Mechanism of laser-induced "fast electron" emission from a metal

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We determine the electron distribution function which is formed under the influence of a high-power laser radiation of frequency ω_L and is a power-law function of E in the energy region $(E-E_F) > \hbar\omega_L$. The obtained distribution explains the experimental results on the current and energy of the emission electrons from a metal foil.

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It is known[1,2] that when a metal foil is irradiated by a nanosecond pulse from a high-power laser, with $q = 10^{14}$ erg/cm^2 sec, two emission-current peaks are observed. The first, which is in synchronism with the laser pulse, contains a large number of "fast electrons" (the maximum energy for tungsten is 14.5 eV). The second peak, which follows with a delay $\tau \sim 10^{-7}$–10^{-8} sec relative to the first, contains electrons with energies not exceeding 2 eV. It is impossible to explain satisfactorily the appearance of "fast electrons" by using a Maxwellian distribution function,[2] since the experimental results[1] would correspond to a temperature of 30 000 °K, whereas the melting point of tungsten is 3300 °K.

1. In the analysis of fast processes, the main contribution to the formation of the electron distribution function is made by electron-electron collisions.[2] The reason is that the electron-electron collision relaxation time τ_e ($\tau_e \sim 10^{-12}$ sec) is smaller by two orders of magnitude than the time for electron-phonon collisions. A comparison of the laser pulse duration with the relaxation times shows that the electron distribution function is quasistationary in our case and is determined mainly by the electron-electron collisions. Consequently, it can be obtained from the condition that the electron-electron collision integral vanish.

It is known that the collision integral is cancelled out by an equilibrium Maxwellian distribution function. However, as will be shown below, the collision integral can be made to vanish by a power-law distribution function.[1)] A power-law function corresponds to a constant flux of particles or energy in momentum space, specified by the source and by the sink, while the equilibrium function corresponds to their absence. The collision integral for normal electron-electron collisions at high temperatures, in the "jellium" model approximation, is given by[3]

$$\left(\frac{\partial f}{\partial t}\right)_{st} = \int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_3 \frac{e^4}{(q^2+a^2)^2}\{f_2 f_3 - f f_1\}\delta \times (\mathbf{p}+\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3)\,\delta(E+E_1-E_2-E_3), \quad (1)$$

$\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_3$, $a^2 = 3\, m\hbar\omega_p^2/2E_F$, $\omega_p^2 = 4\pi e^2 n/m$ is the electron plasma frequency, n is the electron density, and E_F is the Fermi energy.

We consider a power-law solution that causes (1) to vanish ($f_i = Ap_i^{2s}$, A is a numerical factor) for the energy region $(E-E_F) > \hbar\omega_L$, assuming a quadratic dispersion law $E_i = p_i^2/2m^*$ (m^* is the effective mass). Recognizing that $a \sim 10^{19}$ g-cm-sec^{-1} in the case of metals, we obtain by direct integration an expression for the collision integral

$$\left(\frac{\partial f}{\partial t}\right)_{st} = B(s)E^{2s}$$

where $B(s)$ is a function of the exponent s. It can be shown that $B(s)$, meaning also the collision integral, vanishes at $s_p = -3/4$ and $s_\epsilon = -5/4$. Here s_p (s_ϵ) corresponds to a constant particle (energy) flux in momentum space.

Assume that powerful laser radiation of frequency ω_L and intensity q is incident on a metallic foil. In this case three mechanisms can produce the emission current. The first two, mainly multiquantum photoeffects and thermonionic emission, are well known and yield, respectively the following expressions for the emission current density

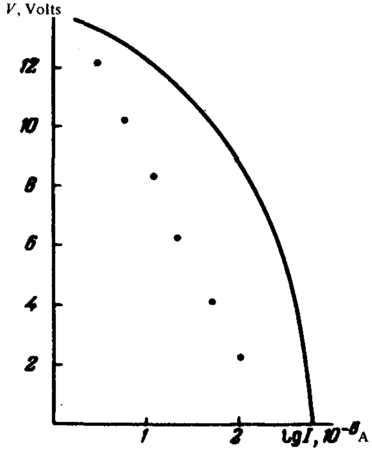
$$J_{\rm ph} = 2^{-3n}\frac{em\omega_A^2}{\hbar}n^{1/2}\left(\frac{8\pi e^2 q}{mc\,\phi\,\omega_A^2}\right)^n,$$

$$J_{\rm te} = C\frac{T_e^3}{\phi}\exp\left(-\frac{\phi}{kT_e}\right),$$

where ϕ is the work function, $n = ent[1+\phi/\hbar\omega_L]$, T_e is the electron-gas temperature, and C is a factor that depends on the distribution of the elumination in the spot.

It seems to us, however, that the considered situation corresponds to the presence of a source (powerful laser radiation) and a sink (emission current) in momentum space, and this should lead to the formation of a quasistationary power-law distribution with a constant energy flux over the spectrum. It is easily seen that the emission current density for such a distribution function is given by

$$J_s = \frac{\pi A E_{max}^{(s+2)}(2m^*)^{s+1}}{(s+1)(s+2)} \times \left[(s+1) - \frac{E_F+\phi}{E_{max}}(s+2) + \left(\frac{E_F+\phi}{E_{max}}\right)^{s+2}\right] \quad (2)$$



Dependence of the logarithm of the emission current, $\log I$, on the retarding potential (points—experimental, curve—theoretical).

where E_{max} is the maximum energy in the power-law distribution.

We present estimates of the emission time corresponding to the three considered mechanisms, for a tungsten foil ($\phi = 4.5$ eV, $m^* = 0.5m$ at $q = 10^{14}$ erg/cm^2 sec, a spot area $F = 10^{-2}$ cm^2, $I_{em} = 4 \times 10^{-4}$ A, $\omega_L = 10^{15}$ sec^{-1}, and $E_{max} = 24$ eV (the numerical values are taken from[1]).

$$\tilde{I}_{ph} = 0.33 \cdot 10^{-14}, \quad \tilde{I}_{te} = 10^{-5} T_e^3 \exp\left(-\frac{5.22 \cdot 10^4}{T_e}\right), \qquad (3)$$

$$I_s = 2.4 \cdot 10^{-18} A, \text{ where } \tilde{I}_i = \frac{I_i}{I_{em}}, \quad I_i = J_i F.$$

To estimate A, we equate the particle density produced by the two-quantum photoeffect to the particle density in a power-law distribution, the lower bound of which is the level at which particles are ejected by the photoeffect from the Fermi sphere. Then

$$A = 10^{18}\ \text{cm}^{-4} (g/\text{cm-sec})^{-1/2}. \qquad (4)$$

According to the theoretical and experimental data,[2] the quantity T_e contained in I_{te} does not exceed 1800 °K, which yields $\tilde{I}_{te} \sim 10^{-6}$.

The dependence of the current density of the retarding potential V is described by formula (2), in which ϕ is replaced by $\phi + eV$. The figure shows a comparison of the theoretical relation with the experimental data.[1]

It can thus be noted that an acceptable value for the emission current and for its dependence on the retarded potential is obtained by using the proposed mechanism.

1) In[4], using the conformal symmetry of the collision integral, we obtained power-law distributions of the particles in a plasma, corresponding to different asymptotic values of the dielectric constant.

2) An analysis of (1) shows that in this case the relaxation of a small fraction of the particles on the thermal particles and on one another result in a quasi-power-law distribution.

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