Compton effect on relativistic electrons for perpendicular collision of the interacting beams

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In order to investigate the properties of the γ-ray beam arising on scattering of laser radiation by relativistic electrons in the case of mutually perpendicular fluxes of the interacting particles, we have performed measurements and calculations of the angular and energy characteristics of this γ beam. An estimate is obtained for the yield of scattered γ rays. It is shown that the experimental distributions agree with the calculated ones if the electron bunch parameters are correctly taken into account.

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1. INTRODUCTION

During the last ten to fifteen years the γ-ray beams arising in scattering of laser light by relativistic electrons have been studied by various workers[1-3] theoretically and experimentally. Such beams have been used in nuclear-physics experiments[4] and for diagnosis of the electron bunch.[5] The photons of laser-produced γ beams have a number of valuable characteristics: small beam divergence (characteristic angle $\vartheta \sim 1/\gamma$, where γ is the Lorentz factor of the electrons), quasimonochromaticity, and high degree of polarization.

This scattering process is of interest also in the case when the direction of propagation of the incident photons forms an angle near 90° with the electron momentum vector. The γ beam obtained in this case has certain peculiarities. The region of interaction of the beams in a perpendicular collision is substantially smaller than in a head-on collision. If the scattering occurs in the internal beam of a cyclic accelerator where the electrons are moving along a curved orbit, the angular spread of the scattered photons in the horizontal plane decreases by a large factor in the transition to perpendicular geometry. In addition, estimates made by us have shown that in a perpendicular collision the degree of polarization of the incident photons in the scattering process is practically completely preserved, which provides the possibility of easily obtaining γ beams with any specified type of polarization. The maximum energy of the produced photons, other conditions being equal, is only a factor of two smaller than in the case of head-on collision of the beams.

We undertook to study the properties of the γ beam arising in scattering of ruby laser photons ($\lambda = 694$ nm) by electrons of the internal beam of the *S*-60 synchrotron. The angle between the directions of the interacting beams was close to 90°.

2. CALCULATION OF γ-BEAM CHARACTERISTICS

The general formula for the differential cross section of the Compton effect for arbitrary electron velocities is given by Akhiezer and Berestetskiĭ.[6] Substituting the parameter values corresponding to our conditions, in the ultrarelativistic case ($\gamma \sim 10^3 \gg 1$) we obtain for the cross section for scattering of a linearly polarized photon

$$\frac{d\sigma}{do_2} = \frac{4r_0^2\gamma^2}{(1+Y^2)^2}\left[1-\frac{4Y^2\cos^2\alpha}{(1+Y^2)^2}\right] \qquad (1)$$

where r_0 is the classical electron radius, α is the angle between the direction of polarization of the incident radiation and the scattering plane, and Y is the reduced angle of emission: $Y = \gamma\vartheta_2$, where ϑ_2 is the angle between the direction of emission of the scattered photon and the electron momentum vector.

To calculate the characteristics of a real beam of scattered photons it is necessary to take into account the size of the region of interaction of the incident beams, the spread of the electrons in direction of momenta and coordinates due to their oscillations about the equilibrium orbit and the curvature of the orbit, and also the distribution of photon density in the focused laser beam.

We designate by $\mathbf{n}_e$ the unit vector coinciding with the electron momentum direction and by $\mathbf{n}$ the unit vector in the direction of observation. It is easy to show that the angular distribution of scattered photons, recorded at a distance L from the interaction region, is given by an expression of the form

$$\frac{dN(\mathbf{n})}{do} = N_e N_p \frac{f}{c}\int \xi(\mathbf{r})\, V(\mathbf{r},\mathbf{n}_e)\frac{d\sigma}{do_2}\left(\mathbf{n}-\mathbf{n}_e-\frac{\mathbf{r}}{L}\right) d^3r\, do_e, \qquad (2)$$

where integration over the spatial variable $\mathbf{r}$ is extended over the entire interaction region. The remaining designations are as follows: do and do_e are the elements of solid angle in the $\mathbf{n}$ and $\mathbf{n}_e$ directions, N_e and N_p are the numbers of electrons and photons taking part in the interaction, $\xi(\mathbf{r})$ is the photon density distribution, $V(\mathbf{r}, \mathbf{n}_e)$ is the distribution of electrons in coordinates and momentum directions, f is the frequency of revolution of the electron bunch (20.4 MHz for the S-60 synchrotron), and c is the velocity of light.

Assumption of uniformity of the photon distribution over the laser beam cross section does not introduce substantial errors into the theoretical result.[7] The distribution of electrons in the angular and spatial variables, according to Ershov,[8] is well fitted by a four-dimensional Gaussian function containing two linear dispersions: a^2 and b^2 and two angular dispersions: A^2 and B^2. The dispersions of the electron distribution were measured by us by the rotating-disk method in the synchrotron radiation of the bunch.[9]

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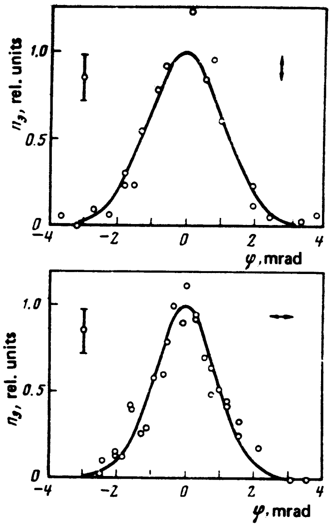

FIG. 1. Horizontal angular distributions of Compton γ-ray beam.

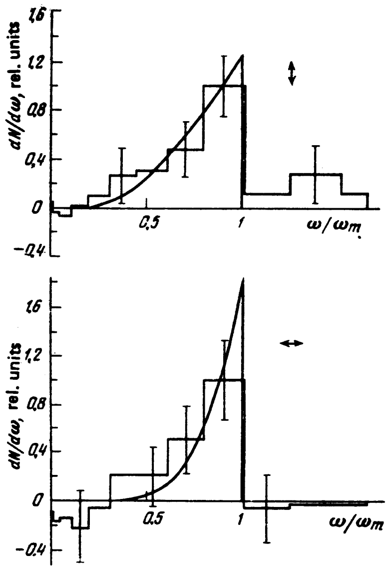

FIG. 3. Energy spectra of scattered γ-ray beam. The detection solid angle is 1.5×10^{-6} sr.

In calculation of the energy spectrum of the γ beam it is necessary to take into account the direct relation between the energy ω of the scattered photon and its emission angle ϑ_2. This relation is given by the well known Compton formula, which under our conditions takes the following form:

$$\omega \approx \frac{2\omega_0\gamma^2}{1+Y^2}, \qquad (3)$$

where ω_0 is the incident photon energy ($\hbar = c = 1$). By means of Eq. (3) it is possible to obtain from (2) an expression for the energy distribution of the scattered photons.[10]

The integrals describing the angular and energy distributions of the γ beam were calculated on the basis of formulas of the Gaussian type.[11] For comparison with the experimental data, the functions obtained were integrated over the solid angles of the collimators. The results of the calculation are shown by the curves in Figs. 1–3.

3. EXPERIMENTAL RESULTS

The experiment was carried out at an electron energy of 485 MeV. The maximum scattered-photon energy in this case was 3.195 MeV. The experimental apparatus used has been described previously.[12] In the angular-distribution measurements the γ rays were detected by a plastic scintillator located beyond a slit collimator of width 6 mm (9.56 mrad), and in the energy-spectrum measurement—by a NaI(Tl) crystal of dimensions 120×100 mm located behind a circular collimator of diameter 15 or 25 mm (1.54×10^{-6} and 4.29×10^{-6} sr, respectively). The measurements were made for two mutually perpendicular directions of polarization of the incident laser radiation—horizontal and vertical.

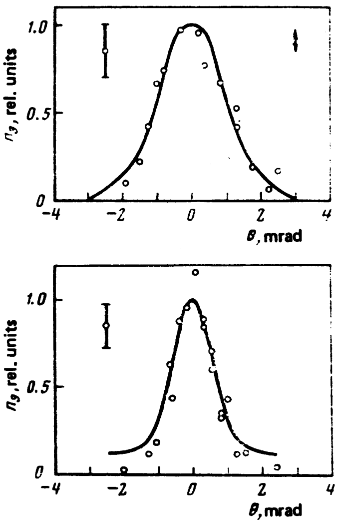

FIG. 2. Vertical angular distributions of Compton γ-ray beam.

In Figs. 1 and 2 we have shown by the points the measurements of the horizontal and vertical angular distributions of the γ beam, respectively. At the left we have shown a typical error bar, and at the right the arrow shows the direction of the electric vector of the incident light. The vertical scale of the theoretical curves and their location on the abscissa axis relative to the experimental points were determined by the method of least squares. Use of the χ^2 criterion showed good agreement between the theoretical and experimental values.

Here we must note the following. The widths of the angular distributions of the scattered-photon beam depend to a significant degree on the angular parameters of the electron distribution A and B. However, diagnosis of the electron bunch on the basis of synchrotron radiation permits direct measurement only of the linear parameters a and b. For the angular parameters only upper-limit estimates are obtained.[7] The best correspondence of the measured and calculated angular distributions in our case was observed for A and B values about 30% smaller than the estimates obtained. The scattering process being discussed therefore presents certain new possibilities for diagnosis of an accelerated electron bunch.

As a characteristic of the γ-ray yield we took the number of photons appearing in scattering of 3.5×10^{18} photons (1 joule) by 10^{11} electrons. The theoretical val-

TABLE I. Expected parameters of laser-induced γ beams.

Storage ring	Electron energy, GeV	Beam current, mA	Maximum energy of scattered photons, MeV	Expected yield, photons/joule
VEPP-3[16]	2.2	80	80	1400
DORIS[17]	3.5	200	190	3300

ues of the yield for vertical and horizontal polarization of the incident radiation were respectively 85 ± 17 and 16 ± 3 photons/(joule-10^{11} electrons). The errors in the theoretical values are due to the fact that the final formula involves the radius of the laser beam at the interaction region, which is known with an accuracy of about 20%. The experimental yield values turned out to be respectively 54 ± 21 and 33 ± 13 in the same units. For typical intensities of the interacting beams (0.5×10^{11} electrons and 20 joules $=7\times10^{19}$ photons) we actually obtained respectively ~700 and ~250 scattered photons per laser pulse.

The γ-ray energy spectra were determined from the measured spectra of pulse heights from the γ detector with use of the method described by Hubbell[13] and Egorov.[14] The histograms in Fig. 3 show the spectra obtained for a collimator of diameter 15 mm and the two polarization directions indicated above for the incident laser radiation. The smooth curves in this figure are the calculated spectra, normalized to the area of the histograms. Correspondence of the calculated and measured spectra was also verified by a χ^2 test.

The results obtained show that the beam of scattered photons for horizontal polarization of the incident radiation has a sharper directivity and harder spectrum than for vertical polarization. However, the γ-ray yield in the case of vertical polarization is somewhat higher.

To obtain laser-produced γ beams it is evidently desirable to use storage rings, which are distinguished by high accelerated currents and small electron-bunch dimensions. In the Table we have given estimates of the γ-beam parameters which can be obtained for perpendicular geometry in two contemporary storage rings (the incident radiation was assumed unpolarized). It was assumed in the calculation that the photon source was a neodymium glass laser with frequency doubling (incident photon wavelength 530 nm). Modern lasers provide the possibility of easily obtaining light pulses with energy of the order of several tens of joules. The prospects for development of laser systems for production of γ beams have been discussed in detail by Milburn.[15] It should be noted that the yield estimates given in the Table are valid for the condition that the laser pulse length is much greater than the revolution period of the electron bunch. In the opposite, case with appropriate synchronization of the laser firing, still higher yield values can be achieved.

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