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Polarized photons from silicon single crystal in the 31-GeV electron beam of the Serpukhov proton accelerator

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A beam of tagged photons emitted coherently is obtained from a silicon single crystal placed in an electron beam from the Serpukhov proton accelerator. The electron energy is $E_e = 31$ GeV, the beam intensity is 4×10^4 particles per pulse of duration 1.7 sec. The photon intensity in each of five almost equal energy intervals in the range $k = 8.2$–24.2 GeV is $I\sim(10^{-1}$–$10^{-2})\gamma/e^-$, and the linear polarization is estimated at $P\sim50$–20%. A method is described for aligning the single crystal in the proton-accelerator electron beam. Unexplained narrow radiation intensity peaks are observed when the single-crystal orientation is varied.

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1. INTRODUCTION

Proton synchrotrons are presently used extensively as sources of electrons and unpolarized photons with energies unattainable in the existing electron accelerators.[1-5] Questions involving the production of polarized-photon beams in a new high-energy region are therefore extensively discussed in recent years.[6-11] The most promising methods for protons accelerators for these purposes are those using effects in single crystals, such as coherent bremsstrahlung of electrons[11,12] and selective absorption of bremsstrahlung photons.[13,14] According to theoretical estimates, these methods will make it possible to obtain linearly polarized photons with respective energies 0.2–0.7 of the electron energy also at the end of their bremsstrahlung spectrum. Linear polarization of photons can be transformed into circular polarization by using a second single crystal of suitable thickness.[15]

The use of coherent bremsstrahlung of electrons to generate polarized photons in proton accelerators has distinctive features connected with the angular divergence of the produced electron beams when their intensity is relatively low, the transverse dimensions are large, and have noticeable nonmonochromaticity. Collimation of the electron beam and a decrease of the electron energy spread make it possible in this case to obtain low-intensity fluxes of quasimonochromatic polarized photons, which can be used only in experiments with bubble chambers. The effective use of the electron beam itself is exceedingly low in this case. A substantial increase in the effectiveness can be obtained by using the method of tagging polarized photons in a wide energy range of the bremsstrahlung spectrum. Beams of tagged polarized photons in proton accelerators make possible experiments with the use of counting and recording apparatus.

We present here a complete description of an experiment, with the Serpukhov accelerator on the production of a beam of tagged linearly polarized photons by the method of coherent bremsstrahlung of electrons in a silicon single crystal, and the results of an analysis of the obtained data.

2. EXPERIMENTAL SETUP

The magneto-optical electron channel 14 E, in which the experiment was performed, is described in Ref. 2.

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Figure 1 shows the arrangement of the experimental equipment, consisting of a tagging system and an avalanche proton detector, scintillation counters for guarding and monitoring the electron beam, as well as a goniometric setup with a single crystal. The optical system of the channel was adjusted to minimize the horizontal angular divergence of the beam and its dimensions in the single crystal. The electron beam was additionally governed by monitoring scintillation counters.

The electron energy was chosen to be 31 ± 0.2 GeV. The useful single-crystal area spanned by an elliptic monitoring counter located directly behind the crystal, was 50×35 mm^2 (horizontal and vertical axes of the ellipse). In this case the intensity of the working beam was 4×10^4 electrons per 10^{12} protons accelerated to 70 GeV in a pulse of duration up to 1.7 sec, and amounted to only 10% of the total flux of particles in the magneto-optical channel. Simulation by the Monte Carlo method and experimental measurements by the "thin beam" method[16] make it possible to describe the angle spread of the electrons in the working beam in the single crystal by means of normal distributions with the variances $\sigma_H = 2 \times 10^{-4}$ rad and $\sigma_V = 6 \times 10^{-4}$ rad in the horizontal and vertical directions, respectively. The agreement between the calculated and experimental characteristics of the electron beams of the Serpukhov accelerator was investigated previously.[1-3] Stabilization of the power supplies for the elements of the magnetooptical channel and stabilization of its optical parameters ensured an angular instability less than $\pm 10^{-5}$ rad for the electron beam in the single crystal, and practical absence of linear displacement. In the region of the possible placement of the experimental target, the distributions of the bremsstrahlung-photon beam intensity in its horizontal and vertical transverse directions had experimental widths ~20 mm at half-height and ~40 mm at the base.

The tagging system (Fig. 1) consisted of a deflecting magnet M and of six tagging scintillation counters S_1–S_6 connected for time coincidence with thin 5-mm scintillation counters C_1 and C_2 that monitored the beam of the primary electrons. The scintillation counters C_A connected in anticoincidence with the tagging system, served to suppress the background due to the tridents. A deflecting magnet momentum-analyzed the recoil electrons from the single crystal, and also

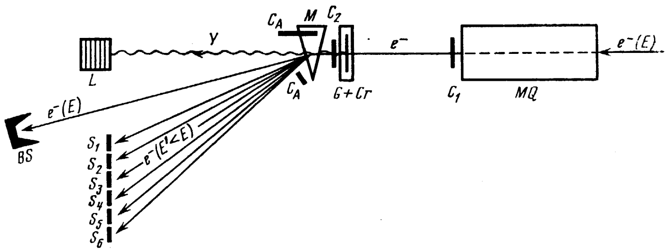

FIG. 1. Setup used to obtain a beam of tagged linear polarized photons: MQ—magneto-optical channel of electrons, C and S—scintillation counters, $G+Cr$—goniometric setup with single crystal, M—deflecting magnet, L—photon avalanche detector, BS—absorber for beam of primary electrons.

separated in space the beams of the electrons and bremsstrahlung photons. The bremsstrahlung photons were registered by a lead-scintillation avalanche detector L having a thickness of 20 radiation lengths along the beam and an energy threshold 2 GeV. The tagging system and its calibration are described in detail in Refs. 2, 3, and 17, and determined in essence the total energy of the bremsstrahlung radiation in the act of passage of the primary electron through the single crystal, i.e., the quantity

$$\sum k = E_e - E_e', \qquad (1)$$

where E_e and E_e' are the electron energies before and after the emission in the single crystal. The experimentally measured quantity was the counting rate in the energy tagging channels

$$I_i = N(C_1 C_2 \bar{C}_A L S_i)/N(C_1 C_2 \bar{C}_A), \quad i = 1-6.$$

The tagging channels covered the energy range $E_e - E' = 8.2$–27.1 GeV.

The goniometric setup was similar to that described in Refs. 18 and 19 and had horizontal and vertical rotation axes that made it possible to orient the single crystal within a range ±0.1 rad with a rotation angle accuracy 2.5×10^{-5} rad. The platform of the goniometer was set horizontally with the aid of a level having a lower accuracy $\sim 5 \times 10^{-5}$ rad, since this circumstance is not critical for the subsequent experimental adjustment of the single crystal in the electron beam.

3. CHOICE OF SINGLE CRYSTAL

The type of single crystal was chosen with allowance for its structural characteristics, the Debye temperature, and the possibility of producing high-grade samples with relatively large dimensions. These requirements are best satisfied by diamond and silicon single crystals. Diamond yields the largest coherent effect and consequently the highest degree of radiation polarization. For the electron beams of the Serpukhov accelerator, however, the use of a silicon single crystal is preferable, since it can provide a a radiator of the desired dimensions, and in addition the single-crystal orientation angles needed for the coherent effect are larger by 1.5 times than the corresponding values for diamond. The last circumstance relaxes the requirements on the angular characteristics of the electron beam.

We used in the experiment silicon single-crystal plates of 70 mm diameter and of thickness equivalent to 0.14 and 0.05 radiation length of its amorphous modification, cut along the (100) plane. The silicon plate was secured in the frame of the goniometer. In the experiment, the crystallographic axes of the thick plate, [010] and [001], whose unit vectors will be designated $\mathbf{b}_2$ and $\mathbf{b}_3$ respectively, were oriented along the vertical and horizontal goniometric axes, respectively, while for the thin plate they were turned relative to the latter through an angle ~45° in the common plane.

At the chosen crystallographic axes, the silicon-single-crystal reciprocal lattice is illustrated in Fig. 2. The components of the reciprocal-lattice vector

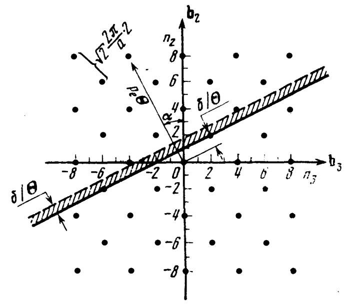

FIG. 2. The (100) plane of the reciprocal lattice of a silicon single crystal (the axis $\mathbf{b}_1$ [100] is perpendicular to the plane of the figure, Θ—polar angle between $\mathbf{p}_e$ and $\mathbf{b}_1$, $\alpha > 0$ in clockwise direction from the projection $p_e\,\Theta$ of the vector $\mathbf{p}_e$ on the plane of the figure; the space of the allowed momentum transfer to the lattice is shown shaded for the coherent bremsstrahlung process.

for its sites are given by

$$g_2=\frac{2\pi}{a}n_2,\quad g_3=\frac{2\pi}{a}n_3, \tag{2}$$

where n_2 and n_3 are the integer indices of the site, $2\pi/a = 4.45\times10^{-3}$, and $a = 1403$ is the lattice constant in units of the Compton wavelength of the electron. The condition for coherent interaction of the electrons with the single crystal is given by[12]

$$\delta\leqslant\Theta(g_2\cos\alpha+g_3\sin\alpha),\quad \delta=\frac{m_ec^2}{2E_e}\frac{x}{1-x},\quad \Theta\ll1, \tag{3}$$

where δ is the minimal momentum transferred to the lattice, $x = k/E_e$ is the relative photon energy, Θ and α are respectively the polar azimuthal angles of the mutual orientation of the single crystal and the momentum vector $\mathbf{p}_e$ of the primary electron, and m_ec^2 is the rest mass of the electron. The strongest coherent effect and consequently the highest degree of polarization of the radiation occur if the equal sign is used in (3) for the sites closest to the $\mathbf{b}_1$ axis [100] with indices $n_2 = \pm2$ and $n_3 = \pm2$.

4. METHOD OF ORIENTING THE SINGLE CRYSTAL IN THE ELECTRON BEAM

Since the primary electrons have an angular distribution, the single crystal is oriented in practice relative to a certain effective electron-beam axis. The single-crystal rotation angles Φ_V and Φ_H about the vertical and horizontal goniometric axes are connected with its orientation angles Θ and α relative to the effective axis of the electron beam by the relation

$$\Phi_V=\Phi_V^0+\Theta\sin(\alpha-\varphi),\quad \Phi_H=\Phi_H^0+\Theta\cos(\alpha-\varphi), \tag{4}$$

where Φ_V^0 and Φ_H^0 are the readings of the initial goniometric angles when the crystallographic axis $\mathbf{b}_1$ is aligned with the effective axis of the electron beam ($\Theta = 0$), while φ is the azimuthal angle of the initial rotation of the crystallographic axes $\mathbf{b}_2$ and $\mathbf{b}_3$ relative to the goniometric axes (the reference direction, see Fig. 4 below). It is obvious that the desired oreintation of the single crystal can be attained in practice only if the initial values of the angles are known. The considerations that follow justify the experimental method used to determine these angles.

In a rectangular coordinate system, Φ_V and Φ_H can be regarded as the auxiliary system Φ_V^*, Φ_H^* rotated relative to the former through an angle φ and having an origin at the point (Φ_V^0, Φ_H^0). In this system we obtain from (2)–(4) the connection between the coordinates Φ_V^* and Φ_H^* for the maximum of the coherent radiation from a discrete site of the reciprocal lattice with indices $\langle 0, n_2, n_3\rangle$:

$$\frac{\Phi_V^*}{1/An_3}+\frac{\Phi_H^*}{1/An_2}=1,\quad A=\frac{4\pi}{a}\frac{E_e}{m_ec^2}\frac{1-x}{x}. \tag{5}$$

Equation (5) corresponds to a linear dependence of the angles, and consequently the single-crystal reciprocal lattice investigated by means of coherent radiation of a monochromatic parallel beam of electrons is mapped in the coordinate plane (Φ_V^*, Φ_H^*) into a family of straight lines corresponding to sites with different sets of indices n_2 and n_3. The straight lines for the sites along a chosen crystallographic chain with fixed value of n_3/n_2 are parallel and are pairwise symmetrical relative to a "reference" line drawn at an angle $\beta = \tan^{-1}(-n_3/n_2)$ to the coordinate axis Φ_V^* through the origin $(\Phi_V^*, \Phi_H^*) = (0, 0)$. The points that lie on symmetrical lines correspond to coherent peaks of equal intensity. Such a map of the discrete values (for a similar method as applied to electron accelerators see Ref. 20) is illustrated for a silicon single crystal in Fig. 3, which shows the straight lines (5) for a group of reciprocal-lattice sites.

It is seen from Fig. 3 that for electron beams with

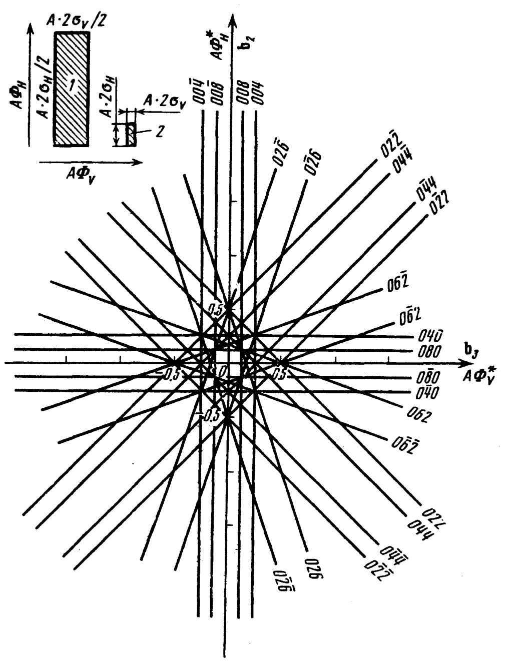

FIG. 3. Connection between the rotation angles $\Phi_H{}^*$ and $\Phi_V{}^*$ of the silicon single crystal around the axes $\mathbf{b}_3$ and $\mathbf{b}_2$, respectively, for coherent bremsstrahlung from discrete sites of the reciprocal lattice in an electron beam with zero angle divergence (the indices of the sites are indicated on the straight lines). The shaded rectangles illustrate the angular divergence of the working beam of the electrons $E_e = 31$ GeV in the system of goniometric angles where $k = 8.2$ GeV (1) and $k = 24.2$ GeV (2). The angles are given in units of the parameter A^{-1}.

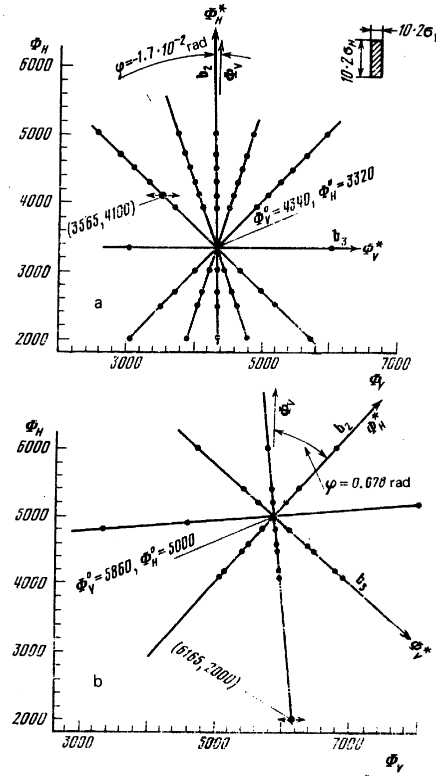

FIG. 4. Experimental determination of the angular orientation of a thick (a) and thin (b) silicon single crystal by the method of "reference" lines in a working beam of electrons with $E_e = 31$ GeV (the points on the lines are the experimental data, the unit of angle is 2.5×10^{-5} rad, the arrows at the points indicate the orientations used in the detailed investigations of the present study).

finite angular divergence the intensity peaks of the coherent radiation will be due in the general case to an integral effect from a chain of sites with a constant n_3/n_2. The largest coherent effect can be ensured at $n_3/n_2 = \pm 1$. In the described experiment, the optimal values of the angle φ are $\pm 45°$, since in these cases a relatively large angular divergence of the electron beam in a vertical direction is not vertical.

The experimental map of the "reference" lines in the (Φ_V, Φ_H) plane makes it possible to obtain the angles Φ_V^0 and Φ_H^0, since the counting rate in the tagging channel, for example $I = f(\Phi_V - \Phi_{V,b})$, at constant Φ_H is symmetrical, as a function of one of the goniometric angles Φ_V, relative to the definite coordinates $\Psi_{V,b}$ of the points of the "reference" lines. The rotation of the experimental map as a unit relative to the coordinate system (Φ_V and Φ_H) determines the angle φ.

The described method of the experimental tie-in of the crystallographic axes with the effective axis of the electron beam and with the goniometric axes is illustrated in Fig. 4 for the employed silicon single crystals. The accuracy of the angles Φ_V^0 and Φ_H^0 in these cases is estimated to be of the order of 5×10^{-5} rad.

5. EXPERIMENTAL RESULTS

We have investigated the dependences of the intensity and of the degree of polarization of coherent bremsstrahlung, in energy intervals set by the tagging channels, on the orientation angles of silicon single crystals. Figures 5 and 6 show these dependences for a chain of sites with $n_3/n_2 = 1$, containing the "strong" $\langle 0\bar{2}\bar{2}\rangle$ and $\langle 022\rangle$ sites. The ranges of the orientation angles of the single crystals in these cases are indicated in Fig. 4.

The dashed curves in Fig. 5a were calculated from the equations of Ref. 12 for the electron bremsstrahlung cross section in a single crystal. The atomic form factor of silicon was taken from Ref. 21 (see also Ref. 22). We took into account in the calculations the horizontal and vertical angular divergences of the electron beam, the finite energy range of the magneto-optical channel and of the tagging counters, and also the contribution made to the investigated effects by the amorphous material located ahead of the deflecting magnet of the tagging system (scintillation counters and air, with total thickness 0.05 radiation length). To take into account the ineffectiveness of the tagging system, the experimental data were normalized to the calculated values in incoherent regions of radiation (with a coefficient 1–2). In the region of small values of the variable orientation angle of the single crystals, a strong discrepancy is observed between the experimental and calculated results. Since the quantity directly measured in the experiment was the intensity of the recoil electrons from the single crystal, this discrepancy may be due to the increase in the probability of multiple emission of photons in this range of angles. The results are direct evidenceof the existence of such a process.

For a detailed analysis of the experimental results, we developed a program for the calculation, by the Monte Carlo method, of the energy spectra of the recoil electrons from the single crystal, with account taken of multiple Coulomb scattering and multiple bremsstrahlung of the electrons. The results of these calculations, shown in Figs. 5a and 6a by the solid curves, are in much better agreement with experiment. For a thin single crystal, however, even these calculations do not account for the presence of narrow experimental radiation-intensity peaks in the region of small values of the orientationangle. These peaks are possibly due to radiation produced when the charged particles are channeled in the single crystals.[23] Under this assumption, which is still debatable, the absence of analogous peaks on the orientation curves of a thick single crystal of silicon could be attributed to the stronger dechanneling effect in the crystal, and also to a different rotation of its crystallographic axes compared with the thin single crystal, which increases the effective angular divergence of the electron beam.

In a "clean" experiment, the amorphous matter along the path of the beams, especially for the electron beam ahead of the deflecting magnet of the tagging system, should be removed where possible. In this case the level of the coherent effect increases (Figs. 5b and 6b). It should be noted that the contribution made to the radiation intensity on the orientation curve from the amorphous matter is not additive.

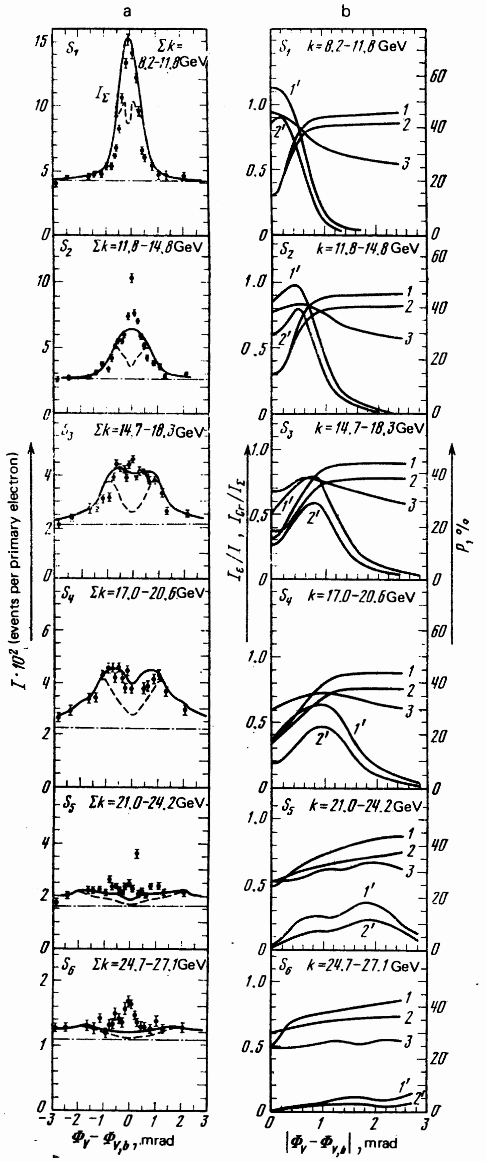

FIG. 5. Effect of coherent bremsstrahlung in a silicon single crystal of thickness 0.05 radiation length in a working beam of electrons with $E_e = 31$ GeV for the tagging channels S_1—S_6. a) Counting rate I of photon bunches, with energy Σk, that are genetically connected with a single electron; points—experimental data, dashed and solid curves—calculated without and with allowance for the multiple processes under the experimental conditions, dash-dot lines—calculated level of incoherent radiation with allowance for multiple processes. b) Curves 1 and 2 correspond to the calculated values of the relative counting rates I_ε/I_{Cr} and I_ε/I_Σ of photons with energy k, accompanied by photon partners with total energy $\varepsilon \leq 2$ GeV, for the single crystal in the absence and in the presence of amorphous matter, with allowance for multiple processes; curve 3—the ratio I_{Cr}/I_Σ. Curves 1′ and 2′ describe the calculated degrees of linear polarization P of photons with energy k, corresponding respectively to curves 1 and 2. For the values of $\Phi_{V,b}$ and Φ_H=const, see Fig. 4. In Fig. 5a, for the tagging channel S_4, three successive experimental points were left out of the intensity peak at $\Phi_V - \Phi_{V,b} \approx 0$ with corresponding values $10^2 I \approx 6.8$.

In physical investigations it is necessary to exclude the influence of multiple emission on the accuracy of the energy tagging of the photons[24] and to ensure for the latter an unambiguous determination of the degree of polarization. One uses for these purposes an avalanche detector in a photon beam passing through the experimental target. The energy threshold for the registered signals from the shower detector is set close to the energy half-width ε of the tagging channels, and these signals are adjusted for temporal angicoincidence with the signals from the other detectors that register the interactions of the photons in the target. This ensures an acceptable error in the energy tagging and eliminates from the useful statistics the case of photon interaction with the experimental target, when photon partners with a total energy larger than ε are present and introduce an ambiguity in the interpretation of the experimental results.

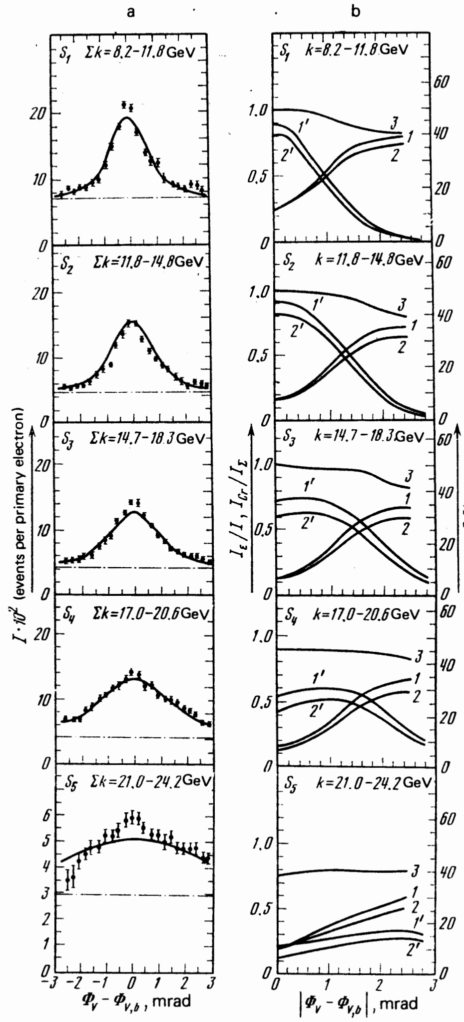

FIG. 6. Data for silicon single crystal 0.14 radiation length thick and for tagging channels S_1—S_5, analogous to those given in Fig. 5.

In the present study, the fraction of the acts of photon emission accompanied only by photon partners with total energy $\varepsilon \leq 2$ GeV was calculated for different tagging channels as a function of the variable orientation angle of the single crystal. The results of the calculations are illustrated in Figs. 5b and 6b for the experimental conditions and for the case when the amorphous matter is removed from the beams. The same figures show the corresponding calculated values of the degree of linear polarization P of the photons.

Thus, we obtain in the Serpukhov proton accelerator, at an electron energy 31 GeV, tagged photons from silicon single crystals in five almost equal intervals of the energy band 8.2–24.2 GeV, with intensities in the intervals $I \sim (0.10\text{-}0.01)\gamma/e^-$ and with a calculated degree of linear polarization $P \sim 50\text{–}20\%$ respectively. An experimental determination of the linear polarization of the photons is the subject of future investigations. Optimization of the conditions for generation of a beam of tagged linearly polarized photons and its production in the larger-luminosity and higher-grade $2E$ electron magneto-optical channel (Ref. 1) will make it possible to increase the factor $N\gamma P^2$ by several times, where N_γ is the number of photons in the tagging channel per accelerated proton. In addition, an increase of electron energy to 40 GeV, which can be obtained in the accelerator should extend the energy range of the polarized photons to 30 GeV.

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