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Nuclear Excitation with High Intensity and Ultra Short Laser Pulses.

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Abstract

Energy and angular distributions of the fast outgoing electron beam induced by the interaction of a 1 J, 30 fs, 2×10^{19} W/cm^2, 10 Hz laser with a thin foil target are characterized by electron energy spectroscopy and photo-nuclear reactions. We have investigated the effect of the target thickness on the electron production. Using a 6 µm polyethylene target, up to 4×10^8 electrons with energies between 5 and 60 MeV were produced per laser pulse and converted to γ-rays by Bremsstrahlung in a Ta secondary target. The rate of photo-fission of U, as well as photo-nuclear reactions in Cu, Au and C samples have been measured. In optimal focusing conditions, about 0.06 % of the laser energy has been converted to outgoing electrons with energies above 5 MeV. Such electrons leave the target in the laser direction with an opening angle of 2.5°.

1 Experimental methods

The experiment was carried out using the chirped pulse amplification beam of the "salle jaune" Ti-sapphire laser system at Laboratoire d'Optique Appliquee (LOA). The laser wavelength was 0.8 µm, the pulse duration was 30 fs and the incident energy on the target was 1 J. The laser pulse was focused within a 10-µm diameter spot including 50 % of the energy, using an f/6 off-axis parabolic mirror. The laser was directed on the target at normal incidence. The energy distribution of the electrons exiting from the polyethylene target was measured with a magnetic spectrometer, which was installed behind the target at 0° with respect to the laser beam direction. The entrance of the spectrometer was defined by a 1 cm diameter diaphragm mounted at 40 cm from the target defining a solid angle of 0.5 msr. The electrons were detected with five Si diodes. The output signals were analysed by a digital oscilloscope. The full electron energy range between 5 MeV and 200 MeV, was covered by changing the current intensity in the magnet. The number of electrons of a given energy detected in a diode was proportional to the voltage output. A nuclear activation method was used separately to determine the total number of outgoing electrons emitted within a 42°

half-angle cone with respect to the laser beam direction. This method selects electrons with an energy larger than the energy threshold of the photo-nuclear reaction involved. In a first step, the electron beam created in the plasma and escaping the target, was incident on a 2 mm thick Ta slab (converter) set a few millimetres behind the target. In the interaction, a significant part of the electron kinetic energy was converted into hard photons *via* the Bremsstrahlung mechanism. In a second step, these photons induced photo-nuclear reactions in samples, placed a few cm behind the converter. This nuclear diagnostic was used for measurements of the integrated flux of gammas, as well as for angular distribution measurements. The nuclear reactions used were $^{12}C(\gamma,n)^{11}C$, $^{63}Cu(\gamma,n)^{62}Cu$ $^{197}Au(\gamma,n)^{196}Au$, $^{238}U(\gamma$, fission). The activity measured in each sample was related to the angular and energy distributions of the photons, and, of the electrons using numerical simulations of particle interaction with the Monte-Carlo code GEANT. This code describes the propagation of high energy electrons and photons through the converter and the activation sample. The experimental set-up, was given as an input to the code. GEANT takes into account elastic and inelastic collisions, production of secondary particles and their secondary processes. Since we were interested in the yield of photo-activation reactions with thresholds of 5.8 MeV and more, only electrons with energies larger than 5 MeV have been considered. 10^6 particles were used in simulations and the initial distribution of outgoing electrons was approximated by a Maxwellian distribution in energy and a Gaussian angular distribution : (1) $d^2N_e/dEd\Omega = N_0 \exp(-E/T_h) \exp(-\theta^2 \ln 2 / \langle\theta_e\rangle^2)$ which is a good approximation to our experimental results. The temperature of hot electrons T_h was taken from the spectrometer measurements of the electron distribution at zero degree and the mean divergence angle $\langle\theta_e\rangle$ has been adjusted to fit the observed angular divergence of photons in the activated samples.

2 Experimental results

We have investigated the production of fast electrons by varying the target thickness and the focusing conditions of laser beam. Thin foils were mounted on a 70 µm thick Ni grid. Figure 1 shows the number of electrons escaping the target, N_e, per energy unit (MeV) and per solid angle unit (sr) measured at 0° with respect to the spectrometer. The targets were polyethylene films with a thickness of 2, 6 and 100 µm. The error bars result from an average of three consecutive measurements made in the same conditions. The energy distributions are well-fitted with the Maxwellian distribution of equation (1), characterized by a hot temperature T_h.

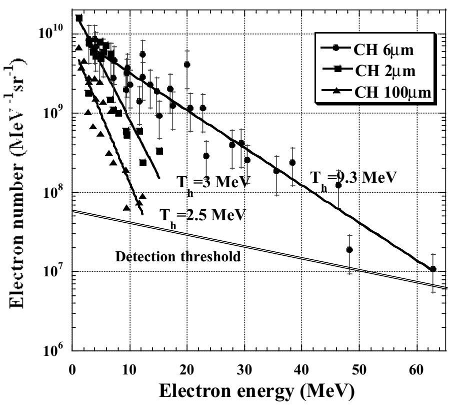

Fig. 1: Experimental electron energy distributions measured at 0°.

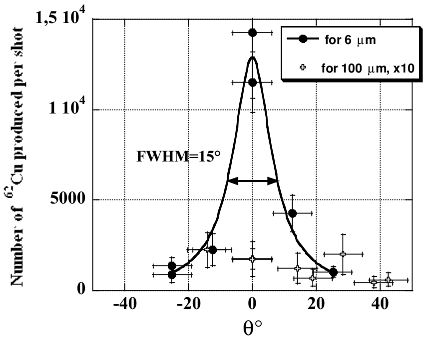

Fig. 2 : Number of $^{63}Cu(\gamma,n)^{62}Cu$ reactions produced per shot using 6 and 100 µm thick CH target .

Large differences were seen in the distributions depending on the target thickness. The 6 µm thick target produced electrons with energies up to 70 MeV, at the limit of sensitivity of the spectrometer, with a temperature T_h = (9.3 ± 0.9) MeV and N_0 = (9 ± 1)x10^9 e/MeV/sr. For the 2 µm thick target, the number of fast electrons decreases steeply with energy. The corresponding temperature was only T_h = (3.0 ± 0.3) MeV, that is, much less than for the 6 µm foil. The ablation rate of polyethylene in laser-plasma interactions at an intensity of 10^{13} W/cm^2 is of the order of 1 µm per ns. In this case, the target is fully exploded by the prepulse, before the arrival of the main fs-pulse, therefore leading to a plasma density that is too low to produce a large number of fast electrons and to accelerate them to high energies. For a 100 µm thick target, the number of electrons measured in the energy range from 10 to 20 MeV is very small compared to the 6 µm case. The temperature deduced from the data, T_h = (2.5 ± 0.3) MeV, is very similar to the 2 µm target case though the ablation of target before the arrival of the fs-pulse can no longer be invoked in this case to explain the small number of fast electrons. The preplasma length and density should be almost the same as in the 6 µm case. Therefore some mechanism, acting on the electron trajectories between their acceleration at the front side of the target and the entrance in the spectrometer, has to be found to explain the electron energy distribution generated in the interaction of the laser with this thick CH target. Such a mechanism could be either deviation of electrons from the zero degree direction at some angle larger than the aperture angle of the spectrometer (0.5°) or some collective mechanism of electron deceleration. Using known values of photonuclear reaction cross-sections, the integrated number of reactions induced in various samples can be used to determine the absolute number of electrons escaping from the target with an energy larger than the reaction threshold energy. The measurements of activities induced in large Copper slabs (0.4x1.9x1.9 cm^3), placed at 1 cm from the Ta converter and covering an angular range ±42° with respect to the laser beam direction, gave a value for N_r, the number of reactions : N_r = (9000 ± 2000) reactions per shot. The normalization of the measured reaction yields to the simulation results allows us to evaluate the number of outgoing electrons, N_e, with energies above the reaction threshold in the experiment. From the results obtained in the photo-activation of Cu, we obtain : $N_e = (3.1 \pm 0.8)\text{x}10^8$. This number allows us to estimate also the solid angle of the electron emission from the target assuming that they have a smooth angular distribution with the maximum in the laser beam direction. Indeed, integrating the electron energy distribution (1) over the energies above the minimum energy of 5 MeV used in GEANT simulations and using T_h = 9.3 MeV and $N_0 = 9\text{x}10^9$ e/MeV/sr obtained with the spectrometer one finds : $dN_e/d\Omega = (5.4 \pm 0.9)\text{x}10^{10} \exp(-\theta^2 \ln 2 / <\theta_e>^2)$ e/sr. Combining these two values, we obtain the mean solid angle value : $\Delta\Omega = \pi<\theta_e>^2$ = (6 ± 2) msr, for the emission of electrons from the CH target with an energy larger than 5 MeV. This solid angle corresponds to a mean opening angle of the electron beam : $<\theta_e>$ = (2.5 ± 0.4)°. We also measured the activation of the Copper sample in interactions with the 100 µm CH target. The number of radioactive ^{62}Cu nuclei in the sample, per laser shot, dropped from approximately 9000 to 2000. Therefore, though electrons with energies above the threshold of the Cu activation were not measured by the spectrometer set along the laser direction, these reactions indicate that a sizable quantity of them was still produced. The results of the photon angular distribution measurement are given in Fig. 2. A fit of the experimental data points with a Lorentzian curve for the 6 µm target gives a FWHM angle for the photon angular distribution of : $<\theta_\gamma>$ = 7.5 ± 1.5 °. The measured angular divergence of the electron beam found for the 6 µm target is in agreement with the value deduced from the integral measurement.

3 Conclusion

We have characterized the energy and angular distributions of high energy outgoing electrons produced in the interaction of a 1 J, 30 fs laser pulse with thin CH foil targets, by measuring the electron energy either with a spectrometer or with photo-nuclear reactions. We have shown that the interaction of a 1 J CPA laser with a 6 µm CH target, produces an electron beam of $3\text{x}10^8$ electrons, collimated within 2.5°, with energies between 5 and 60 MeV and a 9.3 MeV temperature.