

High-energy electron beam production by femtosecond laser interactions with exploding-foil plasmas

D. Giulietti[®], M. Galimberti[®], A. Giulietti, L. A. Gizzi

*Intense Laser Irradiation Laboratory, IFAM, Area della Ricerca CNR, Via Moruzzi 1, 56124
Pisa, Italy*

M. Borghesi

Department of Pure and Applied Physics, The Queen's University, Belfast, BT7 1NN, UK

F. Balcou, A. Rousse, J. Ph. Rousseau

*Laboratoire d'Optique Appliquée, ENSTA, École Polytechnique, Chemin de la Hunière, 91761
Palaiseau, France*

(Received:)

Abstract

The interaction of an ultraintense, 30-fs laser pulse with a pre-formed plasma was investigated as a method of producing a beam of high-energy electrons. We used thin foil targets that are exploded by the laser amplified spontaneous emission preceding the main pulse. Optical diagnostics show that the main pulse interacts with a plasma whose density is well below the critical density. By varying the foil thickness, we were able to obtain a substantial emission of electrons in a narrow cone along the laser direction with a typical energy well above the laser ponderomotive potential. These results are explained in terms of wake-field acceleration.

Typeset using REVTeX

It is well established that the interaction of ultra-short laser pulses with plasmas in the relativistic regime gives rise to the excitation of high amplitude electron plasma waves (wakefields) originating from the ponderomotive expulsion of electrons from the interaction region. In the original scheme of laser wakefield acceleration (LWA) [1] the maximum amplitude of electron plasma waves is achieved when the laser pulse duration is of the order of $1/\omega_p$, where ω_p is the plasma angular frequency. This implies that the shorter the pulse, the higher the plasma density in which these conditions can be achieved, with obvious advantages for the generation of high-energy electrons. In fact higher densities allow higher accelerating electric fields to be achieved [1]. In particular, the density required for this quasi-resonant condition to be established is $n \approx 3 \times 10^{-9} \tau^{-2}$ where n is expressed in el/cm^{-3} , and the laser pulselength, τ in seconds. With τ of the order of several hundreds of femtoseconds, as in the case of recent experiments on LWA [2], this relationship required an electron density of the order of $10^{16} \text{el}/\text{cm}^{-3}$. With a much shorter pulse of 30 fs, as in the case of our experiment, the optimum density for LWA [3] is $\approx 3 \times 10^{18} \text{el}/\text{cm}^{-3}$, i.e. more than two order of magnitude higher.

When this quasi-resonant condition is not satisfied and the laser pulse is longer than $1/\omega_p$, the interaction process enters the regime of self-modulated laser wakefield acceleration (SMLWA) [4]. In this case, electrons are trapped in high-amplitude electron plasma waves generated by stimulated Raman forward scattering (SRFS) [5].

From the point of view of laser-driven, plasma-based accelerators, the original LWA scheme is certainly a more adequate mechanism compared with SMLWA because of the unpredictable behavior of the SRFS instability [2]. Until now, the possibility of investigating the LWA scheme in a relatively high-density plasma has been strongly limited by the lack of intense, ultra-short (< 50 fs) laser pulses. Only recently an experiment has been reported [6] in which electron acceleration was investigated in the interaction of a 29 fs laser pulse with a gas jet at a relatively high intensity. On the other hand, it is well known that in the case of interaction with a gas jet, the CPA pulse itself ionizes the medium, consequently propagation is likely to be strongly affected by refraction. Therefore it is crucial to investigate

the interaction of such very short pulses with a preformed plasma, a configuration in which the lack of experimental data is basically absolute.

In this work we report measurements on fast electron generation which, to our knowledge, are the first in the regime of ultra-short laser interaction with preformed plasmas at ultra-relativistic intensities. The basic idea of the experiment was to try to profit of the nanosecond pedestal arising from amplified spontaneous emission (ASE), typical of CPA laser systems, to pre-form a plasma having a density of the order of the one required for the onset of LWA over a suitable length. The exploding-foil technique is well established as a highly reliable plasma pre-forming method which can provide plasmas of large scalelength with rather controllable density profiles. Such plasmas can also be simulated in advance using hydrodynamic numerical codes and can be characterised experimentally in detail [7] [8]. Foil thickness and material, together with the laser features are the key parameters to be controlled to obtain a plasma of the required peak density and scalelength.

The experiment was carried out using the Ti:sapphire laser at the "Salle Jaune" of the Laboratoire d'Optique Applique which operated at a wavelength of $0.815 \mu\text{m}$ and delivered up to 800 mJ on target in a 30 fs FWHM pulse [9]. The linearly polarized (p on target) beam of the LOA laser was focused in a $5 \mu\text{m}$ (FWHM) diameter spot on a thin plastic (FORMVAR) foil target, by using an $f/5$ off-axis parabolic mirror, with an angle of incidence on target of 20 degrees. In this configuration the intensity of the ASE prepulse on target was greater than 10^{14} W/cm^2 , i.e. well above the plasma formation threshold in such thin plastic foils [10]. Therefore an exploding foil-like plasma could indeed be generated prior to the arrival of the main (30 fs) pulse. Two-dimensional hydro-code simulations performed using the 2D Eulerian hydrocode POLLUX [11] show that with this ASE intensity and focal spot size, a large scalelength (mm-sized) plasma with a peak density of approximately $10^{-3}n_c$, ($n_c = 1.7 \times 10^{21} \text{ el/cm}^{-3}$ being the critical density), i.e. just above 10^{18} cm^{-3} , is produced with a $\approx 1 \mu\text{m}$ thick plastic foil.

A schematic set up of this experiment is shown in Fig.1. High-energy electrons produced by the CPA interaction with the plasma propagate in the vacuum before colliding with the

chamber wall, which acts as a bremsstrahlung γ -ray converter. For a given direction of propagation of the electrons impinging on the converter, bremsstrahlung γ -ray photons are emitted in a cone of aperture $\theta \approx 1/\gamma$ where γ is the relativistic factor of the electrons. Provided that the electron energy is sufficiently high ($\gg 1$ MeV), the original electron angular distribution is then preserved and can be retrieved from the photon angular distribution. Our γ -ray detectors consisted of four 24.5 mm diameter, NaI(Tl) crystal scintillators of 12.5 mm, 25.4 mm, and 50.8 mm thickness respectively, coupled to photomultipliers (PMs). They were calibrated in the single photon regime using emission lines from several radioactive sources including the 511 keV and 1274 keV lines from ^{22}Na source and 898 keV and 1836 keV lines from a ^{88}Y source.

These detectors were placed 5 meters away from the target and could be moved around the chamber to perform angular distribution measurements. They were shielded by the heavy background radiation by means of lead bricks, while the line of sight was attenuated with layers of lead sufficiently thick to keep the PM signal below saturation. The response of each detector to an interaction event consists of pulse with a rise time of the order of a few nanoseconds, set by the photomultiplier tube, and by a fall time of 230 ns, which is the decay time of the scintillator. The height of the pulse is a measure of the energy released in the scintillator crystal by the radiation that reaches the detectors. The lower energy limit of the spectral response window of each detector is approximately 10 keV and is determined by the 1 mm thick Al case which contains the NaI(Tl) crystal. The upper energy limit is instead determined by the thickness of the crystal itself. The thickness of the shortest crystal, i.e. the 12.5 mm corresponds to the attenuation length of ≈ 50 keV photons while the 24.5 mm corresponds to the attenuation length of 300 keV photons. For a thickness greater than 50 mm, the attenuation length is basically independent of the photon energy up to the 100 MeV region. Clearly, when a lead attenuator is used, the overall spectral response of our detection system is modified. As discussed below, additional information is then needed to extract spectral information from the data.

First of all we point out that our detectors measured an intense γ -ray signal in the forward

direction only when the 1 μm thick target was placed in the waist of the focusing optics. In these conditions, the emission was so intense that very thick layers of lead had to be used to reduce the PM signals down to a working regime. Numerical simulations [12] show that in this configuration of very thick attenuator lead basically acts as a simple, energy independent attenuator which reduces the signal by approximately one order of magnitude every 5 cm of lead (exponential law) for all photon energies above a few MeV, which corresponds to an attenuation coefficient $\alpha = 0.46 \text{ cm}^{-1}$. The measured γ -ray signal consisted of a main component due to bremsstrahlung of primary electrons and a diffuse component due to secondary scattering processes. The diffuse component was separated from the main one by taking into account the measured dependence of the γ -ray signal upon of the thickness of lead. Fig.2 shows the dependence of the bremsstrahlung γ -ray signal for all the four detectors, as a function of the thickness of the attenuator. The diffuse component of γ -ray photons was obtained by fitting the data with the function $S(x) = S_c \exp(-\alpha x) + B$, where S_c is the main component, x is the lead thickness and B is the diffuse component. The result of the fit is shown by the curves in Fig.2. According to this result, the signal after 15 cm of attenuator is mostly due to the diffuse component, while for smaller thickness the main γ -ray component accounts for most of the signal.

As mentioned above, the working regime of our detectors was such that additional data is needed to obtain detailed spectral properties of the detected γ -rays. However, detailed Montecarlo simulations [12] compared with our γ -ray measurements strongly suggest that a population of fast electron with energies of many tens of MeV is generated. In fact, from our data a relationship was obtained which links the total number of electrons produced during the interaction and their typical energy. From simple energy balance considerations, and assuming an energy conversion into mono-energetic electrons of 10%, it can be shown that our results are consistent with a beam of 10^{11} electrons with an energy of approximately 30 MeV impinging on the bremsstrahlung converter. If a smaller number of electrons is produced, then a higher electron energy must be assumed in order to satisfy the energy balance. These considerations enable us to reasonably conclude that a fraction of the electrons generated in

our experiment had an energy greater than 30 MeV.

At these values of the electron energy, indirect angular distribution measurements based upon bremsstrahlung emission, like the one used in our experiment, are expected to give a good, though overestimated, measure of the electron beam aperture. The angular distribution of the main component of the γ -ray emission was measured moving the detector assembly around the target chamber at a fixed distance of 5 m as shown in the set up of Fig.1. Data were taken with different attenuator thickness depending on the signal strength. The result is summarised in the plot of Fig.3 where the signals of all the four detectors are shown. In this plot each data-point corresponds to an average of typically 5 shots taken over two different runs (one run from 0 deg to 60 deg and another run back to 0 deg). The vertical error bars represent the actual statistical error of all measurements taken at a given angle and are therefore a measure of the reproducibility of our results. According to this plot, the γ -ray radiation generated by the interaction of primary electrons with the chamber walls is preferentially emitted along the CPA direction. A best fitting of the data yields an aperture of the γ -ray emission cone of approximately $\Theta_{FWHM} = 42$ deg. Measurements performed at angles larger than 60 deg, including the backward direction (with respect to the CPA laser axis), showed only signal due to the diffuse γ -ray component.

The plot of Fig.3 clearly shows that we have generated a population of high-energy electrons that are emitted in a narrow cone along the direction of the laser pulse. In the absence of an detailed information of the spectral distribution of the electrons, an exact evaluation of the electron beam aperture from our γ -ray data would be rather uncertain and is anyway beyond the aim of this work. In fact, further experiments are being planned which will provide more detailed and quantitative measurements of these features. Here we would like to stress that these measurements provide a clear evidence that electron acceleration in a preformed plasma has been activated in our experimental configuration and, as further discussed below, LWA is the most likely candidate to explain our observations.

Optical imaging and spectroscopy in both the forward and the backward directions were also carried out in order to monitor the interaction conditions from the point of view of prop-

agation of the CPA pulse through the plasma. These measurements, a detailed description of which is given elsewhere [13], confirm that the pulse was transmitted through an underdense preformed plasma with no significant changes neither in its cross-section intensity distribution nor in its spectrum. Only a small fraction of the incident laser light was reflected or scattered at large angles from regions that are marginal with respect to the main propagation region. The spectrum of the transmitted light shows a small red-shifted tail which is most likely due to self phase modulation (SPM) originating from the ponderomotive expulsion of electrons in the interactions region. No detectable Raman scattered radiation was found in the forward optical spectroscopy channel. This is consistent with models of interaction with ultrashort, high-intensity pulses [14] which also predict substantial suppression of the SFRS instability.

Finally, thinner targets ($0.1 \mu\text{m}$) were also used to generate a preformed plasma with a much lower peak density at the time of the CPA interaction, roughly $10^{-4}n_c$. In this case no detectable γ -ray signal was found which corresponds to a reduction of more than two orders of magnitude when compared to the case of interaction with a $1 \mu\text{m}$ thick target. A dramatic decrease of the γ -ray signal was also observed when the $1 \mu\text{m}$ foil was moved out of the best focus of the laser focusing optics by more than two Rayleigh lengths. All these observations show that conditions for high-energy electron production only exist in a narrow region (tuning) of our experimental parameters suggesting that quasi-resonant LWA is the most likely candidate to explain our bremsstrahlung γ -ray measurements.

In conclusion we studied the interaction of an ultra-short, ultra-intense, 30 fs CPA laser pulse with a plasma preformed by the laser ASE from a thin foil target using the exploding foil technique. The foil thickness was chosen in order to obtain a preformed plasma of $\approx 10^{-3}n_c$, suitable for quasi-resonant laser wakefield acceleration with a 30 fs laser pulse. Optical measurements confirm that the appropriate interaction conditions for LWA have been achieved. Electron measurements were performed detecting bremsstrahlung radiation from high-energy electrons. Our measurements show for the first time that an intense beam of energetic electrons ($> 30\text{MeV}$) is emitted forward in a narrow cone along the propagation

direction of the CPA pulse interacting with a plasma. These results also demonstrate that our experimental configuration is well suited for studies of the interaction of very powerful, very short (< 50 fs) CPA pulses with preformed plasmas even when multi-beam plasma preforming techniques cannot be implemented.

We would like to thank Antonella Rossi (IFAM Target Preparation Lab.) for target preparation and Alessandro Barbini (IFAM) for data acquisition support, Stefano Silvestri and Ariano Donati (TESRE-CNR) for their invaluable contribution to the calibration of γ -ray detectors and George Grillon (LOA) for technical assistance during the experiment. We also acknowledge the scientific contribution to this work of the two European networks SILASI and GAUSEX. The experiment was partially supported by the EU in the frame of Access to Large Scale Facilities.

REFERENCES

[@] Also at Dipartimento di Fisica Università di Pisa, Unità INFN, Via Buonarroti 2, 56100 Pisa Italy.

- [1] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
- [2] F. Amiranoff et al., Phys. Rev. Lett. **81**, 995 (1998).
- [3] W.P. Leemans et al., Phys. Plasmas **5**, 1615 (1998).
- [4] E. Esarey et al., Phys. Rev. Lett. **80**, 5552 (1998).
- [5] W.B. Mori et al., Phys. Rev. Lett. **72**, 1482 (1994).
- [6] X. Wang et al., Phys. Rev. Lett. **84**, 5324 (2000).
- [7] L.A. Gizzi et al., Phys. Rev. E **49** 5628 (1994)
- [8] M. Borghesi et al., Phys. Rev E **54**, 6769 (1996).
- [9] A. Antonetti et al., Appl. Phys. B **65**, 197 (1997).
- [10] M. Galimberti, L.A. Gizzi, A. Barbini, et al., Laser and Part. Beams **18**, 145 (2000).
- [11] G. J. Pert, J. Comput. Phys. **43**, 111 (1981).
- [12] GEANT4: LCB Status Report/RD44, CERN/LHCC-98-44, (1998).
- [13] M. Galimberti, A. Giulietti, D. Giulietti, L.A. Gizzi, et al, submitted to LPB (2001).
- [14] K.C. Tzeng et al., Phys. Rev. Lett. **79**, 5258 (1997).

FIGURES

FIG. 1. Experimental set up for the study of wakefield acceleration of electrons in the interaction of a ultra-intense CPA pulse with a preformed plasma. The plasma was produced by explosion of a $1\mu\text{m}$ thick plastic foil by the laser prepulse (ASE). Also shown are the main diagnostics for optical and γ -ray measurements.

FIG. 2. Dependence of the bremsstrahlung γ -ray signal as a function of the thickness of the lead attenuator. The diffuse component of γ -ray photons is obtained by fitting the data with a suitable function (see text).

FIG. 3. Angular distribution of bremsstrahlung γ -ray photons detected by the four NaI detectors assembled together. Also shown are the fitting curves which yield an aperture of the angular distribution of approximately $\Theta_{FWHM} = 42$ deg.

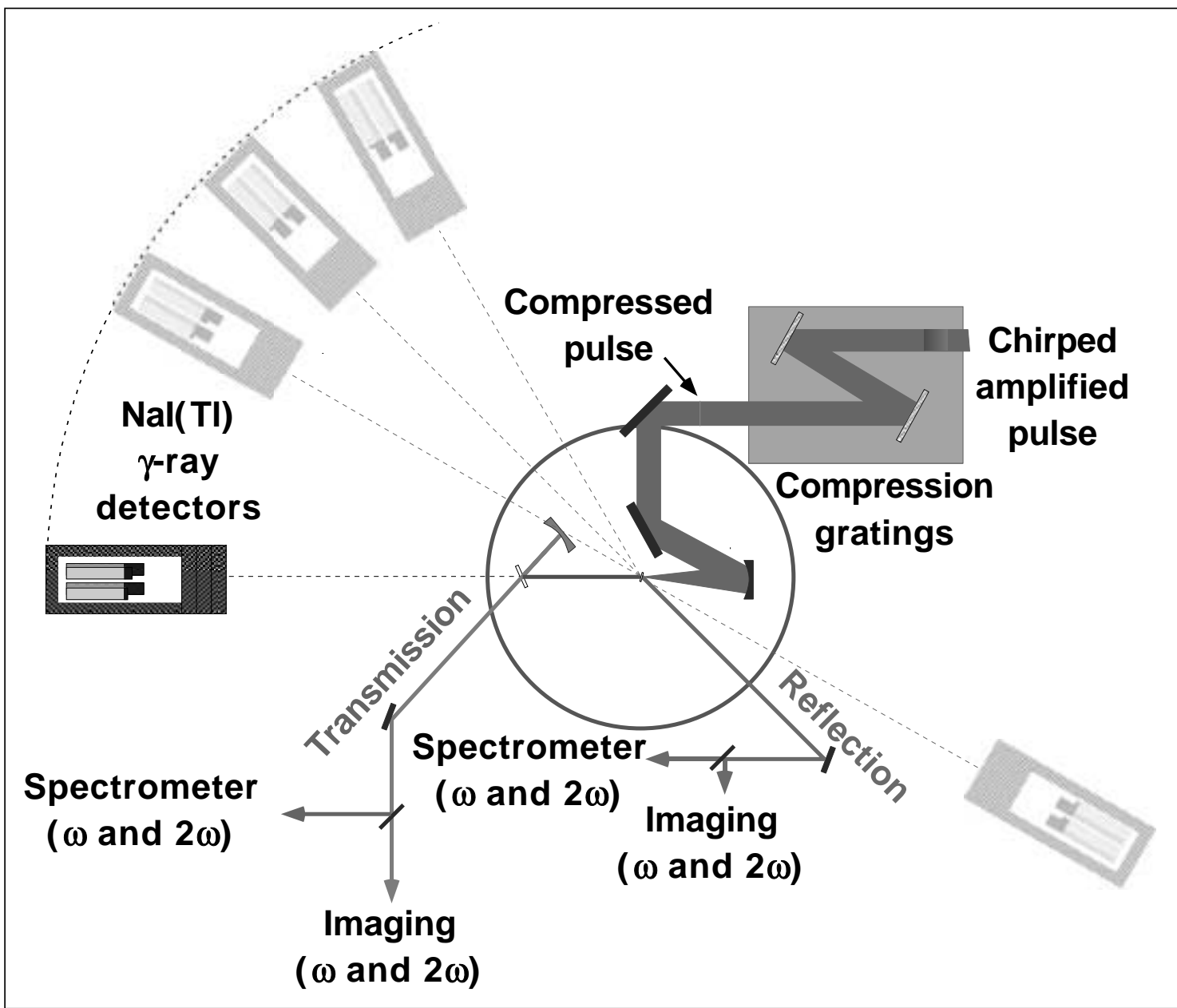


Figure 1

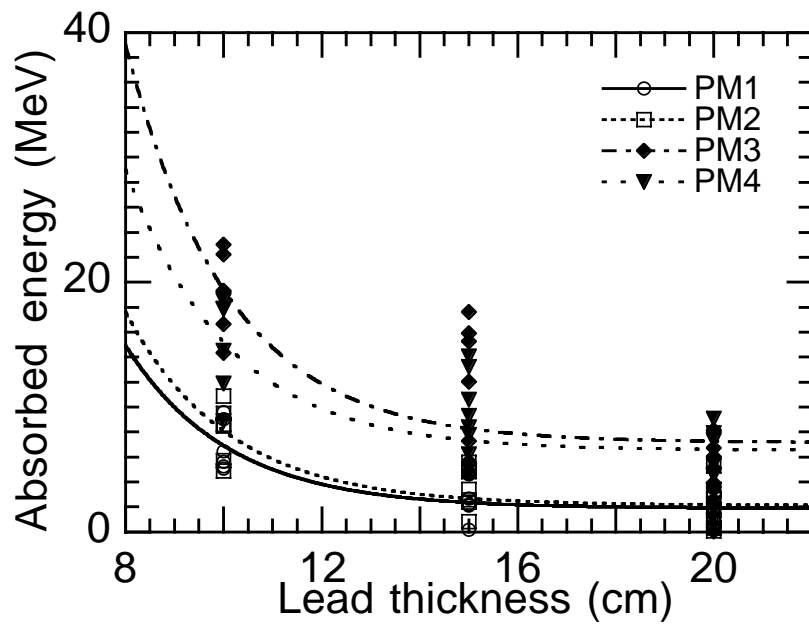


Figure 2

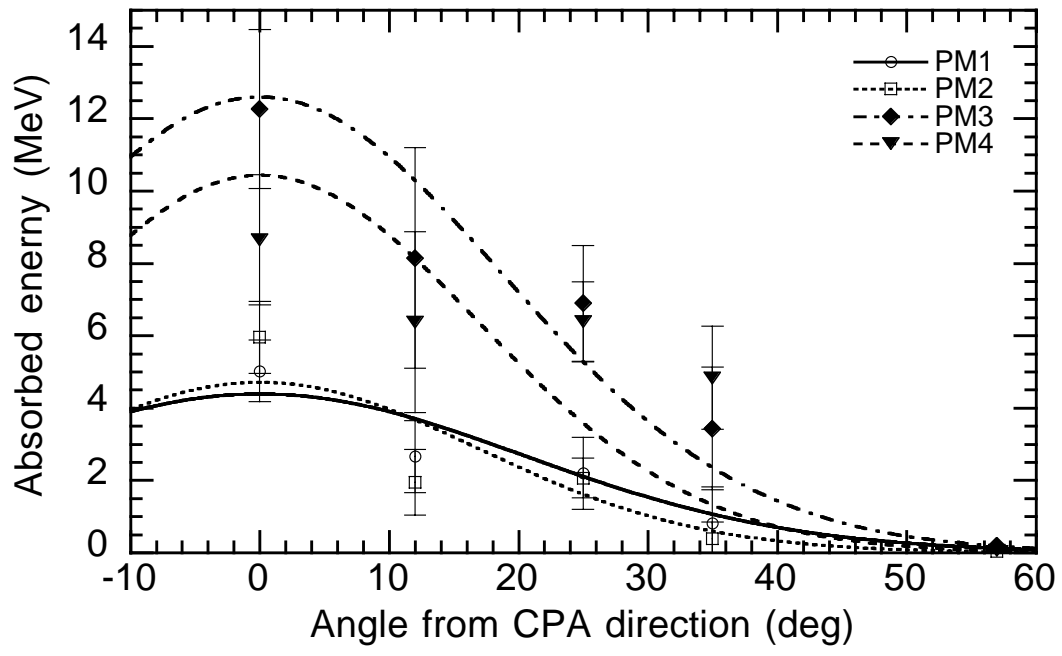


Figure 3