# THE COMPTON EFFECT ON RELATIVISTIC ELECTRONS AND THE POSSIBILITY OF PRODUCING BEAMS OF HARD $\gamma$ RAYS

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The possibility of obtaining beams of hard $\gamma$ rays from the Compton effect on relativistic electrons is considered.[1] It is shown that in this case the energy distribution of the photons is quite different from the bremsstrahlung spectrum, and that at relatively low energies of the photons undergoing the scattering there will be production of hard $\gamma$-ray quanta which are to a considerable degree monoenergetic. The $\gamma$-ray fluxes produced in this way are comparable with corresponding quantities for bremsstrahlung.

A feature of the Compton effect on relativistic electrons is the appearance of photons which are harder than those being scattered. Owing to this, even in the case of scattering of quanta of visible light by extremely relativistic electrons the scattered photons will have energies comparable with those of the electrons. This feature of Compton scattering may be of interest from the point of view of producing beams of hard $\gamma$ rays with high-energy electron accelerators. It is important to note that the characteristics of such $\gamma$-ray beams will be quite different from those of the usual beams obtained when electrons are stopped in matter.

In the Compton effect on a moving electron the energy $\omega_2$ of the scattered photon is connected with the energy $\omega_1$ of the original photon by the well known relation ($\hbar = c = 1$)

$$\omega_2 = \omega_1 \frac{1 - v_1 \cos\theta_1}{1 - v_1 \cos\theta_2 + (\omega_1/\varepsilon_1)(1 - \cos\theta)}, \quad (1)$$

where $v_1$ and $\epsilon_1$ are the speed and energy of the electron, $\theta_1$ and $\theta_2$ are the angles between the direction of motion of the electron and the respective directions of the incident and scattered photons, and $\theta$ is the angle between the incident and scattered photons. The maximum energy $\omega_{2\max}$ of the scattered photons will occur in the case in which the primary electron and photon are moving in opposite directions ($\theta_1 = \pi$) and the scattered photon goes in the direction of motion of the electron. Then ($v_1 \approx 1$)

$$\omega_{2max} = \frac{2\omega_1}{{}^1\!/\!_2(m/\varepsilon_1)^2 + 2\omega_1/\varepsilon_1}, \quad (2)$$

where m is the rest energy of the electron.

The maximum energy which will be reached with electron accelerators in the immediate future is about 6 BeV. Naturally the production of $\gamma$-ray beams by this method requires intense fluxes of primary photons. Lasers are one type of intense source of photons. The best developed laser systems at present are those using ruby crystals. When photons from such a laser ($\lambda = 6943$ Å) are scattered from 6 BeV electrons we shall have $\omega_{2\max} \approx 848$ MeV. The effect rises rapidly with increase of the energy of the electrons. Thus for $\epsilon_1 = 40$ and 500 BeV one has $\omega_{2\max} = 21$ and 497 BeV when the same ruby-laser photons are used.

Of course the use of either lasers working in a shorter-wave part of the spectrum, or other sources of harder photons, would mean that the scattering would produce photons with energies very close to the energy of the electrons.

The differential cross section for Compton scattering on moving electrons is of the following form[2]:

$$d\sigma = r_0^2 \frac{2}{m^2 x_1^2}\left[4\left(\frac{1}{x_1} + \frac{1}{x_2}\right)^2 - 4\left(\frac{1}{x_1} + \frac{1}{x_2}\right) - \left(\frac{x_1}{x_2} + \frac{x_2}{x_1}\right)\right]\omega_2^2 d\Omega_2, \quad (3)$$

where $r_0$ is the classical radius of the electron. For the case $\theta_1 = \pi$ the quantities $x_1$ and $x_2$ are given by the expressions

$$x_1 = -2\omega_1 m^{-2}(\varepsilon_1 + p_1), \qquad x_2 = 2\omega_2 m^{-2}(\varepsilon_1 - p_1\cos\theta_2),$$

where $p_1$ is the momentum of the electron.

By using Eq. (1) we can get from the expression (3) the energy spectrum of the scattered photons. Neglecting small terms in Eq. (3), we get

$$d\sigma = \frac{\pi r_0^2}{2}\frac{m^2}{\omega_1\varepsilon_1^2}\left\{\frac{m^4}{4\omega_1^2\varepsilon_1^2}\left(\frac{\omega_2}{\varepsilon_1 - \omega_2}\right)^2 - \frac{m^2}{\omega_1\varepsilon_1}\left(\frac{\omega_2}{\varepsilon_1 - \omega_2}\right) + \frac{\varepsilon_1 - \omega_2}{\varepsilon_1} + \frac{\varepsilon_1}{\varepsilon_1 - \omega_2}\right\}d\omega_2, \quad (4)$$

where $\omega_2$ can vary from $\omega_1$ to $\omega_{2\,max}$.

This energy distribution for the scattered photons is very different from the corresponding distribution for bremsstrahlung, which is of the form $d\sigma \sim d\omega/\omega$. If the primary photons are in the optical part of the spectrum and $\epsilon_1 \approx 6$ BeV, the scattered distribution in the region $\omega_2 \gtrsim 0.5-0.6\ \omega_{2\,max}$ can be regarded crudely as proportional to $\omega_2 d\omega_2$, and most of the spectral intensity of this radiation is concentrated near $\omega_{2\,max}$ (see Fig. 1).

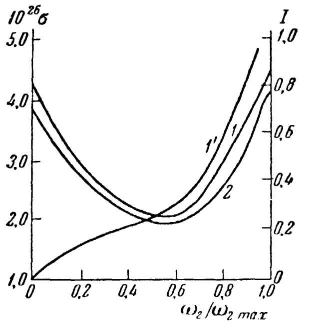


FIG. 1. Energy distribution of the scattered photons. Curve 1: $\epsilon_1 = 6$ BeV, $\omega_1 = 1.78$ eV, $\omega_{2max} = 848$ MeV; Curve 2: $\epsilon_1 = 6$ BeV, $\omega_1 = 3.56$ eV, $\omega_{2max} = 1.48$ BeV; Curve 1′: Spectral intensity distribution for the case of Curve 1 (I is the intensity in relative units, and $\sigma$ is in $cm^2$).

Another, no less interesting feature of this distribution appears for $\omega_{2\,max} \to \epsilon_1$. In this case a larger and larger fraction of the number of scattered photons is concentrated near $\omega_{2\,max}$. For $\omega_{2\,max} \approx \epsilon_1$ the $\gamma$ rays produced are rather monochromatic in energy. The condition $\omega_{2\,max} \to \epsilon_1$ for the maximum energy of the photons is achieved by increasing either $\omega_1$ or $\epsilon_1$. It can be seen from Figs. 2 and 3, for example, that already at $\omega_1 = 178$ eV there is satisfactory monochromaticity, and for $\omega_1 = 127.8$ keV the half-width of the distribution at $\omega_{2\,max} \approx 6$ BeV is of the order of 1 percent. Monoenergetic $\gamma$ rays are also produced in the scattering of red light on electrons with $\epsilon_1 = 500$ BeV (Fig. 3, Curve 2).

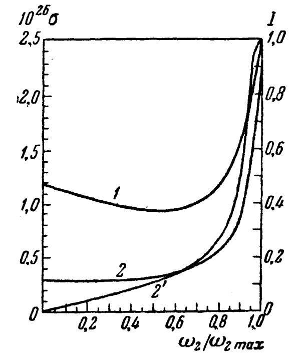


FIG. 2. Energy distribution of scattered photons: Curve 1: $\epsilon_1 = 6$ BeV, $\omega_1 = 35.6$ eV, $\omega_{2max} = 4.58$ BeV; Curve 2: $\epsilon_1 = 6$ BeV, $\omega_1 = 178$ eV, $\omega_{2max} = 5.64$ BeV; Curve 2′: Spectral intensity distribution for the case of Curve 2.

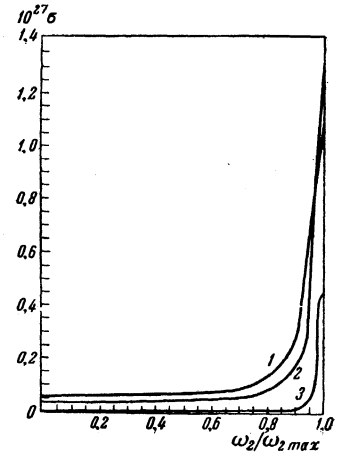


FIG. 3. Energy distribution of scattered photons: Curve 1: $\epsilon_1 = 6$ BeV, $\omega_1 = 1.78$ keV, $\omega_{2\,max} = 5.98$ BeV; Curve 2: $\epsilon_1 = 500$ BeV, $\omega_1 = 1.78$ eV, $\omega_{2\,max} = 497$ BeV; Curve 3: $\epsilon_1 = 6$ BeV, $\omega_1 = 127.8$ keV, $\omega_{2\,max} = 5.9995$ BeV.

The characteristic angles for the scattered $\gamma$ rays with energies $\omega_2 \approx \epsilon_1$ are of the order $\theta_2 \approx m/\epsilon_1$ and for $\omega_1 \ll \omega_2 \ll \epsilon_1$ the angle is given approximately by $\theta_2 \approx 2(\omega_1/\omega_2)^{1/2}$. The exact expression for the angular distribution can be obtained from Eqs. (3) and (1).

We note also that in this way one can produce beams of photons in any prescribed range of frequencies from $\omega_{2\,min} = \omega_1(1-\beta)/(1+\beta)$ to $\omega_{2\,max}$. The beams will evidently have a definite degree of polarization, which may be of interest in itself.

The Compton-effect cross section is $\sigma \approx 6 \times 10^{-25}\ cm^2$. The number of photons emitted by a powerful laser in a pulse of duration $10^{-8}$ sec is $10^{20}-10^{22}$. The scattering of this number of photons by a bunch of electrons containing $\sim 10^9$ electrons and having the same duration will lead to the production of $\sim 10^5-10^7$ hard photons in the range $d\omega_2/\omega_2 = 0.05$. This number of photons is comparable with the number emitted as bremsstrahlung in the same frequency range by a similar bunch of electrons in traversing one radiation length of matter. We emphasize that these $\gamma$-ray fluxes are produced when the light is introduced into the chamber of the accelerator, and the encounter of the electrons with the "light-target" can be arranged at any instant in the acceleration cycle, i.e., at various electron energies. Work with such a "light-target" of course excludes the production of any background.

As was already pointed out, an increase of $\omega_1$ both increases $\omega_{2\,max}$ and enhances the degree of monochromaticity of the $\gamma$ rays produced. When $\omega_1$ is increased the decrease of the differential cross section in the neighborhood of $\omega_{2\,max}$ is slower than that of the total cross section. Thus there is a hope that the use of powerful sources of photons harder than those of visible light will make it possible to produce rather intense monoenergetic beams of $\gamma$ rays. These rays will undoubtedly be very effective in the solution of a wide range of physical problems.

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[1] F. R. Arutyunyan and V. A. Tumanyan, Institute of Theoretical and Experimental Physics Preprint ITÉF-137, 1962.

[2] A. I. Akhiezer and V. B. Berestetskiĭ, Kvantovaya élektrodinamika (Quantum Electrodynamics), Second Edition, Gostekhizdat, 1959, Section 28.

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