ANGULAR AND ENERGY DISTRIBUTIONS OF γ QUANTA IN THE COMPTON EFFECT ON RELATIVISTIC ELECTRONS

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We describe the results of measurement of the angular and energy distributions of γ quanta produced in head-on collisions between a beam of linearly-polarized photons from a ruby laser and relativistic electrons of energy 550 MeV. The results are in good agreement with theoretical calculations in which account is taken of the betatron oscillations of the electrons in the accelerator.

COMPTON scattering of laser photons by relativistic electrons is one of the possible methods of obtaining polarized quasimonochromatic beams of γ quanta. According to theoretical calculations[1,2] photons of the optical spectrum (photon energy 1 eV), when scattered by electrons from modern accelerators, can be transformed into γ quanta with energies of tens, hundreds, and thousands MeV.

The maximum energy of the scattered radiation is reached in the case of head-on collisions of the electron and photon beams. Practically the entire scattered radiation is contained in a small solid angle $\Omega \approx (mc^2/E)^2$, determined entirely by the electron energy E. The axis of the cone of the scattered radiation coincides with the direction of the electron momentum.

The spectrum of the scattered radiation differs radically from the spectrum of the bremsstrahlung customarily dealt with by physicists working with electron accelerators. Whereas in the bremsstrahlung spectrum the entire energy per unit interval of the quantum energy is practically independent of the quantum energy, in the radiation scattered by relativistic electrons this quantity increases rapidly when the energy approaches its maximum value.

Another advantage of the indicated method is that the scattered quanta retain the polarization of the incident light. The degree of polarization depends on the energy of the scattered quanta and is close to the polarization of the laser radiation for quanta with maximum energy, and a simple change of the polarization of the incident light makes it possible to obtain γ quanta of high energy, having both linear and circular polarization.

The Compton scattering cross section is large enough to obtain, at the present level of accelerator and laser technology, polarized quasimonochromatic beams of γ quanta with intensities sufficient to set up experiments using bubble and spark chambers (10^4–10^5 quanta per pulse).

Once the fact of the Compton scattering of laser photons by relativistic electrons was established[3,4], the problem arose of investigating the characteristics of the beam of the scattered photons. The purpose of such a study is to compare the experimental data with the known theory, and principally to determine the degree of influence of real experimental conditions on the properties of the produced radiation, and also to investigate the possibility of using this radiation for research purposes. For an experimental study of the angular and energy distributions of the γ-quantum beam produced in scattering of linearly-polarized light from a ruby laser by electrons of 550 MeV energy, apparatus was constructed, the main elements of which are shown in Fig. 1. We used the internal 680 MeV beam of the FIAN synchrotron. The photon source was a ruby laser operating at a frequency 0.16 Hz and radiating a pulsed energy of 4J. The active element was a ruby crystal 16 mm in diameter.

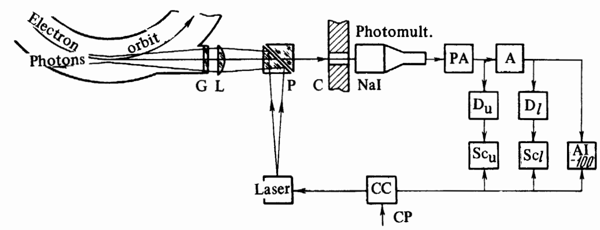

FIG. 1. Block diagram of experimental setup. G – glass, L –lens, P – prism, C – collimator, D_l and D_u – discriminators, AI – 100 – –pulse analyzers, Sc_l and Sc_u – scaler circuits, CC – control circuit CP – control pulse.

To obtain the γ beam, the laser radiation was directed by means of prism P through glass G inside the vacuum chamber of the synchrotron, in a direction opposite to the accelerated electrons. The lens L focused the laser light on to the electron orbit into a spot of 4 mm diameter. A light flash of duration on the order of 1 msec appeared when the electrons reached an energy of 550 MeV. During that time, the electron energy changed by less than 0.2%.

To determine the direction of the tangent to the equilibrium electron orbit, we used the electron synchrotron radiation. All the elements of the setup were adjusted relative to this direction[5].

The scattered photons were registered with a scintillation spectrometer with NaI(Tl) crystal (diameter 120 mm, height 100 mm), located at a distance of 11 meters from the center of the beam interaction region, behind a lead collimator C with solid angle 1.6 $\times 10^{-7}$ sr. The pulses from the spectrometer, following suitable amplification, were fed to an AI-100 pulse analyzer and to scaler circuits. The discrimination level of the discriminators D_l and D_u were chosen such that the scaler circuit Sc_l registered the main part of the pulses from the scattered photons, and the circuit Sc_u counted the high-energy background, which was not registered by the analyzer. The scaler circuits were used in the measurement of the angular distribution of the scattered photons, as well as to estimate the number of missed counts in the analyzer. The control circuit CC, triggered by a control pulse CP, switched on the recording apparatus only during a time when laser radiation was present.

The calibration of the spectrometer was monitored with the aid of a Cs^{137} source and maintained constant with accuracy 3%.

The intensity of the electron beam was measured with monitors located in the bremsstrahlung γ beam of the accelerator, and the laser energy was monitored with an oscilloscope, using a signal from the photomultiplier, and measured with a thermocouple. The relative error of the laser-radiation energy measurement was 5%, and the error in the measurement of the intensity of the electron beam was 1.5%. The systematic error was of the order of 30% in the absolute measurements of the laser energy, and 10% in the measurement of the electron-beam intensity.

In the beam-interaction region, the electrons move in a circular orbit with a radius of two meters. At an electron energy 550 MeV, the cross section of the bunch has the form of an ellipse elongated along the radius of the accelerator. The distribution corresponds to the normal law, with a maximum at the equilibrium orbit of the electrons and with mean-square deviations 2.8 and 0.7 mm radially and vertically, respectively.

The axis of the photon beam was aligned with the chosen direction of the tangent to the electron orbit. The photon beam had a divergence of 2×10^{-2} rad. The transverse dimensions of the interaction region of the beams are determined by the dimensions of the electron and photon beams, and the length of the interaction region is limited by the divergence of the photon and by the curvature of the orbit of the electrons, and equals approximately 400 mm. The particle and counter angle in the interaction region differs from π by less than 0.1 rad, and therefore all the particle collisions can be regarded as head-on collisions. According to calculation, for the colliding-particle energies considered here, the γ quanta produced as a result of the scattering, with energy up to 8 MeV, move in the direction of the primary-electron velocity and are contained in a small angle of the order of 1 mrad.

The characteristics of the produced γ-quantum beam are strongly influenced by the angle spread of the electron velocities in the beam interaction region. The angle spread of the electron velocities relative to the equilibrium orbit is connected with the presence of betatron oscillations of the particles in the accelerator. Betatron oscillations in two mutually perpendicular planes (radial and vertical oscillations) can be regarded as independent. For a harmonic oscillation law, the angular distribution of the electron velocities, connected with the betatron oscillations, turns out to be the same as the aforementioned distribution of the particles in the bunch. The angular distribution of the electron velocities in the vertical plane is described by a normal law with a mean square deviation of 0.32 mrad. The angle spread of the

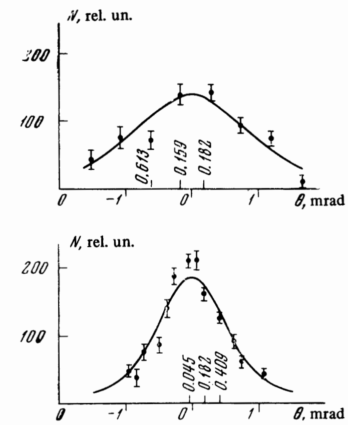

FIG. 2. Angular distributions of scattered γ quanta for two orientations of the electric vector of the laser photons: top – vector direction →, bottom ↓: solid curves – calculated angular distributions. The abscissas indicate the points at which the energy distributions of the γ quanta were measured.

electron velocity is relative to the equilibrium orbit in the horizontal plane, although of the same order (0.75 mrad), turns out to be insignificant, owing to the curvature of the electron orbit in the beam interaction region. The angular distribution of the γ quanta scattered in the plane of the electron orbit is a manifestation of the luminosity[1)] of the different sections of the beam interaction region. The calculated half-width of the angular distribution curve in the horizontal plane is of the order of 80 mrad.

As follows from the theory[6] the angular distribution of the γ quanta produced in scattering of linearly-polarized photons depends on the azimuthal angle between the plane of emission of the scattered quanta and the plane of polarization of the primary photons. The presence of a circular electron orbit in the beam interaction region does not make it possible to reveal the singularities of the scattering process by measuring the angular distribution of the γ quanta in the horizontal plane. Therefore the angular distribution was measured only in the vertical plane, but for two mutually perpendicular orientations of the laser light-wave electric vector, one of the orientations being vertical. A prism placed in the path of the laser beam did not distort the polarization state of the infinite light, since the electric vector of the laser photons was oriented in the plane of that phase of the prism, from which the total internal reflection of the light took place, or else in a plane perpendicular to it. The setting accuracy was such that the degree of polarization of the light after passing through the prism differ from the initial one by less than 1%.

The results of the measurement of the angular distribution are shown by the points in Fig. 2 for two orientations of the electric vector of the laser emission (the vector direction is indicated by the arrow). The errors did not include the relative error in the measurement of the intensity of the laser radiation. In the measurement of the angular distribution, the collimator was moved together with the spectrometer in the vertical plane in

[1)]Luminosity – ratio of the γ-quantum yield to the effective cross section of the process.

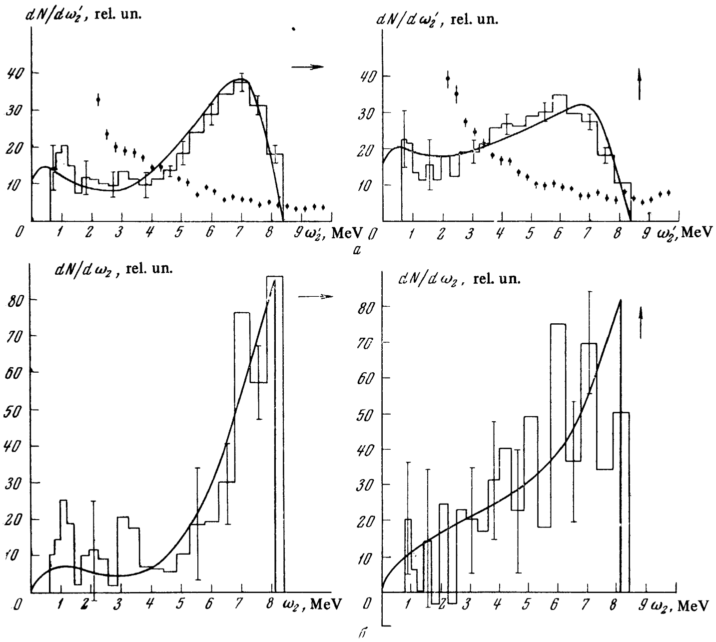

FIG. 3. Amplitude distributions of the pulses of the spectrometer (a) and energy distributions of the γ quanta (b) for an observation angle $\theta = 0.182$ mrad in two directions of polarization of the primary photons (designated by the arrows). Solid curves – theoretical. Black points – amplitude spectrum of the background.

such a way that the collimator axis, passing through the center of the beam interaction region, made an angle θ with the chosen direction of the tangent to the electron orbit. The accuracy of angle setting was 0.23 mrad. The solid lines in the same figure show the angular distribution calculated with an electronic computer for the concrete geometry of the experiment. If the electron beam were of negligibly small diameter and had no angular velocity spread, then the half-widths of the angular distribution would equal 0.3 and 0.62 mrad respectively for the vertical and horizontal orientations of the electric vector of the laser light. The broadening of the angular distributions by 0.12 and 0.43 mrad respectively is due to the curvature of the electron trajectory in the beam interaction region, and the broadening by 0.13 and 0.06 mrad is due to the presence of vertical betatron oscillations. A statistical analysis with the aid of the χ^2 criterion indicates good agreement between the theoretical calculations and the experimental results. The agreement was regarded as good and the obtained probability was $p(\chi^2 > \chi^2_{exp}) > 0.1$. The measurements of the energy distributions of the scattered photons, obtained for three γ-quantum emission angles in the vertical plane at the indicated orientations of the light-wave electric vector, are in equally good agreement with the calculations.

Typical results of the measurement of the amplitude spectra of the scintillation-counter pulses, for a γ-quantum emission angle $\theta = 0.182$ mrad, are shown by the histogram of Fig. 3a. The smooth curve is the result of the theoretical calculations. The points show the amplitude spectrum of the background, normalized to the same electron-beam intensity as the reduced amplitude spectrum of the scattered photons. The background was appreciable and connected with the bremsstrahlung of the electrons on the residual gas in the vacuum chamber of the synchrotron. At a pressure 10^{-6} mm Hg in the vacuum chamber, approximately one effective quantum of bremsstrahlung is produced from one mm of orbit within the duration of the laser pulse. The contribution of the photomultiplier noise and of the cosmic-radiation background to the total background level turned out to be negligibly small.

In comparing the experimentally obtained energy and angular distributions with the calculated ones, account was taken of the absorption of the γ quanta in the material and in the air on the path to the spectrometer, and also of the singularities of the registration of radiation by a scintillation counter[7]. The total thickness of the optical parts located in the path of the produced γ beam was 36 mm. The transmission coefficient of the γ quanta passing through glass and a layer of air 10 meters thick was 0.8 in the energy range 3–8 MeV, and decreased smoothly to 0.4 at an energy 0.5 MeV. The influence of the collimator, the absorption of the γ quanta in the material, and the sensitivity of the operators have little effect on the form of the angular distribution.

Figure 3b shows by way of illustration the calculated energy spectra of the γ quanta (solid curve) in the experimental energy spectrum obtained by recalculation from the amplitude spectra shown in Fig. 3a.

It is seen from the presented data that the presence of an angle spread of the electron velocities hinders the production of monochromatic γ quanta. Nonetheless, the method of Compton scattering of light by relativistic electrons does make it possible to reduce appreciably the background of the low-energy photons.

According to the theoretical calculations, it was expected that approximately 120 γ quanta would be produced from 1 mm of orbit in each accelerator operating cycle (3×10^{10} electrons/cycle, laser energy 4 J). In our case, the γ-quantum yield was independent of the laser-pulse duration, owing to the multiple passage of the same bunch of electrons through the given light pulse, so that the duration of the laser pulse was much larger than the duration of one revolution of the electron bunch in the synchrotron (50 nsec). The average yield in a time equal to the laser-radiation duration turned out to be the same as for uniform time distribution of the intensity of the interacting beam. The experimental yield turned out to be 1/6 the theoretical estimate. This result should not be regarded as poor, since we measured the light energy near the laser, and not the energy introduced to the interior of the synchrotron vacuum chamber.

In the calculations, the distribution of the photon density in the image plane was assumed to be uniform. It actually is far from uniform and depends on many factors that are difficult to control (the accuracy of adjustment of the mirrors of the laser resonator, the relative positions of the pump lamps and the active element, etc.). An exact allowance for this distribution may change the estimate of the absolute yield of the γ quanta, but is a very complicated matter.

By shifting the region of interaction of the light with the electrons to a linear section of the accelerator of approximate length 0.5 m it is possible to obtain 10^4—10^5 γ quanta per pulse. The use of laser systems with large output power may increase by several times the intensity of the beam of scattered quanta. Such a beam, because of its high degree of polarization, can find application in the investigation of certain photonuclear reactions even when a 600 MeV accelerator is used.

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17