The spectrum and polarization of γ-ray beams produced as a result of collision of relativistic ions with laser photons

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Resonant scattering of laser photons by moving ions is studied. At relativistic ion energies a strongly polarized, quasimonochromatic, γ-ray beam can be produced.

An interest in the method of producing quasimonochromatic and polarized γ-ray beams, which was proposed by Ispirian and Margarian[1] in 1973, has recently been increasing in view of the fact that relativistic ion beams will soon be produced by various accelerators.[1] Evidence of this interest has also been indicated in a paper published by Basov *et al.*[2] in 1985, in which this problem was discussed. In this letter we study theoretically for the first time the polarization and the energy and angular distributions of the produced γ rays, i.e., the characteristics which are necessary to set up the experiment. As in the case of the method of Compton backward scattering,[4–6] we use here simple and general equations. Since the resonance scattering cross section is many orders of magnitude larger than the Compton scattering cross section,[1,2] there is the hope that the method of resonant scattering of a laser light by ions will be used extensively in the future.

Let us consider a head-on collision of ions with a momentum p and mass M with photons with a momentum and energy k_1 and ω_1 ($\hbar = c = 1$) in the laboratory frame. In the rest frame of the ions moving relative to the laboratory frame at a velocity β, the frequency of the incident photons is $\omega_1' (1+\beta)\gamma\omega_1$. If ω_1' is approximately or exactly equal to one of the energies ω_{in} of the transitions between the energy levels of an ion, a resonant fluorescence (absorption and emission of photons) will occur. Assuming that in the rest frame of the ions the frequency of the incident photon is the same as that of the scattered photon, $\omega_2' = \omega_1'$, we find the following equation which uniquely relates the energy ω_2 to the angle θ between the momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ in the laboratory frame:

$$\omega_2 = \omega_1(1+\beta)/(1+\beta\cos\theta). \quad (1)$$

The method proposed by Ispirian and Margarian[1] can be summarized as follows. In the limit $\beta\to 1$ or at $\gamma \gg 1$, the frequency ω_2 increases with increasing θ, reaching $\omega_{2\max} \approx 4\gamma^2\omega_1$ at $\theta=\pi$. A large fraction of scattered photons, which has a nearly isotropic distribution in the rest frame of the ions, in this case is emitted in the laboratory frame at small angles θ_1 with respect to the momentum $\mathbf{p}$: $\theta_1 = \pi - \theta \sim 1/\gamma$, transforming the light beam into a quasimonochromatic beam and a polarized γ-ray beam.

Working from the corresponding expressions[7,8] for the resonant fluorescence, we find the following equation for the differential cross section, in the laboratory frame, for the most interesting (from the practical viewpoint) transition $1s^2\,{}^1S_0 \to 1s2p\,{}^1P_1$ and for the head-on collision:

$$d\sigma(\mathbf{k}_1,\mathbf{e}_1,\mathbf{k}_2,\mathbf{e}_2) = A\left|\mathbf{e}_1\mathbf{e}_2^* - \beta\frac{(\mathbf{k}_2\mathbf{e}_1)(\mathbf{k}_1\mathbf{e}_2^*)}{\omega_1\omega_2+\beta\mathbf{k}_1\mathbf{k}_2}\right|^2 \frac{d\Omega}{(1+\beta\cos\theta)^2}, \quad (2)$$

where Γ_{01} is the transition width, e_1 and e_2 are the polarization vectors of the incident and scattered photons, and A represents the expression

$$A = \frac{9}{16}\,\frac{1}{4\gamma^4\omega_1^2}\,\frac{\Gamma_{01}}{(\omega_{01}-2\gamma\omega_1)^2+\Gamma_{01}^2/4}. \quad (3)$$

In the case of total linear polarization of incident photons ($\xi_3^{(1)}=1$) we find, after summing over the final-photon polarizations, the angular distribution [and also the spectral distribution if (1) is taken into account] of scattered photons:

$$d\sigma(\theta,\varphi,\mathbf{e}_1) = A\left[1-\frac{\sin^2\theta\cos^2\varphi}{\gamma^2(1+\beta\cos\theta)^2}\right]\frac{d\Omega}{(1+\beta\cos\theta)^2}, \quad (4)$$

where φ is the azimuthal angle of $\mathbf{k}_2$ [the angle between the $(\mathbf{k}_1,\mathbf{e}_1)$ and $(\mathbf{k}_1,\mathbf{k}_2)$ planes]. The scattered photons in this case are linearly polarized in the $(\mathbf{e}_1,\mathbf{k}_2)$ plane and their degree of polarization after integration over the azimuth φ is

$$\xi_2^{(2)}(\theta,\mathbf{e}_1) = 1 + 2\beta^2\gamma^2\frac{(1-|\cos\theta|)^2}{\sin^2\theta - 2\gamma^2(1+\beta\cos\theta)^2}. \quad (5)$$

At $\gamma \gg 1$ and $\theta \ll 1$, after introducing the notation $u=\gamma\theta_1$, $x=\omega_2/\omega_{2\max}$ and $(1+u^2=1/x)$, we find the following expressions for the spectral (angular) distribution and for the linear polarization:

$$\frac{d\sigma(x)}{dx} = 4\pi\gamma^2 A(1-2x+2x^2), \quad \frac{d\sigma(u)}{d\Omega} = 4\gamma^4 A\frac{1+u^4}{(1+u^2)^4},$$

$$\xi_3^{(2)}(u,\xi_3^{(1)}=1) = 1-\frac{u^4}{1+u^4}. \quad (6)$$

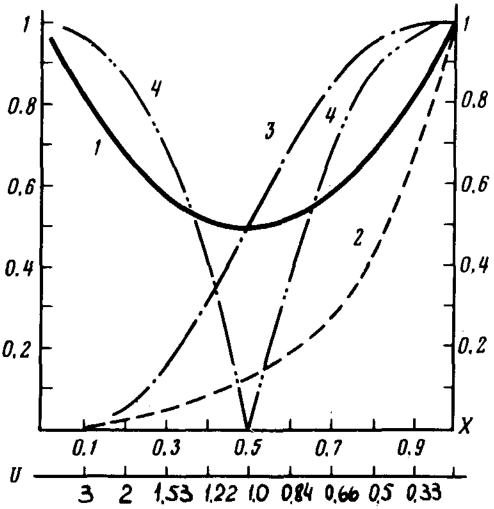

FIG. 1. Spectral and angular distributions and polarizations of scattered photons. Curves 1–4—the x dependence or the y dependence of $(1/4\pi^2 A)\ [d\sigma(x)/dx]\ (1/4\gamma^4 A)\ [d\sigma(u)/d\Omega]$, $\xi_3^{(2)}(u,\xi_3^{(1)}=1)$ and $|\xi_2^{(2)}(u,\xi_2^{(1)}=\pm 1)|$, respectively.

In the case of a total right-handed or left-handed circular polarization of the initial photons ($\xi_2^{(1)} = \pm 1$), the circular polarization $\xi_2^{(2)}$ of the final photons is

$$\xi_2^{(2)}(u,\ \xi_2^{(1)} = \pm 1) = \mp (1 - 2u^4/(1+u^4)) . \tag{7}$$

Figure 1 is a plot of the curves for (6) and (7) versus x or u. These curves are similar to the corresponding curves for the Compton effect induced by a moving electron (see Ref. 6 and the bibliography cited there).

Since colliding ion and photon beams are actually not monochromatic and have definite energy distributions $P(\gamma)$ and $P_1(\omega_1)$, we must take an average, which effectively reduces to taking an average of the coefficient A, in order to take this circumstance into account in all the equations given above. Assuming that the distributions $P(\gamma)$ and $P_1(\omega_1)$ are Lorentzian distributions with the total widths $\Delta\gamma$ and $\Delta\omega_1$, and also assuming that under actual conditions $\Delta\gamma/\gamma \gg \Delta\omega_1/\omega_1 \gg \Gamma_{01}/\omega_{01}$, we find $\overline{A} = (9/4\gamma^2\omega_{01}^2)(\Gamma_{01}/\omega_{01})(\Delta\gamma/\gamma)^{-1}$.

In the case of the transition mentioned above, we have $\Gamma_{01} = 1.364\times 10^{-2}$ eV and $\omega_{01} = 571.3$ eV (Ref. 8) and for $\Delta\gamma/\gamma = 10^{-3}$ the total fluorescence cross section is $\sigma = 5.37\times 10^{-16}$ cm^2 (compare it with the total cross section for the Compton effect, $\sigma_C = 6.65\times 10^{26}$ cm^2). The use of a YAG:Nd laser on an argon laser gives, respectively, $\omega_1 = 1.064$ eV, $\gamma = 268.5$, $\omega_{2\max} = 307$ keV and $\omega_1 = 2.4$ eV, $\gamma = 119$, $\omega_{2\max} = 136$ keV. If a collimator with an aperture angle $\bar{u} = 1/3$ is used, we will have a quasi-monochromatic γ-ray beam with an energy (0.9–1) $\omega_{2\max}$, with $\Delta\omega_2/\omega_2 \sim 10\%$. The degree of polarization in this case will be approximately equal to unity (Fig. 1) and the integral cross section will be 0.14 of $\sigma = 2/3\ \pi\gamma^2 A$. This cross section does not depend on γ, since $A \sim 1/\gamma^2$.

As indicated in Refs. 1 and 2, if the number of primary photons, N_1, is much larger than the number of ions, $N_{\rm ion}$, in the pulses, then under actual conditions the number of γ rays, N_γ, produced in a single collision will be larger, because of the enormously large cross section, $\sim 10^{-16}$ cm^2, than N_{ion} by an amount approximately equal to the number of times the length of the interaction volume is greater than the length along which an excited ion with a lifetime of $\gamma\tau_0$ (for OVII we have $\tau_0 = 5\times 10^{14}$ s) emits a photon.

[1)] At the end of 1986, at SPS in CERN the OVII oxygen ions will be accelerated up to energies[3] with $\gamma = E/M \approx 225$.

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