Estimates of electron–positron pair production in the interaction of high-power laser radiation with high-Z targets

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Electron–positron production processes occurring in the interaction of 10^{18}–10^{20} W/cm^2 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 with 10^2–10^3 TW laser radiation is estimated to be 10^9-10^{11}.

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The possibility of electron–positron production by relativistic electrons accelerated by a laser field was discussed quite a long time ago.[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 high-power 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 (see Ref. 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 yields as functions 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/s. Such positrons have wide applications for the study of Fermi surfaces, defects, and surfaces of materials.[6]

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

(i) $e^- + Z \rightarrow 2e^- + e^+ + Z$;

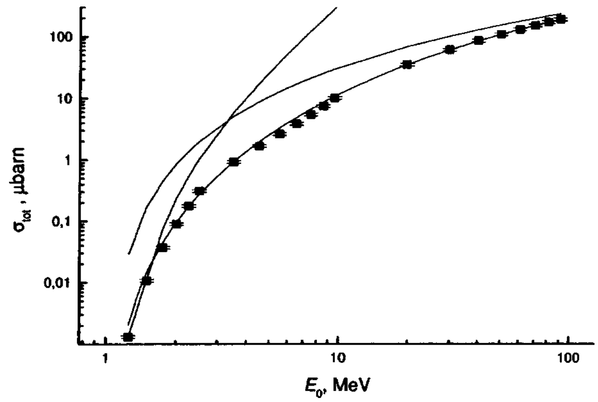

FIG. 1. Total cross section for electron–positron pair production by an electron in the Coulomb field of a $Z = 1$ nucleus; numerical data, asymptotic expressions, and approximation formula.

(ii) $e^- + Z \rightarrow e + \gamma + Z \rightarrow 2e^- + e^+ + Z$.

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

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

where r_e is the classical electron 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]

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

The approximation formula

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

describes both limits.

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

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 stopping in the target can be treated just as in an infinite medium.

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

$$w_e = \int_{2mc^2}^{E_0} \sigma_{e\rightarrow 2ee^+} \left(-\frac{dE}{dx} \right)^{-1} n_i dE, \tag{4}$$

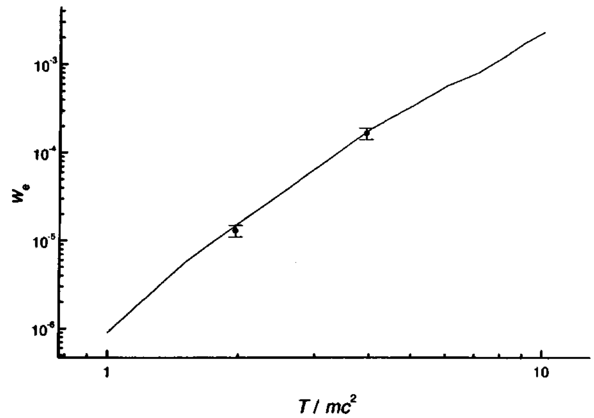

FIG. 2. Probability of positron production by an electron in the Coulomb field of a lead nucleus versus temperature. The data points show the PRIZMA simulation results.

where $\sigma_{e \to 2ee^+}$ is given by Eq. (3), n_i is the ion density, and 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. (4) for the case of lead. Averaging $w_e(E)$ over the relativistic Maxwellian distribution with temperature T, we obtained the number of positrons produced per initial electron versus temperature. This relation is shown in Fig. 2. Performing the same averaging with coefficient E, we obtained the average energy of the positrons produced.

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

$$\rho \Delta_{e^+} = \begin{cases} 0.412 |E|^{1.265 - 0.0954 \ln E}, & 0.01 \leqslant E \leqslant 3, \\ 0.53E - 0.106, & 3 < E < 20, \end{cases} \tag{5}$$

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

Let us 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 the target. The cross section of the process $\gamma \to e^+ e^-$ is tabulated in Ref. 11 (p. 267). Data on the incoherent photon absorption cross section $\sigma_{\alpha \mathrm{incoh}}$ can also be found there.

The probability of pair production by one photon with energy ϵ equals

$$w_\gamma(\epsilon) = w_\alpha \frac{\sigma_{\gamma \to e^+ e^-}(\epsilon)}{\sigma_{\alpha \mathrm{tot}}(\epsilon)}, \tag{6}$$

where $\sigma_{\alpha \mathrm{tot}}(\epsilon) = \sigma_{\gamma \to e^+ e^-}(\epsilon) + \sigma_{\alpha \mathrm{incoh}}(\epsilon)$, $w_\alpha(\epsilon) = 1 - \exp(-\sigma_{\alpha \mathrm{tot}}(\epsilon) n_i \Delta)$, and Δ is the thickness of the target. For an infinite target

$$w_\gamma^\infty = \sigma_{\gamma \to e^+ e^-} / \sigma_{\alpha \mathrm{tot}}. \tag{7}$$

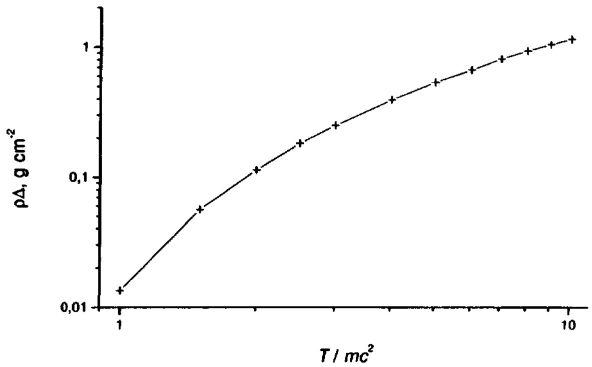

FIG. 3. Mean free path of positrons produced by an electron in lead versus temperature.

We take the photon spectrum in the form

$$dN/dE \simeq \epsilon_{e\to e\gamma} T^{-1} \exp(-\epsilon/T), \tag{8}$$

where $\epsilon_{e\to e\gamma} = 3\times 10^{-4} ZT/mc^2$ is the ratio of the total energy transferred to the bremsstrahlung photons to the total energy of the electrons and was determined in Sec. IV-20 of Ref. 12. Averaging $w_\gamma(\Delta,\epsilon)$ over the spectrum (8) we obtain

$$w_\gamma(\Delta,T) \simeq \epsilon_{e\to e\gamma} T^{-1} \int_{2mc^2}^{+\infty} \exp(-\epsilon/T) w_\gamma(\Delta,\epsilon) d\epsilon. \tag{9}$$

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

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

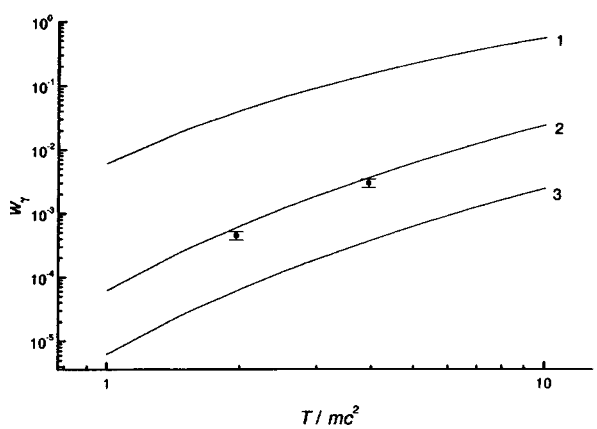

FIG. 4. Probability of positron production by an electron via bremsstrahlung photons in lead for thicknesses $\rho\Delta=\infty$ (curve *1*), $\rho\Delta=3\ \mathrm{g\cdot cm^{-2}}$ (curve *2*), $\rho\Delta=0.3\ \mathrm{g\cdot cm^{-2}}$ (curve *3*) versus temperature. The data points show the PRIZMA simulation results for a lead sphere of radius $\rho R=2.2\ \mathrm{g\cdot cm^{-2}}$.

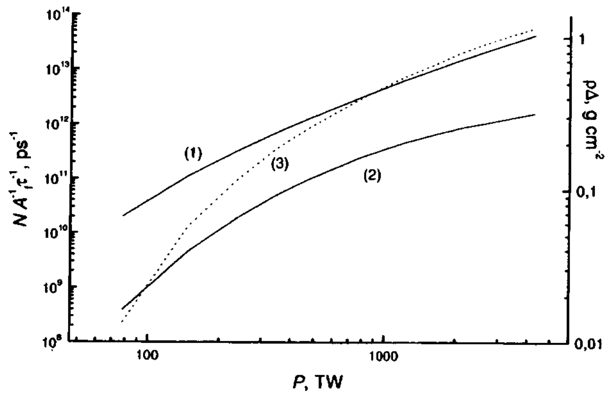

FIG. 5. Photon (*1*) and positron (*2*) yields $N/A_f\tau$ versus laser power. Curve *3* shows the optimum size of a target for a positron source.

positron mean free path (see Fig. 3) but less than the photon mean free path (≈ 6 g$\cdot$cm^{-2} for lead). The channel (ii) predominates here. For thickness 2–3 g$\cdot$cm^{-2} the photon yield reaches 0.04% per electron in a source with temperature $T\simeq 1$ 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 (1D, 2D, and 3D) by the Monte Carlo method. The calculations were performed for a lead sphere with radius $R=0.2$ cm and an electron source with temperature $T=1$ and 2 MeV at the center. The results are presented in Figs. 2 and 4. They are in agreement with our estimates.

According to Ref. 3, the temperature of fast electrons which arise during the interaction of laser radiation with matter equals approximately

$$T_f \simeq mc^2[(1+0.7q_{18})^{1/2}-1], \tag{10}$$

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

We propose a sphere of finite density as a target into which the laser radiation is focused.[14] Such a target gives $A_f\approx 0.3$, high luminosity, and isotropic positron and photon yields. The target material should have a high atomic number *Z*, and the optimal diameter of the target is determined by the problems of the experiment and by the laser power.

To detect annihilation photons the size of the target was chosen to be $\rho R\approx 2-3$ g$\cdot$cm^{-2}. The annihilation-photon yield N_γ divided by A_f and τ versus laser power is shown in Fig. 5. The diameter of the focal spot equals $d_f=30$ μm. The photon yield reaches 10^{10}–10^{12} for a 10^2–10^3 TW picosecond laser.

The positron yield from the target can be estimated as

$$N_{+}\simeq N_{e}\frac{\rho\Delta_{e^{+}}}{\rho\Delta_{e^{+}}+\rho\Delta}\left(w_{e}+w_{\gamma}^{\infty}\frac{\rho\Delta}{\rho\Delta_{\gamma}}\right). \quad (11)$$

Here $\Delta_{e^{+},\gamma}$ are the positron and photon mean free paths. The target for positron production must be of the order of $\Delta_{e^{+}}$ in size (see Fig. 3). The positron yield N_{+} divided by A_f and τ is plotted versus the laser power 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 10^2–10^3 TW picosecond laser.

Since the target is smaller in size than existing positron sources, the laser positron source can have a very high luminosity. The efficiency of conversion of fast positrons (MeV) to slow positrons (1–10 eV) can reach 10^{-2} (Ref. 15). Therefore, to produce a quasistationary source of slow positrons with an intensity of 10^8 particles/s requires a laser with an energy of 10–30 J in a 10–30 fs pulse with a repetition frequency of 10–30 Hz. Undoubtedly, such a source would be useful for fundamental and applied investigations in solid-state physics, chemistry, and biology.

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