Polarization of the radiation scattered as a result of interaction of laser photons with relativistic electrons

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Theoretical calculations are made of the orthogonal-geometry interaction between electron and photon beams and experimental studies are reported of the polarization characteristics of the scattered radiation. Measurements were made using an automated system based on a Compton scintillation polarimeter. The results indicated that it should be possible to generate a polarized gamma-ray beam in the orthogonal geometry.

Quasimonochromatic polarized low-divergence gamma-ray beams, currently generated in various accelerators,[1–4] are created by the process of Compton backscattering of laser radiation by relativistic electrons.[5–7] As a result of this process the secondary gamma photons acquire a considerably higher energy than that of the incident photons. The scattering of laser photons usually takes place in a rectilinear section of an electron orbit of an accelerator in the head-on beam interaction geometry (encounter angle of about 180°) because this geometry ensures the greatest yield of secondary ("laser") gamma photons and maximizes the energy of the scattered photons which can be reached in this process.

In contrast to the head-on configuration, the orthogonal geometry (encounter angle 90°) is characterized by a very small region overlap of the beams and is therefore undoubtedly of interest in spite of a reduction in the yield of laser gamma photons. The orthogonal geometry can be used for diagnostics of electron bunches, localization of the emitting part of an orbit, and studies of the scattering processes that require a high photon density.

We used the S-60 synchrotron at the Lebedev Physics Institute to study the characteristics of a laser gamma-ray beam created as a result of scattering of a linearly polarized beam of ruby laser radiation ($\lambda = 694$ nm) interacting with an internal beam of 485 MeV electrons in a near-orthogonal geometry. The energy and angular characteristics of the beam and estimates of the yield obtained earlier[8] demonstrated that when the laser radiation energy was 10 J and there were 10^{11} electrons in a synchrotron orbit, it was possible to generate pulses representing about 10^3 photons with about 3 MeV energy and an angular divergence of about 2 mrad. The experiments described below were intended to study the polarization characteristics of the scattered radiation and to determine the feasibility of creation and control of the parameters of such a beam on the basis of an analysis of the operation of the apparatus used in our experiments.

The results of theoretical calculations of the polarization of a laser gamma beam[9] carried out for the photon-electron encounter angle 90° and for the electron energy 485 MeV are presented in Fig. 1. An examination of the calculated polarization characteristics together with the energy distribution[8] (with a spectrum characterized by a sharp maximum near $\nu = 1$) demonstrated that the orthogonal geometry could easily ensure generation of quasimonochromatic gamma-ray beams with specified polarization properties and this could be done by altering the incident photon polarization.

An experimental determination of the polarization characteristics of a laser gamma-ray beam of energy amounting to several megaelectron-volts was based on the dependence of the scattering cross section of polarized gamma photons by free electrons[9] on the angle Φ between the scattering plane and the polarization vector. Our measurements were carried out using a Compton scintillation polarimeter[4] consisting of three detectors: a central scattering sensor (plastic scintillator) and two analyzing sensors. (NaI:Tl). The latter were oriented at angles of $\Phi = 0$ and $\Phi = 90°$, which made it possible—in conjunction with a determination of the energy of the incident gamma rays—to estimate the number of the scattering events in the central sensor along two mutually perpendicular directions $N_\perp$ and $N_\parallel$, where N is the number of coincidences registered by the relevant pairs of the polarimeter sensors. The degree of polarization of the laser gamma-ray beam incident on the polarimeter was deduced from the formula

$$P_e(\omega) = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \frac{R(\omega)+1}{R(\omega)-1}, \tag{1}$$

where $R(\omega)$ is the asymmetry coefficient of the polarimeter which in an ideal case is equal to the ratio of the scattering cross sections for the angles $\Phi = 90°$ and $\Phi = 0$.

We used the experimental geometry shown in Fig. 2. Here, X is the axis directed toward the center of the electron orbit, whereas the direction of the electron momentum $\mathbf{p}$ coincides with the tangent to the orbit at the point of encounter between the beams (Z axis); the same direction is the central axis of the polarimeter. In our experiments the encounter angle was 105° and the maximum energy of the scattered gamma photons was then 4.02 MeV; the angular divergence of the resultant beam did not exceed 2.5 mrad. The background received by the polarimeter detectors was reduced by placing the polarimeter at a considerable distance (11 m) from the beam encounter point. An automated system used to measure the polarization was described in detail in Ref. 10.

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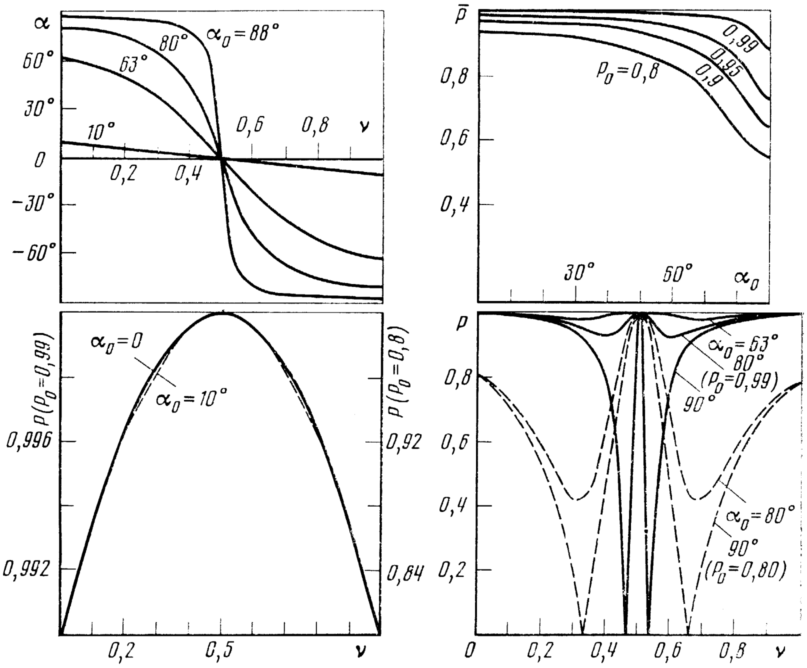

FIG. 1. Results of calculations of the polarization of scattered photons. Here, P_0 and α_0 are the degree and direction of the polarization of the incident photons; P, α, ν, and $\bar{P}$ are the degree, direction, reduced energy ($\nu = \omega/\omega_{\max}$), and the spectrum-average polarization of the scattered photons; ω is the energy of the scattered photons.

Our measurements were made for three directions of the linear polarization of the laser photons: $\alpha_0 = 0$, 63, and 90°. The polarimeter construction made it possible to rotate it as a whole about the central axis. The systematic errors associated with the detector orientations were eliminated by gathering the information for each polarization at four positions of the polarimeter, whereby each detector pair was used twice in the vertical ($N_\perp$) and horizontal ($N_\parallel$) orientations. The resultant amplitude spectra for all three polarizations of the laser photons are shown in Fig. 3.

The conversion from the amplitude to the energy spectra was made by solving a system of n linear equations of the $Ax = b$ type by the method of successive elimination (Gauss method). The coefficients a_{ij} of a matrix A $(i, j = 1, \ldots, n)$ represented effectively the response function of the polarimeter, x_j was the required energy spectrum, and b_i was the content of the ith interval in the experimental amplitude spectrum. The response function of the polarimeter was determined by calibrating it first using ^{60}Co and ^{137}Cs sources. The amplitude spectra were calculated for the other energies by the Monte Carlo method. The results of this calibration and of the calculations carried out for different gamma photon energies were used to construct a 9×9 matrix of the a_{ij}

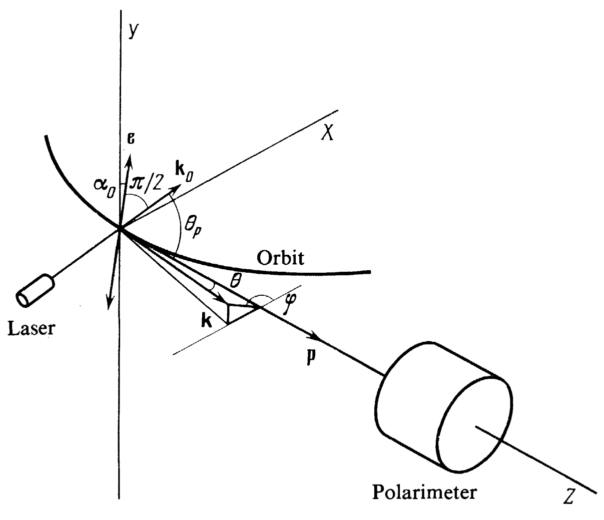

FIG. 2. Experimental geometry: $\mathbf{k}_0$ and $\mathbf{k}$ are the momenta of the incident and scattered photons; $\mathbf{p}$ is the initial electron momentum; $\mathbf{e}$ is the polarization vector of the incident photon; θ_p is the angle of encounter between the beams.

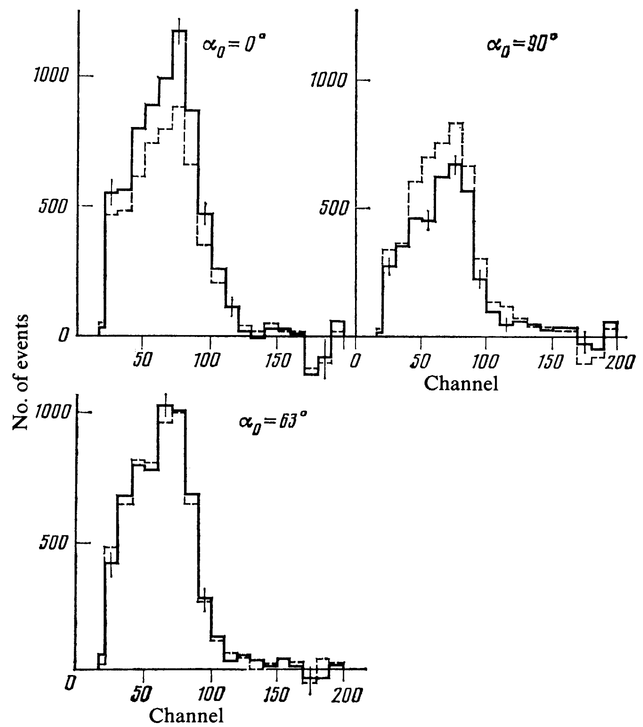

FIG. 3. Amplitude spectra. The continuous line represents the results obtained using the horizontal pair of polarimeter detectors, whereas the dashed line represents the results produced by the vertical pair. The scale of the abscissa is 20 channels/MeV.

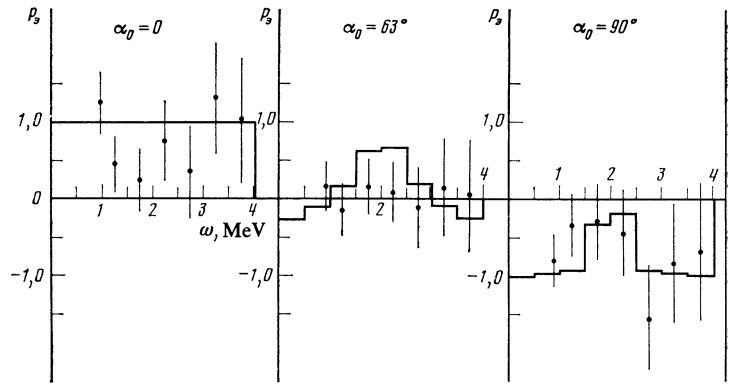

FIG. 4. Energy dependence of the degree of polarization of laser gamma photons obtained for $\theta_p = 105°$. The histogram is theoretical and the points are experimental.

coefficients (from 0.5 to 5.0 MeV) in steps of 0.5 MeV.

The conversion to the energy spectra was made using available programs.[11] The relationship between the solution error and the error on the right-hand side of the system $Ax = b$ was estimated for the general case from the expression

$$\frac{\|\Delta x\|}{\|x\|} \leqslant \operatorname{cond}(A)\frac{\|\Delta b\|}{\|b\|}. \tag{2}$$

Here, Δx and Δb are the absolute errors in the quantities x and b; $\|x\|$ and $\|b\|$ are the norms of the corresponding vectors ($\|x\| = \Sigma_{j=1}^{n} |x_j|$); cond ($A$) is the conditionality number of a matrix defined as the product of the norms of the normal and inverse matrices. In our case the conditionality number was 2.04; an estimate of the error of the solution was made on the assumption that the relative error was constant for all the values of x_j and was given by Eq. (2), i.e., that $\Delta x_j / x_j = \|\Delta x\|/\|x\|$.

The experimentally determined degree of polarization $P_e(\omega)$ of laser gamma photons obtained for the 105° encounter angle is plotted in Fig. 4 together with the results of the theoretical calculations for three directions of the polarization of the primary laser radiation and for the degree of polarization $P_0 = 0.99$. Application of the χ^2 criterion to the results in Fig. 4 indicated that at the confidence level in excess of 30% the experimental data agreed with the calculations for all three directions of the primary polarization.

The large errors in Fig. 4 were mainly due to unsatisfactory statistics in the determination of the amplitude spectra. However, a significant improvement in the statistics could not be achieved because of the limitations imposed by the "instrumental lifetime" and several other factors. This lifetime was the average time interval during which a calibrated and fully aligned (relative to the beam encounter point) system was used to measure the amplitude spectra while the main working characteristics (laser power, transmission coefficient of the optical system for coupling-in laser radiation, precision of alignment of the polarimeter relative to the center of the laser gamma beam) were maintained within the permissible limits.

By way of illustration of the instrumental lifetime, we shall give the following numerical values. In the determination of the amplitude spectra for the vertical polarization of the laser photons ($\alpha_0 = 0$) we required about 94 000 laser pulses of about 1 msec duration generated at a repetition frequency of 0.16 Hz, which amounted to about 160 h. During this time it was necesary to interrupt seven times the acquisition of data in order to restore the operating parameters of the system (mirrors and ruby crystal ends were repolished, flash lamps were replaced, the system was realigned relative to the beam encounter point, etc.). Therefore, the instrumental lifetime was about 25 h (15 000 laser pulses) and the ratio between this lifetime and the system maintenance time was about 1:4. The accumulated experience in the use of the system demonstrated that a further increase in the acquisition time would result in a disproportional increase in the total time of the experiments because of the time needed for regular servicing.

We can summarize the results of our investigation by noting that even under the above nonoptimal conditions in the S-60 accelerator it was possible to generate a laser gamma-ray beam with specified polarization properties and of intensity in excess of 10^4 photons per acceleration cycle. This could be done using a Q-switched laser emitting pulses of total energy 10–20 J; the laser pulses should be phase-locked to the revolution of an electron bunch along the orbit. However, generation of such a polarized laser gamma beam meets with a number of operating difficulties, in spite of the apparent simplicity of the method.

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