backgrounds obtained in this manner are indicated as the dashed curves in the figures.

[5]Interferences between resonance and background have been neglected as well as interferences between the decay modes of the $K(1420)$. A good fit to the Dalitz plot has been obtained without invoking interference effects, whose inclusion greatly increases the number of parameters.

[6]Instead of the simple $|f_{BW}|^2 \sin^2\theta$ density function we have also used $[(\vec{p}\times\vec{q})^i \cdot \vec{p}^j + (\vec{p}\times\vec{q})^j \cdot \vec{p}^i]^2 |f_{BW}|^2 \sim p^4 q^2 \sin^2\theta |f_{BW}|^2$, which takes into account angular-momentum barriers, where $\vec{p}$ is the momentum of the vector meson in the $K(1420)$ rest frame and $\vec{q}$ is the momentum of one of the decay particles in the 1^- rest frame. The branching ratios so obtained agree within one-half standard deviations with the ones quoted in the text. We have used

$$|f_{BW}|^2 = \frac{m}{q} \frac{\Gamma}{(m^2-m_0^2)^2 + m_0^2\Gamma^2}$$

with $\Gamma = \Gamma_0 (q/q_0)^{2l+1}$, $m_0 = 0.895$ (0.760) GeV, and $\Gamma_0 = 0.050$ (0.130) GeV for the $K(890)$ (ρ).

[7]We assume that only quasi two-body decay modes of the $K(1420)$ are present. The fit has also been performed allowing an uncorrelated $K\pi\pi$ decay mode without any significant improvement in the likelihood function.

[8]An estimation of the parameters β_1 and β_2 has been obtained by fitting the Dalitz plots in 160-MeV bands a adjacent to the $K(1420)$ and linearly interpolating the $K(890)\pi$ and $K\rho$ ratios into the $K(1420)$ region. The values used for the Dalitz plot analysis are $\beta_1 = 0.57$ and $\beta_2 = 0.06$.

[9]A χ^2 test on the $K(1420)$ Dalitz plot gives a probability of 10%.

[10]Neglecting decay modes other than the $K\pi$, $K(890)\pi$, and $K\rho$, the decay rates are 0.63, 0.28, and 0.09, respectively.

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[14]The resonance bands were defined as $0.535 \leq M(\pi^+\pi^-\pi^0) \leq 0.565$ GeV for the η and $0.75 \leq M(\pi^+\pi^-\pi^0) \leq 0.81$ GeV for the ω.

Polarization of High-Energy Photons Using Highly Oriented Graphite*

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We have demonstrated the feasibility of a new method of polarizing high-energy photons, by preferential attenuation of photons polarized in one plane as a result of coherent pair production on passage through a single crystal of specific orientation. Highly oriented graphite is a particularly favorable material. The method, feasible at presently available energies, is predicted to be especially useful at higher energies.

In 1962, Cabibbo, Da Prato, De Franceschi, and Mosco[1] suggested a new method for producing linearly polarized γ-ray beams. Just as visible light can be polarized by being passed through an anisotropic absorber (such as Polaroid film), so also could high-energy photons be polarized. The suggested anisotropic media were copper or silicon single crystals oriented at specific angles to the beam. In this orientation the cross section for coherent electron-pair production from the crystal is different for photons polarized in and normal to the plane of incidence. Since this process contributes substantially to the total cross section at high energy, polarization of the unabsorbed photons results.

At the time this method was suggested, coherent bremsstrahlung from crystals was known to be a feasible source of polarized photon beams. This was due to the theory of Überall[2] and the experiments of Bologna, Diambrini, and Murtas.[3] Subsequent work has further clarified the understanding of this process.[4] For experimental use, polarized-photon beams produced in this way have three important deficiencies. First, the polarization is large only for those photons of energy substantially less than the incident electron energy. This limits the energy at which experiments can be performed. Second, the polarized photons are accompanied by a substantial intensity of unpolarized, or slightly polarized, photons of energies all the way up to the energy of the incident electron. These can cause unwanted inelastic background events. Third, at high energy the required angular positioning tolerances become very hard to achieve. The attenuation method overcomes these disadvantages, at the cost of loss in intensity.

We have experimentally demonstrated the feasibility of the attenuation method using the Cornell 10-GeV synchrotron. We expected, and observed, an effect somewhat larger than was indicated by Cabibbo et al.[1] That was mainly due to our use of graphite rather than the silicon or copper which they felt were the most promising materials. Discussion of the relative merit of various materials, as well as detailed formulas describing the process, will be given elsewhere.[5]

The graphite used in the experiment is a highly oriented form obtained by the compression annealing of pyrolytic graphite.[6] This form of graphite was developed by the Union Carbide Corporation for use as highly efficient monochromators for x-ray and neutron diffraction.[7] It has a density of 2.26 g/cm^3, and a crystallite interlayer spacing ($c_0/2$) of 3.355-3.357 Å, compared with single-crystal values of 2.267 g/cm^3 and 3.354 Å, respectively. The mosaic spread, defined as the full width at half-maximum intensity of the 002 orientation distribution function, is $0.4 \pm 0.1°$, though values as low as 0.2° may be measured on small areas (1×5 mm). There is no ordering of the a axes in this graphite, so it behaves as a single crystal in one dimension only. Both microstructural defects (e.g., dislocations) and gross warpage cause increased mosaic spread of the c axis.

The polarizing device consisted of 14 pieces of highly oriented graphite of total dimension 12× 3/8 in. This sample, shorter than optimum by perhaps a factor of three, was used for reasons of economy. After the polarization experiment, the graphite was cut and cleaved into smaller pieces and 41 rocking curves were measured using Cu $K\alpha$ radiation on areas approximately 1×5 mm. The main bulk of the graphite in the photon beam was found to be highly oriented, but warpage and stacking serve to increase the average mosaic spread for the entire assembly. This effect is observed by comparing x-ray (small surface area) readings with neutron (entire volume) readings on large monochromators.

Coherent electron-pair production from crystals has been observed previously[8] and the theory closely resembles that for coherent bremsstrahlung.[4] If attention is focused on the recoiling particle (that is, the whole crystal) then the coherence conditions are the same as the Bragg conditions for x-ray scattering. Namely, the recoil momentum $\vec{q}$ must be normal to a specific set of parallel lattice planes, and its magnitude must be related to the spacing a between the planes by $q = h/a$. For a general crystal there are many sets of lattice planes, but for graphite only the natural cleavage (002) planes contribute. Define a vector $\vec{g}$ normal to the 002 planes of magnitude $h/a = 0.722\times 10^{-2} m_e$, where m_e is the electron mass and $c = 1$. $\vec{g}$ can be called the recoil momentum which the lattice demands in order to recoil coherently. Actually, higher-order coherent scattering allows recoil momenta which are integral multiples of $\vec{g}$. The Bragg coherence conditions can then be succinctly written as

$$\vec{q} = n\vec{g}, \quad n = 1,\ 2, \cdots.$$

The important orders are $n = 1$ and $n = 2$.

In calculating coherent production from the crystal it is necessary to calculate the amplitude from a single atom using the Bethe-Heitler formula and then to sum the amplitudes from all the atoms. Because the outgoing electron-positron system has nonzero rest energy, the crystal-recoil momentum necessarily has a component $q_\parallel$ along the beam direction. Define $E_+ = yk$, $E_- = (1-y)k$, where E_+, E_-, and k are the energies of the positron, electron, and photon, respectively. Kinematics shows that $q_\parallel$ cannot be less than

$$\delta = (m_e^2/2k)[y(1-y)]^{-1}.$$

The Bethe-Heitler formula, on the other hand, is large only for $q_\parallel \sim \delta$, although the perpendicular recoil $q_\perp$ can be much larger. ($q_\perp \lesssim q_{\rm typ} = m_e$.) Summarizing, the relevant quantities are typically in the ratio

$$\delta : g : q_{\rm typ} = 10^{-4} : 10^{-2} : 1.$$

The first ratio tells us that the incident photon angle, away from the 002 planes, must be about 10^{-2} in order that the crystal recoil normal to the the 002 planes. On the other hand, since $q_{\rm typ} \gg g$, incoherent production from the separate atoms is not appreciably affected by the crystal periodicity. This means that there is an isotropic attenuation approximately equal to that of

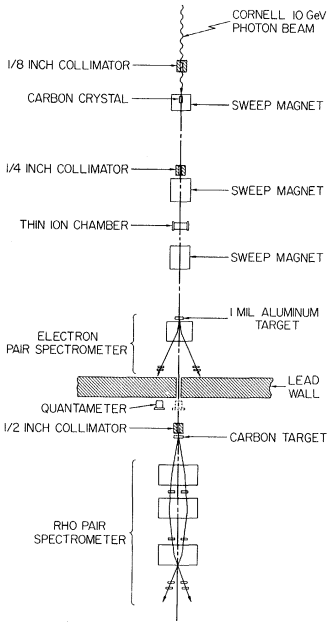

FIG. 1. Layout of apparatus.

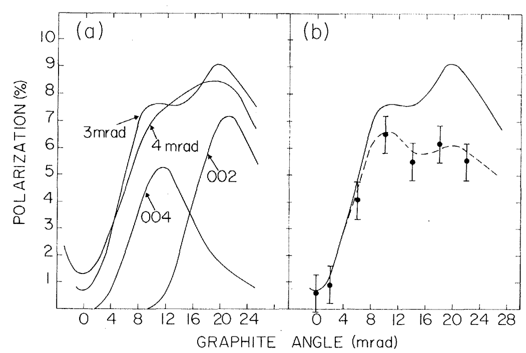

FIG. 2. Expected polarizations as a function of crystal angle. (a) 3 mrad and 4 mrad refer to the assumed crystal quality. The curve labelled 002 is the polarization resulting just for first-order coherent attenuation. 004 refers to second order. (b) The points are our measurements. The theory curve is the 3 mrad curve from (a). The dashed curve is a fitted curve as described in the text.

amorphous material. This does not contribute to the polarization. However, the ratio of coherent to incoherent production is proportional to k. Hence the effect becomes arbitrarily large at high energy and is already useful at 10 or 20 GeV.

As an analyzer of the polarization we used coherent ρ^0 photoproduction from amorphous carbon. This process has been well studied and is known experimentally to be a near-perfect analyzer.[9] This is in agreement with the vector-dominance picture according to which the photon, in some sense, turns into a ρ^0 meson which undergoes diffraction scattering from the nucleus. The ρ^0 decays into a π^+ and a π^-, the orientation of the decay plane being observable. Since the three stages all preserve the polarization, measurement of the azimuthal distribution of the decay planes around the incident direction gives a direct measure of the polarization of the incident beam. Since the ρ^0 detection apparatus detected only ρ^0's whose decay planes were nearly horizontal it was necessary to rotate the plane of polarization by rotating the graphite. For this purpose the graphite was mounted in a goniometer which allowed that rotation as well as rotations around the other two perpendicular axes. The polarization was then calculated from the relation

$$P=(C_\perp-C_\parallel)/(C_\perp+C_\parallel),$$

where $C_\parallel$ ($C_\perp$) was the counting rate with the graphite 002 planes parallel (perpendicular) to the ρ^0 decay planes.

In Fig. 1 we illustrate the apparatus. A 9.5-GeV bremsstrahlung beam from the Cornell accelerator passed through the graphite which was in a 10-kG magnetic field. The field swept out electron-positron pairs produced in the graphite, as they could produce unpolarized photons in the remaining graphite. The thin ion chamber was used as a secondary-beam intensity monitor, calibrated periodically against a quantameter, which could be placed in the beam as indicated. The electron-pair spectrometer enabled us to measure the photon energy spectrum. ρ^0's of energy 8.7 ± 0.6 GeV were counted by detecting the two pions in the ρ^0 pair spectrometer which has been described elsewhere.[10] Figure 2(b) shows the measured polarization P as a function of graphite angle,[11] together with the predicted values. In calculating the expected polarization there were three parameters which we felt were uncertain. They were the effective Debye temperature, which we took to be 530°K[12]; the electronic screening form factor, which we assumed to be equal to the form factor of a free carbon atom[13]; and the crystal perfection, for which we assumed a Gaussian distribution of the angle of the c axis with standard deviation 3 mrad. The prediction using these values differs somewhat from our measurement. To try to account for this discrepancy consider the curves of Fig. 2(a).

The polarization resulting from first-order Bragg coherence is indicated by 002 and is large at about 20 mrad. Second-order coherence (004) contributes at smaller angles near 10 mrad.

These are broadened by crystal imperfection. The low polarization measured at zero angle shows that the crystal imperfection cannot be much worse than 3 mrad. The measured deficit is greatest in the 002 region which is the region of low recoil momentum. Hence the Debye temperature cannot be much below 530°K as that would preferentially suppress the high recoil-momentum region. We speculate then that the deficit is due to the electrons' screening being somewhat more effective in graphite then it would be for a free atom. Reducing the 002 contribution by a factor 0.6 and the 004 by a factor 0.8 yields the good fit shown in Fig. 2(b). Since the electron form factor F enters the calculation in the form $(1-F)^2$, these represent changes of only 8% for the 002 line and 12% for the 004 lines. Subsequent calculations use these modified screening functions.

As a further check of our understanding of the effect, we measured the energy spectrum of the polarized-photon beam and compared it with the energy spectrum with the graphite crystal replaced by amorphous carbon. The results are shown in Fig. 3. As expected, the increased attenuation due to coherent pair production in the crystal depletes the upper end of the spectrum.

Another check was a measurement of the relative response of the thin ion chamber (which responds primarily to soft photons) and the quantameter (whose response is proportional to intensity independent of wavelength), as is done in studying coherent bremsstrahlung.[14] We observed a 5% change in relative response as the graphite angle was changed from 0 to 20 mrad. While a small effect, the precision of the ion chambers was good enough to allow us to check the symmetry about 0 mrad, thus confirming our graphite orientation with an accuracy of ±1 mrad.

Having demonstrated our understanding of the

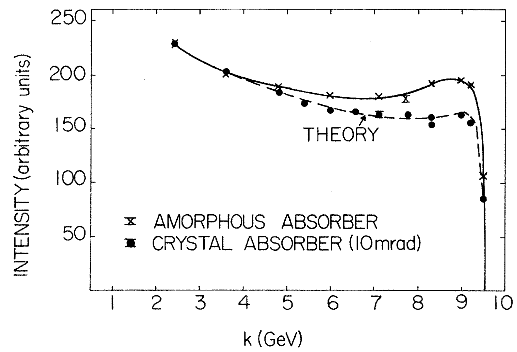

FIG. 3. Intensity spectra, at 10 mrad crystal angle. The upper curve is a smooth curve through the measured points of a bremsstrahlung spectrum. The lower curve is reduced at high energy by coherent absorption with the best-fit parameters of Fig. 2(b).

effect it is useful to consider the practical use of the method. The beam which we actually produced had rather small polarization. There are two ways of increasing the polarization: lengthening the graphite and increasing the photon energy. The information in Table I allows one to calculate the effect of such changes. The thickness, at each energy, is chosen to give an attenuation of a factor of 20 in $I_\perp$, the perpendicular intensity. From the numbers given, beam properties for other thicknesses can be easily calculated. In each case the assumed angle of incidence, near optimum, is indicated. At very high energies the effect becomes very large. It is noteworthy that the angular tolerance does not become particularly critical at high energy. The angular tolerance is the change in graphite angle which yields a change in polarization of only a few percent. Values are listed in Table I. This generous tolerance will make the physical positioning of the graphite rather easy. In conclusion, we expect that this method will prove useful both in polarizing photons and in measuring the polar-

Table I. Beam properties after a thickness of graphite sufficient to reduce $I_\perp$ by a factor of 20.

Energy (GeV)	Angle (mrad)	Angle tolerance (mrad)	Thickness (cm)	$I_\parallel/I_\perp$	Polarization
10	10	3	68.0	0.72	0.16
20	5.5	2	62.5	0.57	0.27
40	2.5	2	54.5	0.45	0.38
80	1.0	1	42.7	0.27	0.57
160	0.0	1	32.1	0.22	0.64
320	0.0	1	26.6	0.29	0.55

ization of photons.

We would like to thank Dr. Roy Schwitter for his advice on crystals and coherent production. Our calculations were based largely on a modification of his computer program. We are grateful to Professor Giordano Diambrini-Palazzi for mentioning to us this method of polarizing photons.

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[11] Instead of using the coincident $\pi^+\pi^-$ rates, we used the single-arm pion rates, since, for the average of the polarization at the four points of highest polarization, they gave ($\pm 1.0\,\%$) the same value for P as did the coincident rates. This allows us to study the angular dependence of Fig. 2 with better statistics. The fact that the production plane of single pions photoproduced from complex nuclei can serve as an analyzer is entirely reasonable. That is because the dominant source of such pions is photoproduced ρ^0 mesons. These are concentrated in a forward cone which is small compared with the ρ^0 decay cone. As a result, detecting a single pion from the decay fixes the decay-plane azimuth with fair accuracy. This assumption yields an upper limit for the analyzing power.

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Search for Violation of *CP* Invariance in $\tau^\pm$ Decay*

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We report a comparison of the Dalitz-plot distributions of 1.6 million τ^+ decays ($K^+ \to \pi^+\pi^+\pi^-$) and an equal number of τ^-decays. No significant asymmetry has been found in any region of the plot. In terms of the difference in the slope parameters a^+ and a^- for the odd-pion c.m.-energy spectra, the asymmetry is $\Delta = (a^+-a^-)/(a^+ + a^-) = -0.0070 \pm 0.0053$. We also present a preliminary result for the slope parameter itself: $a = 0.283 \pm 0.005$. New measurements of the $\tau^\pm$ decay rates and their difference confirm previous results.

In an experiment at the Brookhaven alternating-gradient synchrotron, we have analyzed ~3.2 million τ decays ($K^\pm \to \pi^\pm\pi^\pm\pi^\mp$), ~1.6 million for each charge of the kaon. The purpose of the experiment was twofold: (1) To search for a violation of *CP* invariance in τ decay by comparing the τ^+ and τ^- Dalitz plots. Any difference would indicate a *CP* violation outside the neutral kaon system, and hence one which could not occur via the "superweak" interaction.[1] (2) To determine the structure of $|M|^2$, the square of the τ-decay matrix element. All existing data on τ decay[2] (~58 000 τ^-, ~37 000 τ^+ events) are consistent with the linear approximation $|M|^2 dXdY \propto (1 + aY)dXdY$, where a is a constant, and $X = \sqrt{3}\,|T_1 - T_2|/Q$ and $Y = (3T_3 - Q)/Q$ are the Dalitz-Fabri coordinates.[3] Here T_1, T_2, and T_3 are the c.m. kinetic energies of the two "even" pions (same charge as the kaon's) and the "odd" pion, respectively; $Q = T_1 + T_2 + T_3$. In addition to reducing the uncertainty in the slope parameter a, this high-statistics experiment should give new information as to the presence of higher terms in the expansion of $|M|^2$. In this Letter we report the final results