

Electron-positron pair production during focusing of laser radiation in dense plasma

F. V. Bunkin, A. E. Kazakov

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Abstract

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PHYSICS

F. V. BUNKIN, A. E. KAZAKOV

PRODUCTION OF ELECTRON-POSITRON PAIRS

UPON FOCUSING LASER RADIATION

IN A DENSE PLASMA

(Presented by Academician A. M. Prokhorov on 30 I 1970)

Electrons with energy greater than $3mc^2$ (m is the electron mass, c is the speed of light) can produce electron-positron pairs when scattered by nuclei. Such a situation can be realized experimentally even in a nonrelativistic plasma with temperature $T \ll mc^2$, if it is irradiated by a sufficiently intense electromagnetic wave (a focused laser beam). Qualitatively, this question was discussed in ⁽¹⁾. Below we give a quantitative estimate of the effect.

First of all, let us note that the possibility indicated in ⁽²⁾ of pair production in the interaction of intense radiation with "free" electrons (i.e., without their scattering by other particles), at the present level of development of high-power laser technology, is in probability many orders of magnitude less effective than the production process considered here, which includes scattering by nuclei. Indeed, as shown in ⁽³⁾, the process of production without scattering is determined by the parameter

$$\gamma = \frac{\varepsilon}{mc^2} \frac{H_0}{H_{cr}} = \frac{\varepsilon}{mc^2} \frac{E_0}{E_{cr}} \quad (1)$$

(ε is the electron energy; $H_{cr} = E_{cr} = m^2 c^3 / e \hbar$; E_0, H_0 are the amplitudes of the electric and magnetic fields of the wave; e is the electron charge) and becomes comparable in probability with the process considered by us only for $\gamma \gtrsim 1$. At the maximum laser-radiation intensities attainable in the near future, $I \sim 10^{19}$ W/cm², the parameter $\gamma \sim 10^{-5}$. Therefore below we shall assume $\gamma \ll 1$, and the process without scattering will not be taken into account.

With accuracy sufficient for carrying out an estimate, one may then assume that the role of the radiation field reduces to imparting initially to the nonrelativistic electrons an energy sufficient for pair production, without exerting any substantial influence on the cross section of the process itself; i.e., one may assume that free electrons are scattered, whose energy ε is equal to the electron energy in the field of a plane monochromatic wave.* For the case of a circularly polarized wave, for example (see ⁽⁴⁾),

$$\varepsilon = mc^2(1 + 1/2x^2), \quad (2)$$

where $x = eE_0/m\omega c$ is a relativistically invariant parameter characterizing the intensity of the wave $I = \frac{m^2\omega^2 c^3}{4\pi e^2} x^2$. For $\varepsilon \gg mc^2$ the production cross section

* In addition, it is essential that the radiation field of the optical range changes little during the scattering time. Characterizing the region of action of the nuclear field by the Debye radius $d = (T/8\pi e^2 N_e)^{1/2}$, where N_e is the electron density in the plasma, we obtain for $\varepsilon \gg mc^2$ that the characteristic time of flight through this region is d/c . For $N_e \sim 10^{21} \text{ cm}^{-3}$, $T \sim 10^6 \text{ deg}$, $d/c \sim 10^{-17} \text{ sec}$, i.e., $d/c \ll 1/\omega$ (optical $\omega \sim 10^{15} \text{ sec}^{-1}$). Consequently, during the scattering time the wave field has practically no time to change. Therefore the instantaneous value of the electron energy may be taken as ε .

the pair is determined, in order of magnitude, by the formula ^(5,6)

$$\sigma = Z^2 r_0^2 \frac{\alpha^2}{\pi} \ln^3 \frac{\varepsilon}{mc^2} \quad (3)$$

($r_0 = e^2/mc^2$ is the classical electron radius, $\alpha = e^2/\hbar c$, Z is the nuclear charge).

The number N_p of pairs produced during a time τ in a plasma volume V with electron concentration $N_e = ZN_n$ (N_n is the concentration of nuclei) is

$$N_p = \frac{Z}{\pi} r_0^2 \alpha^2 N_e^2 c \ln^3(1 + 1/2x^2) V \tau. \quad (4)$$

The maximum possible value of the electron concentration at which radiation with wavelength λ can still penetrate into the plasma is determined by the well-known formula

$$N_{e_{cr}} = \pi mc^2 / e^2 \lambda^2. \quad (5)$$

For $\lambda = 1.06 \mu$ (neodymium-laser radiation) $N_{e_{cr}} \sim 10^{21} \text{ cm}^{-3}$. Assuming in this case $I = 5 \cdot 10^{19} \text{ W/cm}^2$ ($x \simeq 5$), a laser-pulse duration $\tau = 10^{-12} \text{ sec}$, and

a focusing volume $V = 10^{-7} \text{ cm}^3$, we obtain, according to (4), $N_p \simeq 8 \cdot 10^4 Z$ pairs.

The estimate given indicates a quite realistic possibility of observing the effect of electron-positron pair production in a laser experiment. We note that in the experiment it is not necessary to prepare the plasma in advance; the radiation can be focused in a nonionized gas with atomic density $N_a < N_{ecr}/Z$. For $x \gg 1$ the parameter $eE_0/\omega\sqrt{m}\Delta$ (Δ is the energy of Z -fold ionization of the atom) is always large compared with unity. In this case, as is known ^(7,8), complete ionization of the atoms occurs over a time of the order of the light-wave period (due to the tunneling effect).

Let us also estimate the absorption coefficient β of the energy of the electromagnetic field in the plasma due to the pair-production process described. It is expressed by the formula

$$\beta \simeq \sigma N_e^2 c \varepsilon_p / Z I, \quad (6)$$

where $\varepsilon_p = 2mc^2 f(x)$ is the average energy of a pair.

In accordance with (2),

$$1 \leq f(x) \leq 1/2 [(1 + 1/2x^2) - 1] = 1/4x^2. \quad (7)$$

For $x \simeq 5$, $N_e = N_{ecr}$, $\beta \simeq Z \cdot 10^{-9} \text{ cm}^{-1}$.

Under the same conditions, the absorption coefficient due to the multiphoton Compton effect ⁽⁹⁾ is of order 10^{-3} cm^{-1} . This means that, in the range of intensities under consideration, radiation absorption is determined by the Compton effect.

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Lebedev Physical Institute
Academy of Sciences of the USSR
Moscow

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Note: Figure translations are in progress. See original paper for figures.

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