

Estimations of electron-positron pair production at high-intensity laser interaction with high- Z targets

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Electron-positron pairs' generation occurring in the interaction of 10^{18} – 10^{20} W/cm² laser radiation with high- Z targets are examined. Computational results are presented for the pair production and the positron yield from the target with allowance for the contribution of pair production processes due to electrons and bremsstrahlung photons. Monte-Carlo simulations using the PRIZMA code confirm the estimates obtained. The possible positron yield from high- Z targets irradiated by picosecond lasers of power 10^2 – 10^3 TW is estimated to be 10^9 – 10^{11} .

The possibility of electron-positron pair production by relativistic electrons accelerated by a laser field has been discussed since many years [1]. It was estimated that the positron production efficiency can be high [2]. The papers cited considered the case of pair production during oscillations of electrons in an electromagnetic wave in the focal region of laser radiation. Here we examine a somewhat different pair production scenario.

The interaction of high-power laser radiation with matter results in the production of fast, high-temperature electrons [3]. Relativistic temperatures of fast electrons $T_f \approx 1$ MeV have been observed in experiments with powerful picosecond lasers [4]. Self-consistent electric fields confine these electrons in the target. When the electrons interact with the matter in a high- Z target, electron-positron pairs are produced [5]. The annihilation photon spectrum can be used for diagnostics of the electron-positron plasma.

In the present letter we make estimates of the positron and photon yield as function of the laser power. We have made an assessment of the possibility of using high-power (10^2 – 10^3 TW) ultrashort-pulse lasers to produce a high-luminosity positron source. Such sources are required for the production of slow (1–10 eV) positrons with an intensity of 10^8 positrons per second. Such positrons find wide applications for the study of Fermi surfaces, defects and surfaces of various materials [6].

The interaction of relativistic electrons with matter can lead to electron-positron pair production in the following two processes:

$$\begin{aligned} \text{(i)} \quad & e^- + Z \rightarrow 2e^- + e^+ + Z; \\ \text{(ii)} \quad & e^- + Z \rightarrow e + \gamma + Z \rightarrow 2e^- + e^+ + Z. \end{aligned}$$

In Ref. [7] analytical and numerical calculations of the total cross section of the pair electroproduction process are performed using the differential cross section of Ref. [8]. According to this work the total cross section of the process (i) near the threshold equals

$$\sigma_{e \rightarrow 2ee^+} = \frac{7Z^2 r_e^2 \alpha^2 (E_0 - 2mc^2)^3}{2304 (mc^2)^3}, \quad (1)$$

where r_e is the classical electron's radius; $\alpha = 1/137$; mc^2 is the electron mass, and E_0 is the kinetic energy of the initial electron. At high energies the cross section grows as [9]

$$\sigma_{e \rightarrow 2ee^+} = \frac{28\pi Z^2 r_e^2 \alpha^2}{27} \ln^3 E_0 / mc^2. \quad (2)$$

The approximation formula

$$\sigma_{e \rightarrow 2ee^+} = 5.22 Z^2 \ln^3 \left(\frac{2.30 + E_0 [\text{MeV}]}{3.52} \right) \mu\text{barn}. \quad (3)$$

describes both limits.

Fig. 1 shows the points obtained by numerically integrating the exact formulas for the differential section [7], the asymptotic cross sections (2) and (1), and a plot of the approximating function (3).

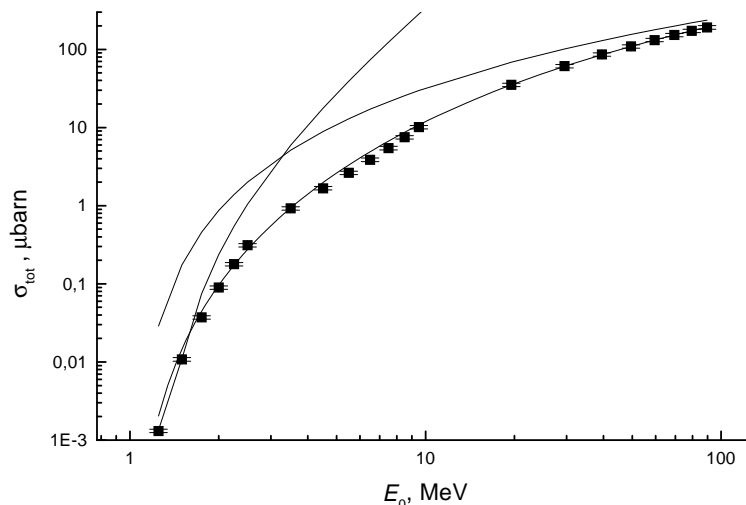


FIG. 1. Total cross section of electron-positron pairs production by electron in a Coulomb field of nucleus with $Z = 1$; numerical data, asymptotics and approximation

The average energy of the positron produced is given by

$$\langle E_+ \rangle = E_0 \left(\frac{1}{3} - .0565 \ln \frac{E_0}{3mc^2} \right). \quad (4)$$

Let us examine the contribution of the process (i) to the electron-positron pair production in matter. Let us assume that the fast electrons produced when the high-intensity laser radiation interacts with matter are confined by self-consistent electric fields, so that electron moderation in the target can be treated just as in infinite media.

The probability of pair production during electron moderation in matter with energy loss from E_0 to threshold $2mc^2$ equals

$$w_e = \int_{2mc^2}^{E_0} \sigma_{e \rightarrow 2ee^+} \left(-\frac{dE}{dx} \right)^{-1} n_i dE, \quad (5)$$

where $\sigma_{e \rightarrow 2ee^+}$ is given by (3), n_i is the ions density, dE/dx is the electron energy loss per unit path length.

Taking the Rohrlich-Carlsson formula [10] for dE/dx , we carried out a numerical computation of the integral in Eq. (5) for the case of lead. Averaging $w_e(E)$ over the relativistic Maxwell distribution with temperature T , we obtained the number of positrons produced relative to one initial electron versus temperature. This dependence is shown in Fig. 2. Performing the same averaging with weight $\langle E_+ \rangle$ from (4), we obtained the average energy of the positrons produced.

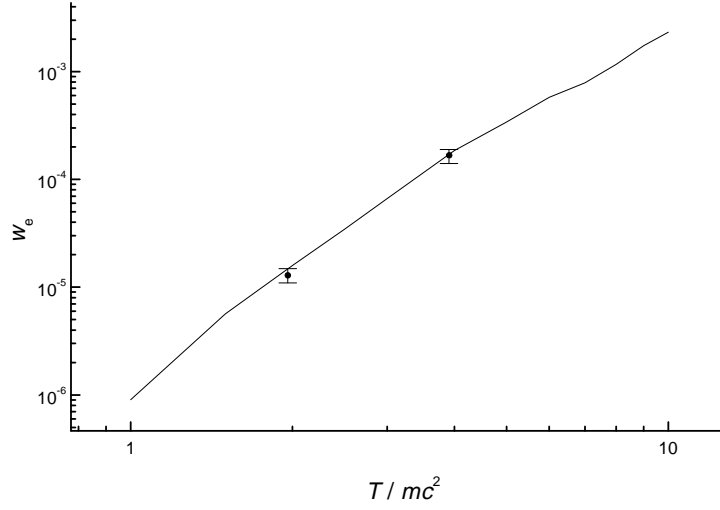


FIG. 2. Probability of positrons production by electron in the Coulomb field of lead's nucleus versus temperature; points — PRIZMA simulation results

The average positron energy determines the required thickness of the target, since the mean free path in matter depends upon energy. For lead this dependence is determined by [11]

$$\rho\Delta_{e^+} = \begin{cases} 0.412 |E|^{1.265-0.0954 \ln E} & 0.01 \leq E \leq 3, \\ 0.53E - 0.106 & 3 < E < 20, \end{cases} \quad (6)$$

where E is given in MeV, $\rho\Delta$ in g cm^{-2} . The positron mean free path in lead for different temperatures of the initial electrons is shown in Fig. 3.

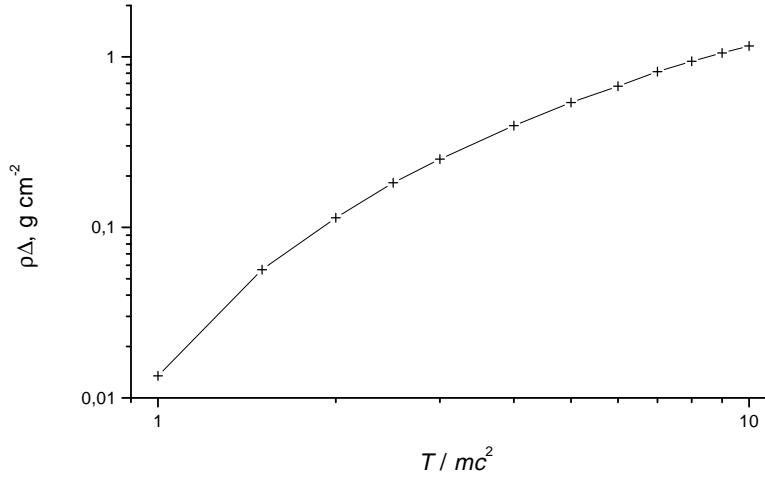


FIG. 3. The free path length of positrons, produced by electrons, in lead as a function of temperature

Let's estimate the probability of pair production by bremsstrahlung photons (process (ii)). In contrast to the electrons confined in the target by the self-consistent electric field, photons can escape from it. The cross section

of the process $\gamma \rightarrow e^+e^-$ is tabulated in Ref. [11] (p. 267). Data on the incoherent photon absorption cross section σ_{aincoh} can also be found there.

The probability of pair production by a single photon of energy ε equals

$$w_\gamma(\varepsilon) = w_a \frac{\sigma_{\gamma \rightarrow e^+e^-}(\varepsilon)}{\sigma_{\text{atot}}(\varepsilon)}, \quad (7)$$

where $\sigma_{\text{atot}}(\varepsilon) = \sigma_{\gamma \rightarrow e^+e^-}(\varepsilon) + \sigma_{\text{aincoh}}(\varepsilon)$, $w_a(\varepsilon) = 1 - \exp(-\sigma_{\text{atot}}(\varepsilon)n_i\Delta)$, Δ is the thickness of the target. For an infinite target

$$w_\gamma^\infty = \frac{\sigma_{\gamma \rightarrow e^+e^-}}{\sigma_{\text{atot}}}. \quad (8)$$

We take the photon spectrum in the form

$$dN/d\varepsilon \simeq \epsilon_{e \rightarrow e\gamma} T^{-1} \exp(-\varepsilon/T), \quad (9)$$

where $\epsilon_{e \rightarrow e\gamma} = 3 \times 10^{-4} ZT/mc^2$ is the ratio of the total bremsstrahlung power radiated to the total power in the incident electron beam determined in Sec. (IV-20) of Ref. [12]. Averaging $w_\gamma(\Delta, \varepsilon)$ over spectrum (9), we obtain

$$w_\gamma(\Delta, T) \simeq \epsilon_{e \rightarrow e\gamma} T^{-1} \int_{2mc^2}^{+\infty} \exp(-\varepsilon/T) w_\gamma(\Delta, \varepsilon) d\varepsilon. \quad (10)$$

The dependence of the number of positrons produced by bremsstrahlung photons relative to one initial electron upon temperature for an infinite slab and two thicknesses is presented in Fig. 4.

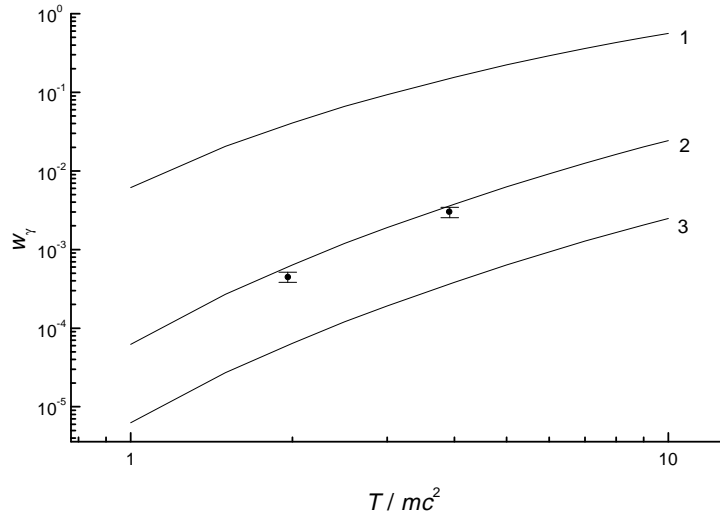


FIG. 4. Probability of positrons production by electron through bremsstrahlung photon in lead for thicknesses $\rho\Delta = \infty$ (curve 1); $\rho\Delta = 3. \text{ g cm}^{-2}$ (curve 2); $\rho\Delta = 0.3 \text{ g cm}^{-2}$ (curve 3) versus temperature; points — PRIZMA simulations with sphere target $\rho R = 2.2 \text{ g cm}^{-2}$

The results of the estimation of the number of positrons produced can be used to estimate the number of annihilation photons in targets with thickness greater than the positrons mean free path (see Fig. 3) but less than that of photons ($\approx 6 \text{ g cm}^{-2}$ for lead). The channel (ii) predominates here. For thickness about $2\text{--}3 \text{ g cm}^{-2}$ the photon yield reaches 0.04% per one source electron with temperature $T \simeq 1 \text{ MeV}$.

To check the estimates, calculations were performed using the PRIZMA code [13], which simulates all basic electron, photon and positron transport and production processes for any geometry (one-, two- and three-dimensional) by the Monte Carlo method. The calculation were performed for a lead sphere with radius $R = 0.2 \text{ cm}$ and an electron source

with temperature $T = 1$ and $T = 2$ MeV at the center. The results are presented in Figs. 2,4. They are in good agreement with our estimates.

According to Ref. [3], the temperature of fast electrons arising during interaction of laser radiation with matter is about

$$T_f \simeq mc^2 \left[(1 + 0.7q_{18})^{\frac{1}{2}} - 1 \right], \quad (11)$$

where q_{18} is the laser power density in $10^{18} \text{ W cm}^{-2}$. When a laser pulse with energy $E_l[\text{J}]$, duration $\tau[\text{psec}]$ is focused into a circle of diameter $d_f[\mu\text{m}]$, the intensity equals $q_{18} = 400 E_l / \pi d_f^2 \tau$. The number of electrons produced is determined by $N_e = A_f E_l / \langle E_f \rangle$, where A_f is the efficiency of laser energy conversion to fast electrons, $\langle E_f \rangle$ is the average energy of fast electrons.

As a target we propose a sphere with conical cavity into which laser radiation is focused [14]. Such a target gives $A_f \approx 0.3$, high luminosity and isotropic yield of photons and positrons from the surface. The target must have high Z , and its optimal diameter is determined by experiment tasks and laser power.

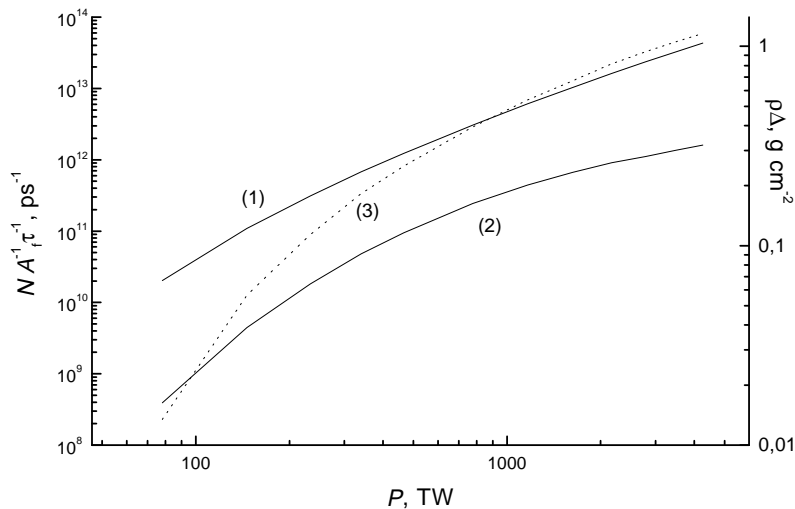


FIG. 5. Dependence of photon (1) and positron (2) yield $N/A_f\tau$ on laser power. Curve (3) shows the optimum size of a target for a positron source.

To detect annihilation photons the target has to be of size $\rho R \approx 2-3 \text{ g cm}^{-2}$. The dependence of annihilation photon yield N_γ divided by A_f and τ , on laser power is shown in Fig. 5. The focal spot is $d_f = 30 \mu\text{m}$. The photon yield is about of $10^{10}-10^{12}$ for a power 10^2-10^3 TW picosecond laser.

The positron yield from the target can be estimated as

$$N_+ \simeq N_e \frac{\rho \Delta_{e^+}}{\rho \Delta_{e^+} + \rho \Delta} \left(w_e + w_\gamma^\infty \frac{\rho \Delta}{\rho \Delta_\gamma} \right). \quad (12)$$

Here $\Delta_{e^+,\gamma}$ are the positron and bremsstrahlung photon mean free paths. The target for positron production must be of order Δ_{e^+} in size (see Fig. 3). The dependence of positron yield N_+ divided by A_f and τ , on laser power is shown in Fig. 5. The dotted line in this figure shows the optimal target size $\rho \Delta$ for such an experiment. The positron yield reaches 10^9-10^{11} for powers 10^2-10^3 TW picosecond laser.

Since the target could be smaller than existing positron sources, the laser positron source can have a very high brightness. The efficiency of conversion of fast positrons (MeV) to slow (1–10 eV) can be as high as 10^{-2} [15]. Therefore, to produce a quasi steady-state source of slow positrons with an intensity of 10^8 positrons per second requires a laser with energy of 10–30 J in 10–30 fs pulse with a repetition frequency 10-30 Hz. Undoubtedly, such a source would be usefull for fundamental and applied researches in solid state physics, electronics, chemistry and biology.

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