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PRODUCTION OF A HIGH ENERGY, HIGH POWER POLARIZED PHOTON BEAM AT SLAC*

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Abstract

Attenuation by coherent pair production in highly oriented compression annealed pyrolytic graphite has been used to polarize a 16 GeV bremsstrahlung beam. Graphite pieces of total volume $0.95 \times 0.95 \times 5.1\ cm^3$ were assembled in water-cooled precision holders. Eighteen of these units were mounted in two independent coaxial assemblies. Each assembly provided precision angular orientation with respect to the beam direction, rotation of the graphite by 90^o about the beam axis to rotate the plane of polarization, and removal from or insertion into the beam. One assembly, with 61 cm of graphite, served as a polarizer; the other, with 30.5 cm of graphite, was used as an analyzer. The complete device was placed between collimators in a sweeping magnet. Polarization of the attenuated beam, measured with the SLAC pair spectrometer, was 0.255 ± 0.020. This number, and the measured spectrum, are in qualitative accord with the calculations. The beam has yielded intensities greater than 4×10^8 equivalent quanta per pulse, and has been used in an experiment to measure asymmetries in pseudoscalar meson photoproduction.

Linearly polarized photons have proven extremely useful in the detailed study of photoproduction mechanisms. Previous techniques for production of polarized photon beams have been hampered either by very low intensities or by large backgrounds from higher energy unpolarized photons. In this paper, we describe the practical realization of a polarized photon beam of high intensity which is highly polarized at the highest energies in the spectrum. This beam has been used in a study of a variety of very small cross section photoproduction processes. As the effect responsible for the beam polarization improves with increasing energy, we anticipate this technique should see application at higher energy accelerators.

The polarized beam is made by selective absorption, through coherent pair production, of one linear polarization state from an initially unpolarized bremsstrahlung beam. This method for making polarized photon beams was originally proposed by Cabbibo et al.,[1] and was experimentally demonstrated by Berger et al.[2] at the Cornell 10-GeV synchrotron. As coherent pair production is well described in the literature,[1,3] we give only a brief description here.

For pair production to be kinematically possible, the momentum transfer, $q_{\parallel}$, along the direction of motion of the photon, must be greater than a minimum value δ, where

$$\delta = \frac{m^2}{2k} \frac{1}{y(1-y)} \quad .$$

Here k is the photon energy, m is the electron mass, and y is the fraction of the photon energy carried by one member of the pair. The pair production cross section decreases rapidly for values of $q_{\parallel}$ greater than δ, which is typically a few tens of eV/c. The scale of the allowed momentum transfer transverse to the photon direction is considerably greater than that for $q_{\parallel}$, on the order of mc. These considerations lead to the description of the region of allowed momentum transfers for pair production as a "pancake" perpendicular to the direction of motion of the photon.

In the case of pair production in an amorphous material, this momentum transfer is provided by the recoil of an individual nucleus. With a crystalline material, however, pair production is significantly enhanced for those combinations of photon energy and pair energy division which have a momentum transfer pancake which includes a reciprocal lattice vector of the crystal. Furthermore, pair production is more likely for photons polarized perpendicular to the momentum transfer than for those polarized parallel to the momentum transfer. Consequently, production of a polarized photon beam by this technique involves selection of an appropriate thickness of a suitable crystalline material, and orientation of this material with respect to the incident photon direction to optimize the polarization of the beam at the bremsstrahlung tip.

Practical considerations such as atomic form factors and Debye temperatures limit the choice of materials to beryllium and carbon, the latter in the form of highly oriented, compression annealed, pyrolytic graphite.[4] At the time of the decision to construct the beam described here, only graphite was available in sufficient quantity, and in adequate crystalline perfection, to consider. All further discussion, therefore, refers to a graphite polarizer. It is worth noting that because there is no ordering in the a-axis dimensions of graphite, it behaves as a crystal only in the c-axis dimension. This makes all the reciprocal lattice vectors parallel, and consequently, the crystal orientation can be described by a single angle, θ.

Figure 1 shows the necessary crystal motions for the polarizer. Changing the angle θ changes the energy at which the polarizing power is maximum, and rotation of the crystal about the beam axis by 90^o rotates the polarization plane. As more photons polarized perpendicular to the reciprocal lattice vector are absorbed, the transmitted beam is polarized in the plane containing the reciprocal lattice vector and the beam direction.

Figure 2 shows the pair production cross sections for photons polarized parallel and perpendicular to the c-axis in graphite as a function of the energy partition y, for a particular θ and photon energy k. The sharp discontinuities occur when a particular reciprocal lattice vector no longer fulfills the necessary kinematic condition on the longitudinal momentum transfer. These cross sections are integrated over the pair energy partition to give cross sections as a function of k and θ only. This result is then folded with a Gaussian distribution in θ to account for mosaic spread and other imperfections in the crystal.

The results of these calculations for both 15 and 16 GeV incident photons are shown in Fig. 3 as a function of θ. The attenuation function, $A(k, \theta)$, is the other parameter besides the beam polarization $P(k, \theta)$, necessary to describe the beam. It represents the degree by which the incident bremsstrahlung beam is degraded in the crystal, i.e., the photon

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spectrum after passing through the crystal is given by: $n(k)dk = A(k, \theta)B(k, k_{max})dk/k$, where $n(k)$ is the number of transmitted photons of energy k per equivalent quantum of the transmitted beam, k_{max} is the energy of the bremsstrahlung tip, and $B(k, k_{max})dk/k$ gives the spectrum of the incident bremsstrahlung beam. The functions $P(k, \theta)$ and $A(k, \theta)$ vary slowly as a function of energy, as indicated in Fig. 3.

The polarizing device had to be designed to meet a number of requirements. These we outline below.

1. Crystal length. As the crystal length is increased, the beam polarization increases at the expense of beam intensity. Normally, one would optimize the product of beam intensity with the square of the beam polarization to find a suitable crystal length. This process gives an optimum length of 40 cm at 16 GeV, with a corresponding polarization of 15%. However, potential systematic errors in the actual execution of an experiment favor a higher polarization. We chose a crystal length of 61 cm (3.18 radiation lengths) with a corresponding polarization of 26%.

2. Analyzing crystal. As there are too many uncertainties in the computer calculations of the beam properties, these must be measured. To measure the beam polarization, we chose to construct a second crystal assembly to act as an analyzer.

3. Segmentation of crystal. The cost of the graphite crystals is both very high and proportional to total crystal volume. Since the crystals must be mounted at an angle to the incident photon beam, it is thus desirable to make a number of short crystal assemblies, each held at the same angle to the beam. We constructed 18 crystal units, each 5.08 cm long. Twelve of these were used in the polarizer and six made the analyzer.

4. Angular range. To vary the energy at which the maximum polarization occurs, it is necessary to vary the crystal angle with respect to the photon beam. The range of this adjustment must cover about 0 to 25 mrad, with all crystals held to the same angle to within a few tenths of a mrad.

5. Polarization rotation. To rotate the plane of polarization to permit asymmetry measurements to be made, both the polarizer and analyzer had to be rotatable through 90°. The axis of rotation had to be coincident with the beam axis to within ± 0.3 mrad to insure that the polarization and spectrum were the same for each of the two angular orientations.

6. Sweeping magnet. A large fraction of the energy in the incident bremsstrahlung beam is deposited in the absorber by the electron-positron pairs. To remove as much of this energy deposition as possible from the graphite and to prevent the spectrum from being dominated by secondary and higher order radiative processes from these pairs, a sweeping magnet was placed around the crystal assemblies. A C-magnet with a 10-kG field was available for this purpose. The 15-cm gap and 91.5-cm length of this magnet placed severe dimensional restrictions on the polarizer and analyzer assembly, which had to fit within the poles.

7. Water cooling. Even with the sweeping field, between 300 and 400 watts were deposited in the graphite by the pairs. Each individual crystal assembly was water-cooled to prevent unreasonable temperature increases, with concomitant polarization changes.

8. Collimation. Water-cooled collimators were placed both before and after the polarizer and analyzer unit. These served to insure that the incident bremsstrahlung beam passed through only graphite, and that the photons leaving the device came only from a volume defined by the first collimator. Furthermore, the first collimator was constructed in two sections, with an ion chamber placed between them. This chamber, operated in air, had a hole along the beam line. A minimum signal from this chamber was an indication of a properly steered incident beam.

9. Removal from and insertion into the beam. Both the polarizer and analyzer assemblies had to be separately removable from the beam, and reproducibly reinserted into the beam, with a tolerance of a few mils.

10. Radiation resistance. The polarizer was intended for use in high-power (several kilowatts average) bremsstrahlung beams. Consequently all the electrical and mechanical pieces had to be capable of operation in a high radiation environment, and any portions which were in the beam or had beam swept onto them by the magnet had to be cooled.

11. Interlock and control system. All motions of the crystal assembly were remotely controllable, and an extensive system of interlocks was provided to prevent catastrophic damage by the beam to the crystals or the surrounding mechanical assembly. The 90° rotation of the polarizer or analyzer, which was the most frequently exercised function, could be controlled by an on-line computer, which was also capable of monitoring the complete status of the polarizer assembly.

Figure 4 shows a drawing of the completed device. While the device is clearly too complex to be readily understood from such a drawing, many of the general features can be seen. This device will be described in considerably more detail in a separate publication.[5]

The properties of the beam were determined by a series of measurements using both the 20-GeV/c spectrometer[6] and a large pair spectrometer at SLAC.[7] We will give here only a general description of the measurements made. A more detailed discussion, along with the interpretation of the results, will be given in the separate publication noted above.

First, with 16-GeV bremsstrahlung incident on the polarizer, the angle θ which gave maximum polarization at the bremsstrahlung tip was determined by measuring the asymmetry in the reaction $\gamma p \rightarrow \pi^+ n$ at $t = -0.15\ (\text{GeV}/c)^2$ as θ was varied about the calculated optimum value. The 20-GeV/c spectrometer was used to detect the photoproduced pions. While the analyzing power of single pion photoproduction is large,[8] the reaction was used as a relative monitor of beam polarization only, so the exact asymmetry did not need to be known. The computed value of θ, 10.5 mrad, was found to be a good operating point. When the value of θ had been settled on, measurements were made with a 15-GeV incident bremsstrahlung beam to check that the polarization did not have a rapid energy dependence. Similar measurements were made on the analyzer.

With the value of θ determined, the attenuation function and absolute value of the beam polarization were determined using the pair spectrometer. The attenuation function was obtained from measurements of both the incident and transmitted spectra for both the polarizer and analyzer. The measured spectra are shown in Fig. 5. A gas-filled quantameter was used as a monitor for the spectrum measurements.

For the beam polarization determination, the pair spectrometer was used to measure the transmitted intensity of the polarizer-analyzer combination with the c-axes either crossed or aligned. Since one wishes to know the transmission of the polarizer-analyzer pair per incident photon for these measurements, and since the transmitted spectrum depends upon whether the two crystals are crossed or aligned, the quantameter is not a suitable monitor. To provide a monitor, a second radiator was installed in the pair spectrometer magnet at such a location as to make the detection system sensitive to 4-GeV photons, as well as the 16-GeV photons of the bremsstrahlung tip. The detection system of the pair spectrometer was easily able to resolve photons which converted on the two different radiators. Since the graphite assembly had a negligible polarizing power at 4 GeV for the angle θ used, the number of 4-GeV photons made a good monitor for the 16-GeV polarization measurements. To be certain that the polarizer did not produce a polarized beam at 4 GeV, a measurement was made of pion photoproduction with 4-GeV bremsstrahlung incident on the polarizer, with the expected result.

The crossed to aligned asymmetry measured with the pair spectrometer is the product of the polarizing powers of the polarizer and analyzer. The ratio of the polarizing power of the polarizer to the analyzer obtained from the 20-GeV/c spectrometer measurements was 1.80 ± 0.08, in slight disagreement with the expected value of 1.97.

To check for systematic errors, asymmetries were formed between the polarizer spectra (normalized per equivalent quantum of the transmitted beam) with the beam polarization in the horizontal and vertical planes. Asymmetries were also formed between the two crossed and between the two aligned configurations of the polarizer-analyzer combination, normalized per transmitted 4-GeV photon. No evidence was found for false asymmetries within the statistical errors of about $\frac{1}{2}$%.

The results of the attenuation function and the crossed to aligned asymmetry measurements are presented in Fig. 6a and 6b, respectively. The solid curves are fits to the data with an arbitrary normalization allowed, while the dashed curves are calculated, with no free parameters allowed. As the calculated beam properties did not include secondary processes in the graphite absorber, the disagreements are not unexpected. The value of the crossed to aligned asymmetry obtained corresponds to an average beam polarization from the polarizer alone of 0.255 ± 0.020 over the energy interval from 15 to 16 GeV.

This beam has been used for a $2\frac{1}{2}$-month period for a series of photoproduction asymmetry measurements which would not have been possible with any other previously produced polarized photon beam.[9] During the entire data-taking period, the polarizer was used with a bremsstrahlung beam of 3 to 5 kW average power. This gave a polarized beam intensity greater than 4×10^8 equivalent quanta per pulse. Repeated measurement of single pion photoproduction at $t = -0.15\ (\mathrm{GeV}/c)^2$ showed the beam polarization to remain unchanged to within ± 0.008 over this period, indicating that the polarizing power was unaffected by the high radiation levels. We believe we have demonstrated the usefulness of an excellent method of polarizing high-energy bremsstrahlung beams, and that this technique should see further application at higher energies.

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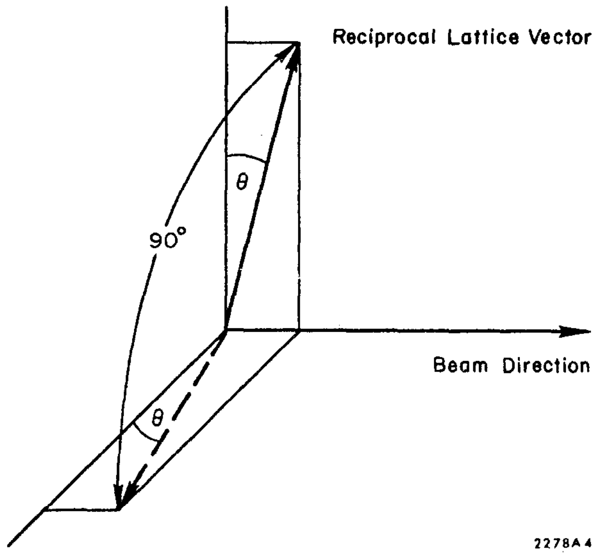

FIG. 1--Necessary crystal motions for the photon polarizer.

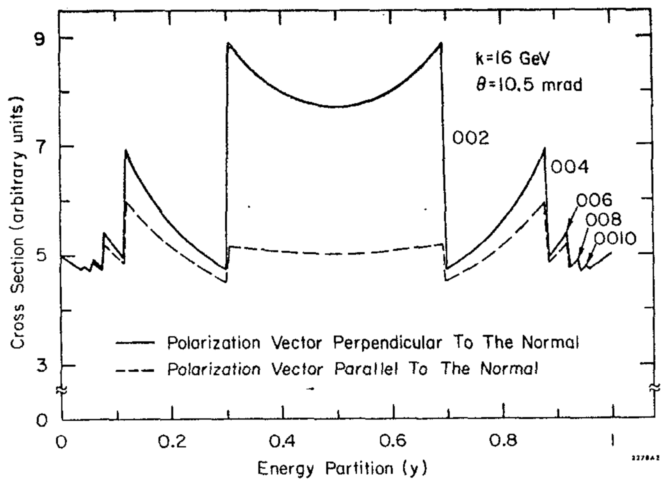

FIG. 2--Pair production cross sections for photons polarized parallel or perpendicular to the c-axis in graphite.

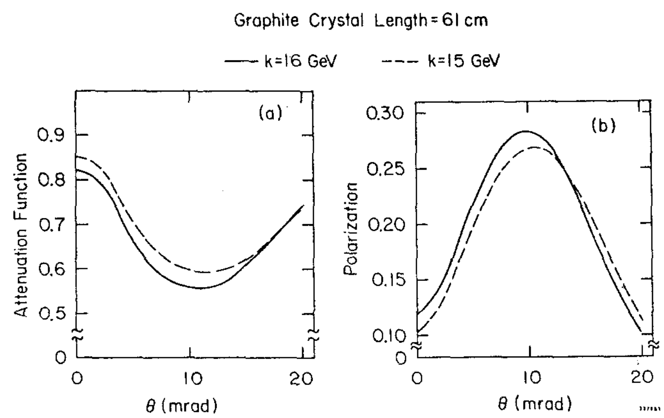

FIG. 3--Calculated attenuation function and beam polarization for the graphite polarizer.

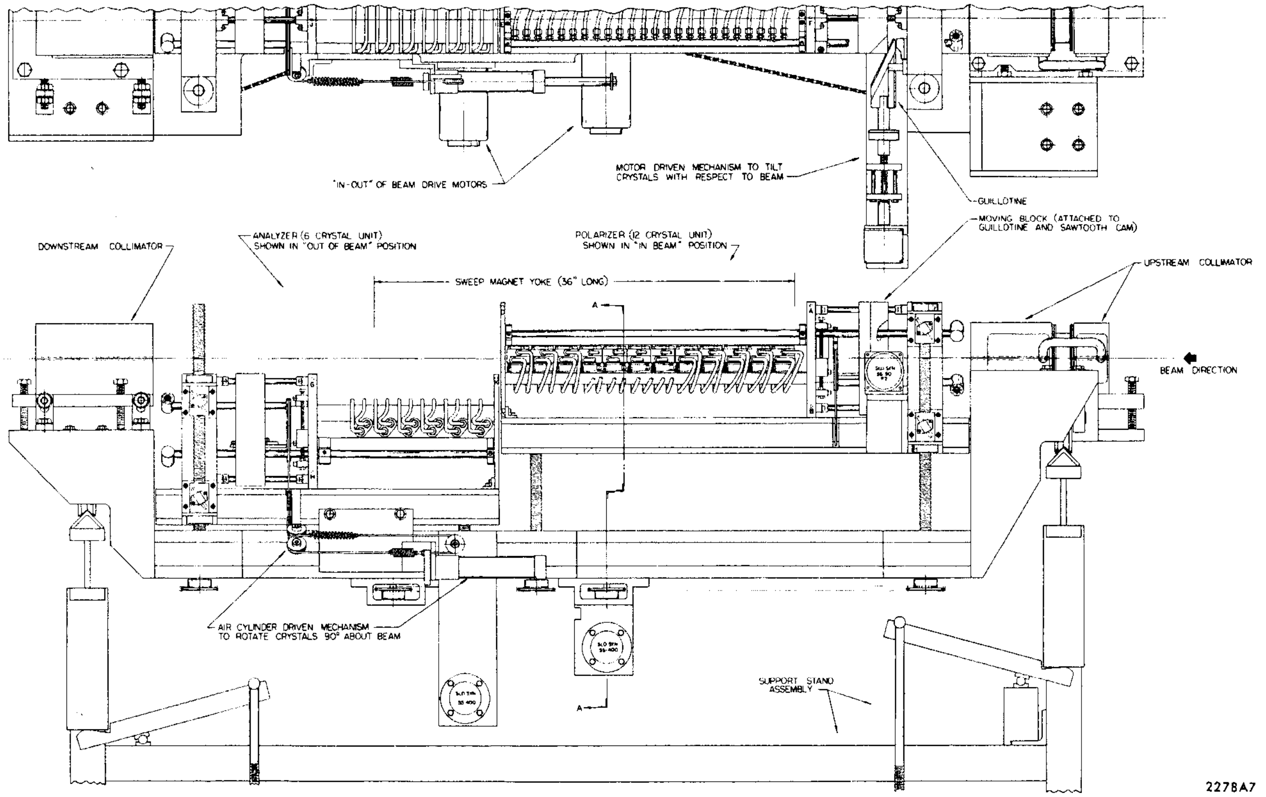

FIG. 4--Drawing of the complete polarizer-analyzer assembly.

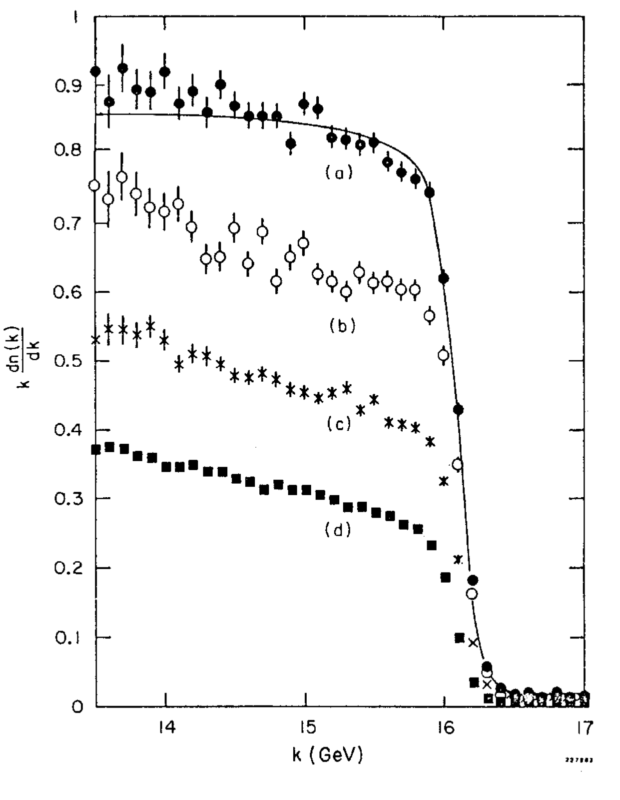

FIG. 5--Measured beam spectra for (a) the incident bremsstrahlung beam, and the incident beam attenuated by (b) the analyzer, (c) the polarizer, and (d) both the analyzer and polarizer.

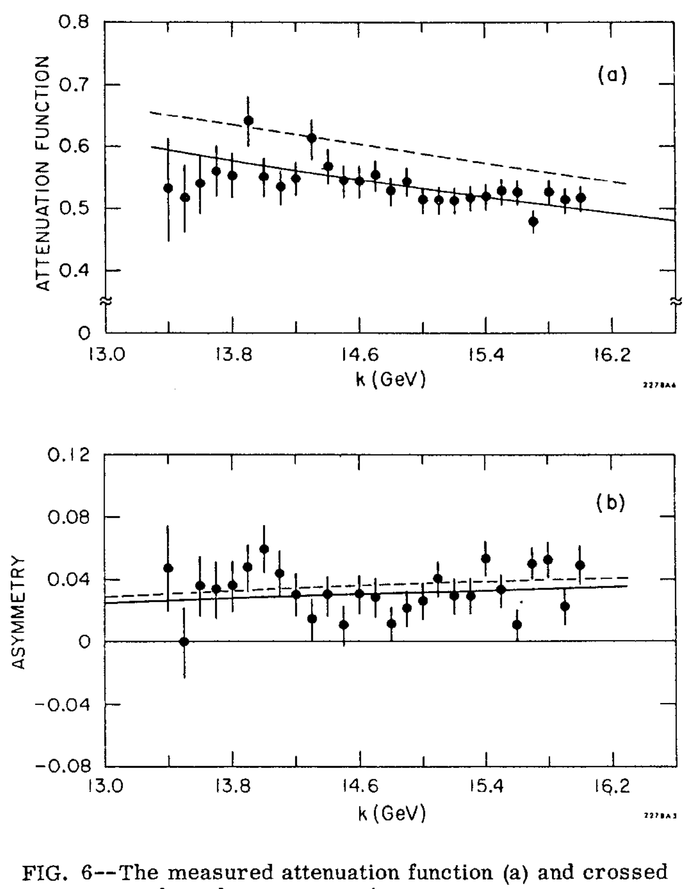

FIG. 6--The measured attenuation function (a) and crossed to aligned asymmetry (b).