristic intensity dependence, or in the absolute K_α-yield was found.

Interpretation and modeling of K_α-production. – We calculate the K_α-yield involving a relativistic energy distribution $f(U_0,T)$ of the electrons and the relativistically correct K-ionization cross-section σ_K for electron impact. Additionally, we take into account the energy-dependent path length of the electrons in a target of finite thickness. The number of K_α-photons produced in a titanium foil with a density of atoms n_{Ti} and the fluorescence quantum yield η of the K-transition is given by

$$\mathrm{d}^2 N_\alpha \;=\; \eta\, n_{\mathrm{Ti}}\, N_{\mathrm{e}}\, f(U_0,T)\sigma_K(U_0)\,\mathrm{d}x\,\mathrm{d}U_0. \tag{1}$$

N_{e} is the number of laser-accelerated electrons incident on the target. Their energy distribution $f(U_0,T)$ is assumed to be a 3-dimensional relativistically correct normalized distribution function. With the relativistic energy $\varepsilon(\boldsymbol{p})$ and a normalization factor N, it follows from $f(\boldsymbol{p}) = N\cdot\exp[-\varepsilon(\boldsymbol{p})/T]$:

$$f(U_0,T)\,\mathrm{d}U_0 = \frac{e^{-1/\alpha T}}{T K_2(1/\alpha T)} e^{-U_0/T}(1+\alpha U_0)\sqrt{(1+\alpha U_0)^2-1}\,\mathrm{d}U_0, \tag{2}$$

wherein $K_2(1/\alpha T)$ is the modified Bessel function of second order, $T = k_{\mathrm{B}}T_{\mathrm{e}}/E_K$ (T_{e} the electron temperature) and $\alpha = E_K/m_0c^2$. In the low-temperature limit, for $T \ll m_0c^2$ this distribution becomes the classically correct Maxwellian velocity distribution. $f(U_0,T)\,\mathrm{d}U_0$ may also be derived in the general framework of relativistic thermodynamics [11]. This distribution function assumes that electrons enter the target isotropically, which is an adequate assumption for weakly relativistic electrons up to a few MeV as has been verified by experiments [2]. As K-ionization cross-section σ_K we use a semiempirical expression derived by Quarles *et al.* [12], based on the Bethe theory of ionization [13] corrected for relativistic electron energies:

$$\sigma_K(U_0) = 828\cdot 10^{-16}\frac{R}{E_K^2}\frac{\ln U_0}{U_0}\,\mathrm{cm^2eV^2}. \tag{3}$$

Figure 4 shows a collection of measured K-ionization cross-section data compared to eq. (3). The cross-section yields its maximum at about four times the ionization edge ($U_0 \approx 4$). In a nonrelastivistic treatment the cross-section would decrease for higher electron energies. The relativistic correction factor R in eq. (3) behaves as $R \approx 1$ for small U_0 and $\alpha \ll 1$ and as $R \sim U_0$ for $U_0 \gg 1$. It therefore reproduces the logarithmic increase of the cross-section for relativistic electrons.

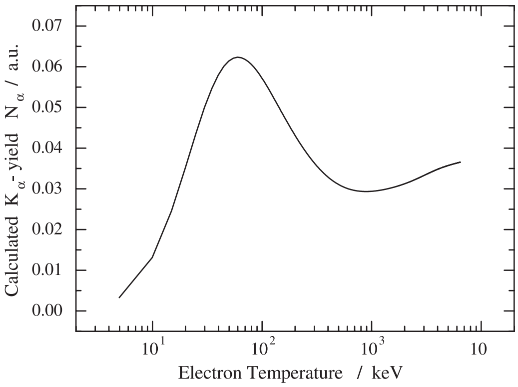

Fig. 5

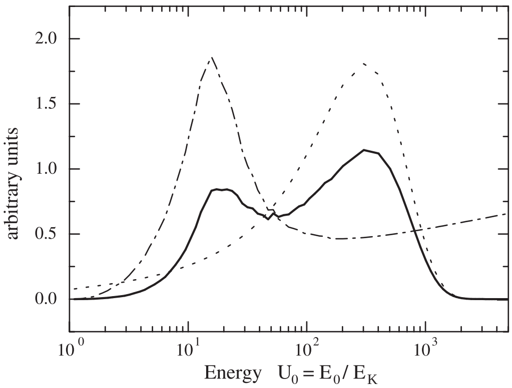

Fig. 6

Fig. 5 – Calculated Ti K_α-yield from the laser-irradiated titanium foil as a function of electron temperature T, determined for the relativistic electron energy distribution function $f(U_0, T)$ in eq. (2).

Fig. 6 – Comparison of $f(U_0)$ (dotted line), $I(U_0)$ (dash-dotted line), and $f(U_0) \cdot I(U_0)$ (solid line) as defined in eqs. (5) and (2) for a relativistic electron temperature $T = 1\,\mathrm{MeV}$.

The path length $\mathrm{d}x$ in eq. (1) which the hot electrons with energy U_0 may cover inside the target depends on their incident energy and on the target thickness d. For low-energy electrons which are completely stopped inside the $12\,\mu\mathrm{m}$ target $\mathrm{d}x$ represents the Bethe range r_B. This length is defined by the stopping power S of the continuous slowing-down approximation [13]:

$$r_\mathrm{B} = \int_1^{U_0} \frac{E_K}{\rho \cdot S}\,\mathrm{d}U \qquad \text{with} \qquad S = -\frac{E_K}{\rho}\frac{\mathrm{d}U}{\mathrm{d}x}. \tag{4}$$

As their energy increases, the electrons may escape from the target with a rest energy U_B, which increases with the incident energy U_0. The travelled path length of the electrons and the rest energy U_B were determined by Monte Carlo simulation. As the electrons loose energy while scattered in the target, the ionization cross-section $\sigma_K(U_0)$ changes during the stopping process (see fig. 4) and has therefore to be integrated over the energy loss $\mathrm{d}U$. For high-energy electrons with $E_0 > 700\,\mathrm{keV}$, *i.e.* $U_0 > 140$, the energy loss inside the target material is so small that the cross-section $\sigma_K(U_0)$ can be considered to be constant between U_0 and U_B, and the path length $\mathrm{d}x$ reduces to the target thickness $d = 12\,\mu\mathrm{m}$. In principle, the space charge built up in the foil due to the escaping electrons could lead to an oscillating motion of some electrons and thus to an increased K_α-yield due to returning electrons. This effect is, however, estimated to be small since the return time of the electrons is considerably larger than the laser pulse duration. These considerations lead to the following equation for the K_α-production in the titanium foil:

$$N_\alpha(T) = n_\mathrm{Ti}\,\eta\,N_\mathrm{e} \int_1^\infty f(U_0, T) I(U_0)\,\mathrm{d}U_0, \tag{5}$$

with

$$I(U_0) = \begin{bmatrix} \displaystyle\int_{U_\mathrm{B}}^{U_0} \frac{\sigma_K(U)}{\rho \cdot S(U)} \cdot E_K\,\mathrm{d}U, & U_0 \le 140 \\ d \cdot \sigma_K(U_0), & U_0 > 140 \end{bmatrix}. \tag{6}$$

Solving this integral leads to the number of K_α-photons as a function of the electron temperature as plotted in fig. 5. The qualitative behaviour of the calculated K_α-yield obviously shows the same characteristics as the experimental results in fig. 3: after reaching a maximum at an electron temperature of 60 keV the K_α-yield drops at higher temperatures before it rises again above $T = 900\,\text{keV}$. Figure 6 shows the cross-section weighted by the path length $I(U_0)$, the energy distribution $f(U_0, T)$ for the relativistic temperature $T = 1\,\text{MeV}$ and the product $f(U_0, T)I(U_0)$, which is the argument in the yield integral equation (5). Notice the logarithmic energy scale. From $f \cdot I$ it is obvious that mainly electrons with energies E_0 in the range of 500 keV to 5 MeV contribute to the K_α-yield at relativistic temperatures. With increasing temperature the share of relativistic electrons in the K_α-production grows further. The increasing yield which has been measured for intensities above $10^{18}\,\text{W/cm}^2$ is therefore due to the growing ionization cross-section at relativistic electron energies. This result is in good agreement with the fact that at laser intensities above $10^{18}\,\text{W/cm}^2$ plasma electrons are accelerated to relativistic energies by the ponderomotive potential of the intense laser field [14].

Nevertheless, comparing quantitatively the intensity scale of the experimental data at the maximum and minimum (fig. 3) and the electron temperatures of the model (fig. 5) a discrepancy with previous experimental data is conspicuous [15]. Following the ponderomotive scaling $T \sim (I\lambda^2)^{1/2}$ [14], intensities of $3 \cdot 10^{17}\,\text{W/cm}^2$ (corresponding to the maximum of the K_α-yield presented here) and $2 \cdot 10^{18}\,\text{W/cm}^2$ (at the minimum) should cause hot electron temperatures of about 35 keV and 200 keV, respectively. The calculated K_α-yield, however, reaches its maximum at an electron temperature $T = 60\,\text{keV}$ and the minimum at $T = 900\,\text{keV}$. In the same way vacuum heating ($T \sim (I\lambda^2)$) [16] and resonance absorption scalings ($T \sim (I\lambda^2)^{1/3}$) [17,18] do not correspond satisfactorily to our experimental data.

Since there is no doubt in the correctness of the K-ionization cross-section σ_K and the interaction length $\mathrm{d}x$ between electrons and target, the only free parameter in the integral eq. (5) is the energy distribution $f(U_0, T)$ and its normalization. In the model we assume a relativistic energy distribution, which requires a thermal equilibrium and a constant number of accelerated electrons over the whole intensity regime. However, to date no detailed knowledge about the actual shape of the hot electron distribution in laser-produced plasmas exists. For example, the number of accelerated electrons may well depend on the laser intensity, as the small 600 fs prepulse generates a preplasma whose scale length increases with intensity. To describe phenomenologically electron spectra from laser-produced plasmas a biexponential distribution function $f'(U_0, T_1, T_2) = Ae^{-U_0/T_1} + Be^{-U_0/T_2}$ is frequently assumed [19]. We solved the yield integral eq. (5) for a biexponential distribution taking the ratios A/B and T_1/T_2 from experimental data at a laser intensity of $5 \cdot 10^{18}\,\text{W/cm}^2$ on a $12\,\mu\text{m}$ tantalum target. These values and the total absorbed energy were assumed to be constant over the entire intensity range from $10^{16}\,\text{W/cm}^2$ to $10^{19}\,\text{W/cm}^2$. The calculated K_α-yield exhibits a maximum at about 200 keV and does not rise at relativistic temperatures. In contrast with this result different 1-dimensional, single-exponential distribution functions were tested, and all of them produced the same qualitative behaviour as shown in fig. 5 with the K_α-yield increasing at relativistic temperatures.

These results support the choice of the relativistic energy distribution (eq. (2)), which does not overestimate the contribution of low-energy electrons at high temperatures, as the biexponential distribution does. On the other hand, the discrepancy between the experimental data and the model, even with the relativistic distribution function, points to the fact that the shape and the nature of the electron distribution function of plasmas produced by high-intensity lasers is still unknown.

Conclusions. – We have experimentally determined the yield of Ti K_α-radiation from a relativistic laser-produced titanium plasma. The yield exhibits a pronounced maximum at a laser intensity of $3 \cdot 10^{17}\,\text{W/cm}^2$, corresponding to a plasma electron temperature of about five times the titanium K-shell ionization energy. Above laser intensities of $10^{18}\,\mathrm{W/cm^2}$ the K_α-yield increases due to the influence of the logarithmically increasing cross-section at relativistic electron energies. This can be deduced from our analytical model including a relativistic electron energy distribution and the cross-section for K-shell ionization.

Since the number of fast electrons still increases with laser intensity, a further increase of the K_α-yield above the reached maximum of 10^{12} photons/shot/4π appears to be possible at higher laser intensities. Furthermore, at high intensities mostly the high-energy electrons contribute to the K_α-radiation as we have shown before. These electrons are not significantly deflected inside the titanium foil, from which it follows that the emission volume of K_α-radiation due to relativistic electrons should be in the order of the focus size.

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