CERN-EP/82-186
19 November 1982

A POLARIZED HIGH-ENERGY TAGGED PHOTON BEAM

P.J. Bussey, C.N. Paterson and C. Raine

University of Glasgow, UK

R.E. Hughes-Jones, G.D. Lafferty, J.B. Lane and D. Mercer

University of Manchester, UK

ABSTRACT

An 80 GeV electron beam has been used to generate plane polarized photons by means of coherent bremsstrahlung in a silicon crystal. The photons are tagged in the energy range 25-70 GeV, and have been used in a photoproduction experiment at the Omega Spectrometer at CERN.

(Submitted to Nuclear Instruments and Methods)

1. INTRODUCTION

Since 1976, the Omega Photon Group at CERN has operated a photon beam in which the individual photons are tagged in an energy range of approximately 25–70 GeV. It is advantageous to know the photon energy in photoproduction physics for two main reasons. Firstly, one may wish to investigate in a general way the behaviour of photoproduction processes as a function of beam energy; for this purpose a fairly crude energy determination (e.g. to within a few per cent) would normally be adequate. Such a precision is given by a number of high-energy photon tagging systems which have been constructed at various laboratories. The Omega Photon beam, however, has the distinctive feature that the photon energies are determined to a much greater precision of 100–200 MeV. This further degree of accuracy allows detailed kinematic constraints to be applied in selecting events containing specific final states, and greatly enhances the capabilities of the system. A detailed description of the Omega photon beam and tagging system has been published¹⁾.

The photons used in the first measurements using this system (experiment WA4) were unpolarized. It is often desirable to have polarization, because this can provide information concerning reaction mechanisms in the processes under investigation. In exchange processes, for example, the form of the azimuthal asymmetry exhibited in the final state can allow the naturality of the exchanged particle to be determined. In the case of vector meson photoproduction, the hypothesis of s-channel helicity conservation can be tested. Thus, for a second experiment performed at the end of 1979 (WA57), the group wished to incorporate a substantial degree of polarization into the tagged photon beam, but without degrading its other characteristics. The purpose of this paper is to describe the method which was employed to achieve this. A brief preliminary account has been published elsewhere²⁾.

2. PRINCIPLES OF THE POLARIZED BEAM

2.1 Coherent bremsstrahlung

In normal circumstances the photons radiated in a bremsstrahlung process form an incoherent mixture of polarization states; each photon

individually has a polarization, but the mean polarization averaged over all the photons is zero. By using a crystal instead of amorphous material as a radiator, however, it is possible to enhance a subset of bremsstrahlung processes (those in which the recoil momentum equals a reciprocal lattice vector of the crystal) and obtain sizeable overall degrees of plane polarization. This phenomenon is known as coherent bremsstrahlung (CB); full theoretical details of the process have been given by Diambrini-Palazzi³⁾ and Timm⁴⁾. Many groups have previously employed CB to generate polarized photon beams at energies of up to a few GeV⁵⁾.

A coherent bremsstrahlung spectrum does not have the smooth shape of a normal bremsstrahlung spectrum, but is characterized by a sharp spike in intensity with a discontinuity at its upper edge. Within this spike, the photons are polarized. The spike sits on a background of unpolarized photons whose spectrum resembles a normal bremsstrahlung spectrum. A typical CB spectrum is illustrated in Fig. 1. The background originates from zero-point and thermal motion of the atoms in the crystal, which destroy its perfect regularity; it is of slightly lower intensity (e.g. by 10-20%) than would be obtained from the same thickness of amorphous material. Thus the effect of the CB process is to generate an additional contribution to the photon spectrum which may be considerably more intense than the normal bremsstrahlung. The intensity of the coherent contribution at a given value of x ($= E_\gamma/E_e$) is proportional to the incident electron energy E_e . The polarization is highest at the discontinuity value x_d of x . As x_d varies from 0 to 1, the maximum polarization falls from a value that may be close to unity, down to zero.

Coherently produced spectra are obtainable only when the electron is incident at a small angle with respect to a set of crystal planes, a consequence of the need to impart to the crystal a momentum equal to a reciprocal lattice vector. This small angle is called the "sensitive angle" θ_s , and is given by the relationship

$$\theta_s = \frac{A}{E_e} \cdot \frac{x_d}{1 - x_d}.$$

A is a constant taking the value 20.2 MeV for the silicon 022 reciprocal lattice vector. If the crystal is oriented with its 100 axis along the beam line, it is this and the corresponding $0\bar{2}2$ reciprocal lattice vector (and, equivalently, their negatives) which give the most intense CB spectra. These two reciprocal lattice vectors are also mutually perpendicular; thus since the photon polarization (electric vector) is parallel to the reciprocal lattice vector, a simple reorientation of the crystal can be used to invert the direction of the polarization.

The sensitive angle is the angle at which the electron beam is pointing out of the chosen set of crystal planes. The direction of the electron beam within the planes does not affect the CB spectrum, and this is called the "insensitive" angle. It should be noted that the effects of different reciprocal lattice vectors add up independently of each other. Thus if the electron direction in space should be such that the sensitive angle is suitably small for several reciprocal lattice vectors simultaneously, then the respective CB spectra will all be present and the observed spectrum will be their sum.

2.2 Arrangement of the beam

Figure 2 shows the arrangement of the beam line and tagging system, which were located in the West Hall at CERN. The energy of each electron is measured before and after it radiates, by means of multiwire proportional counter arrays in the beam line and the tagging system. The difference between the initial and final energies of the electron is the energy E_γ of the radiated photon. The intensity of the electron beam was up to $10^7/s$, with a beam diameter of approximately 40 mm at the radiator. The radiated photons converge on to the liquid hydrogen target in the Omega spectrometer.

The 10 mrad bending magnet B2, immediately upstream of the radiator, served to control the direction of the photon beam as it entered the Omega spectrometer, but also had the important function of removing from the beam line all the photons radiated in the material (MWPCs, etc.) in region B. Such photons were detected in the so-called "radiation veto counters" adjacent to the beam line, a signal from which vetoed the event. Since

these photons were unpolarized, and the material amounted to some 0.5% of a radiation length, their presence in the photon beam would have significantly reduced the mean polarization.

The experiment used as a radiator a silicon monocrystal of diameter 75 mm and thickness 2.2 mm. Diamond is in principle a better material to use, since it gives more photons with higher polarization up to higher photon energies. Our choice of silicon was determined purely by the availability of large defect-free samples of this material. The choice of thickness was a compromise between two conflicting requirements, namely the need for a high photon intensity while at the same time keeping the number of electrons undergoing double bremsstrahlung to a minimum. Radiation damage in the crystal was not a problem with these values of beam intensity and beam diameter.

The nominal electron energy was 80 GeV and the r.m.s. beam divergence at the crystal was ± 0.3 mrad. It is calculated that useful polarizations (e.g. $> 20\%$) are obtainable only from θ_s values within the range ± 0.75 mrad at this electron energy, corresponding to E_γ values of up to 60 GeV. In principle, the photon polarization can be evaluated simply from a knowledge of E_e , x and θ_s . Unfortunately, however, in the present case the beam divergence smears the CB spectra over a significant range in θ_s . This would seriously degrade the mean polarization values obtained if the value of θ_s taken were simply that corresponding to the centre of the beam, with a correction made for the smearing.

The solution to this difficulty was to make use of the capability of the tagging system to measure accurately the direction of each incoming electron. The MWPCs in region B give such a measurement to a precision of approximately ± 0.06 mrad horizontally and vertically, and a somewhat better precision can be obtained by evaluating the direction vector in space between the point of radiation and the event vertex in the Omega hydrogen target. Figure 3 illustrates the variation of intensity and polarization of the CB spectrum at fixed E for varying θ_s if different values of the measurement uncertainty $\delta\theta$ are folded in. Both the intensity (I) and polarization (P) diminish as E_γ and θ_s increase, and the observed spectrum depends appreciably on $\delta\theta$. Without the MWPCs in region B, a $\delta\theta$ value of around 0.3 mrad would be required.

It should be noted that in practice, a calculation of a physical polarization asymmetry will include all events, weighted as a function of the measured polarization. This averages the polarization over the whole θ_s range, and removes some of the sensitivity of the physics to the precise value of $\delta\theta$. Nevertheless, it is evident that a reasonably good understanding of the size of $\delta\theta$ is needed, and that it is probably more important to know $\delta\theta$ reliably than to minimize it.

The measurement errors on the region B MWPCs were therefore the subject of a careful investigation. Charged pions were obtained in the beam line and their direction as measured in region B was compared with the corresponding direction as measured by linking the position measured in region B with the position in a set of accurate drift chambers just downstream of the Omega spectrometer, with the Omega field turned off. It was found that the actual angular errors agreed to within approximately 10% with those calculated using the nominal errors on the MWPC measurements. The mosaicity of the crystal also contributes to $\delta\theta$, but for a good quality silicon monocrystal the mosaicity is negligible at these beam energies.

Thus with knowledge of E_e , E_γ , θ_s and $\delta\theta$ the polarization of each photon can be calculated. More details will be given below. Only a minority of photons have useful polarization, but these can be selected offline as required.

3. OPERATION OF THE BEAM

The vertical direction of the magnetic field in the Omega spectrometer had two consequences for the present experiment. The first is that the acceptance for detecting hadronic final states will tend, in general terms, to have an asymmetry between those events with horizontal track configurations and those with vertical track configurations. More important, however, is the fact that large numbers of electron-positron pairs, arising from photon conversion in the hydrogen target, are found in a narrow region of space in the horizontal median plane of the spectrometer. It is essential to avoid triggering on these as much as possible, and to prevent any remaining events of this type from contaminating the final event sample. Thus the online and offline event selection procedures were arranged to

eliminate events whose particles emerged in the horizontal median plane; this gives rise, however, to a horizontal-vertical asymmetry which can be very marked for certain types of event. The photon polarization was therefore set to be along directions at $\pm 45^\circ$ to the vertical, so as to minimize any uncorrectable systematic effects which might arise from the above asymmetry of the system. Errors in the understanding of acceptance should then have their maximum effect for event configurations in which the analysing power of the polarization is smallest.

3.1 Orientation of the crystal

At the rear of the tagging system were two scintillator hodoscopes whose principal function was to provide a fast trigger signalling the arrival of a tagging electron. The output of a chosen set of these counters was also fed into 19 scalers whose contents were recorded on tape after each beam burst and provided an immediate record of the experimental photon spectrum. These scalers were also used in orienting the crystal relative to the electron beam, by making use of the fact that electrons that pass parallel to a plane of atoms in a crystal have a particularly strongly enhanced probability of radiating photons of lower energies.

In order to orient the crystal accurately, it was first necessary to select electronically a subset of electrons in the beam whose angular spread was as small as possible and substantially less than that of the beam as whole. The crystal was then oriented relative to these electrons.

The electron selection was performed as follows. Signals were taken from the read-out from the central eight wires in the first and last MWPC planes of a chosen orientation in region B. The orientations used were the so-called "u" and "v" directions at $\pm 45^\circ$ to the horizontal (y) direction of the tagging system. Coincidences were formed between corresponding pairs of wires in the two chosen planes, and the logical OR of the eight coincidences was taken. The final signal thus indicated an electron travelling parallel to the chosen plane, to a precision given by the wire spacing in the MWPCs and the distance between the latter, nominally ± 0.07 mrad. When desired, it was possible to apply simultaneously the two conditions that the electron be travelling parallel to the $u = 0$ plane and also to the

$v = 0$ plane. This greatly reduced the useful beam intensity but enabled angular scans to be carried out with high angular resolution over both directions at once.

In practice, random coincidences in the MWPCs degraded the angular resolution somewhat. A further difficulty came from the fact that the momentum spread of the electron beam introduced some angular divergence as the beam passed through magnet B2. These effects were reduced by including in the coincidence a signal from the central portion of the counter hodoscope situated at the momentum focus of the beam in the centre of region A.

The crystal was mounted in vacuum on a goniometer fitted with precision micrometers (manufactured by Lansing Corp.) and remotely controlled by stepping motors through a backlash-free gear system. Tests had indicated that hysteresis and instability in this system were at a level much lower than the errors in the measured angles in the experiment. The micrometers rotated the crystal about horizontal and vertical axes (called "tilt" and "turn", respectively) and one digitization of the stepping motor control equalled 10 μ rad of rotation.

The first stage of the orientation of the crystal was the construction of a "spoke diagram" ⁶⁾. This consists of a map in angular space of those crystal orientations (specified by the values of tilt and turn in mrad) which correspond to the electrons passing parallel to a set of atomic planes in the crystal. One set of planes gives rise to a line (or "spoke") on this diagram; the various spokes converge on to one point representing the crystal orientation at which the electrons pass along a major axis of the crystal. The spokes were identified by selecting electrons travelling parallel to the beam line, and seeking those crystal orientations which gave the maximum number of counts in the hodoscope element closest to the beam. This corresponded to a photon energy of about 20 GeV; much bigger enhancements could have been obtained if the tagging range had extended to lower photon energies than this, but the spokes were easily visible nevertheless. The most prominent spokes corresponded to the dominant 022 and $0\bar{2}2$ reciprocal lattice vectors. A preliminary orientation of the

crystal had been performed on the basis of X-ray photographs; the crystal was now rotated manually in azimuth to put these spokes at $\pm 45^\circ$ to the vertical.

3.2 Data taking

For data taking, the crystal was oriented to put the 022 or $\bar{0}\bar{2}2$ plane at a suitable distance away from the selected electron direction. This angular distance equalled the mean sensitive angle; typically, values of around 0.5 mrad were used with the 80 GeV electron beam. The effect of making θ_s smaller is to move the centre of the beam closer to the crystal plane and enhance the production of lower energy but highly polarized photons. A compromise is needed, therefore, between the desire for a high mean polarization and that for enhanced production of higher energy photons.

The spectrum recorded by the tagging hodoscope was continuously monitored during the data taking. A typical hodoscope spectrum is shown in Fig. 4, with the channel contents normalized to the spectrum obtained using an unpolarized beam (obtained by orienting the crystal far from a spoke). These spectra were found in practice to be considerably smeared, with a high background beneath the broadened peak. As indicated above, this was attributed to random coincidences between signals in different MWPC wires in the electron selection (the pulse width from the MWPCs was about 30 nsec, and the overall electron rate was as high as 10^7 per sec.). Nevertheless, the maximum of the peak was sufficiently visible to enable the crystal orientation to be monitored, and the position of the peak in E_γ was found to vary with crystal orientation in a manner consistent with expectations.

It was found that the crystal orientation was extremely stable, and was reproducible to within about 0.1 mrad over periods of several weeks. Adjustments to the crystal orientation were rarely needed and were made manually as required. Changeovers from one direction of photon polarization were made every few days of running. At the beginning of each set of data taking with a changed polarization direction, a scan was taken through the spoke to verify that its orientation had not changed, and

then the crystal was set up at the desired mean θ_s value relative to this spoke.

4. ANALYSIS OF RESULTS

4.1 Calculation of polarizations

We have already seen that in order to evaluate the polarization of a given photon it is necessary to know the four quantities E_γ , E_e , θ_s and $\delta\theta$. The first two of these are given from the tagging system as described in Ref. 1, and we have discussed how $\delta\theta$ is obtained from a study of the measurement errors in the system. It remains to evaluate θ_s . θ_s is the angular difference ($\theta_e - \theta_o$) between the electron direction θ_e and the direction θ_o of the crystal planes, both projected on to the appropriate u or v direction in space. Of these, θ_e is determined from the MWPC data in region B, using the known electron energy to calculate the precise angle of bend in B2.

We require to determine the crystal orientation θ_o in the same set of spatial coordinates that are used in measuring θ_e . Although the spoke diagram gives some information, a more precise determination is necessary. Two approaches were tried. The first method involved the histogramming of θ_e to reconstruct distributions similar to the theoretical curves illustrated in Fig. 3. Figure 5 shows the result obtained for one band of photon energies. There is a double peaked structure, the two peaks representing the coherent enhancements at positive and negative θ_o . Such plots confirmed that the experimental spectra resembled those predicted from theory.

Two difficulties were encountered in using these plots to evaluate θ_o . The first was that the angular spectrum of the photons must be normalized to the angular distribution of the incoming electron beam, and in practice there were some uncertainties concerning this latter distribution since the high electron rates made it difficult to monitor precisely. Secondly, fairly large data samples are required to obtain a sufficiently accurate representation of the double-peaked structure.

A second and simpler method made use of the counter BV ("Beam Veto") located behind the Omega spectrometer. The primary purpose of BV was to veto hadronic events in which double bremsstrahlung occurs, such that the primary photon which interacts in the hydrogen target is accompanied by a secondary photon whose energy is more than a few GeV. If there was a secondary photon of lower energy, however, the event was not vetoed but the magnitude of the BV signal was recorded along with the event. Double bremsstrahlung is very much more probable when the incoming electron is incident along a crystal plane, in other words when θ_s is small. By plotting the probability of observing a BV count as a function of θ_s , we observe a strong enhancement at $\theta_e = \theta_o$. This is illustrated in Fig. 6. The results from the two methods were in agreement. The second method was used in practice to determine the θ_o values, owing to its greater simplicity.

The polarization of a given photon was now obtained as follows:

- i) The ratio $x = E_\gamma/E_e$ was evaluated. The ratio $r = E_e/E_o$ was also evaluated, where E_o is the mean incident electron energy.
- ii) Theoretical data on coherent bremsstrahlung were held in a two-dimensional array as a function of x and θ_s . The calculation included the folding in of a certain minimal smearing $\delta\theta_o$. The polarization of a given real photon was calculated by interpolating in these tables and smearing (ny Hermite integration) through a further amount in $\delta\theta$ when the actual experimental uncertainty in θ_s was greater than $\delta\theta_o$.
- iii) In performing the above, the polarization and θ_s values were scaled by factors of r and $1/r$, respectively, to take account of effects of varying E_e .

The tabulated data consisted of intensities and polarizations evaluated from the appropriate formulae^{3,4)} with all the contributing reciprocal lattice vectors taken into account (not just the principal one). The aim was for an error of less than 1% in the tabulated polarizations. Account was taken of the crystal thickness and of double bremsstrahlung, and its

vetoing by BV, in the calculations. The errors on the experimental polarization values are at the level of a few percent of P. In practice, the statistical error on the determination of the asymmetry in a physical process will dominate over the error in the mean polarization.

4.2 Confirmation of results

The fact that CB has been used successfully in photoproduction experiments at lower energies gives one confidence that the polarizations obtained by this process in the present experiment will be evaluated correctly. Nevertheless, it is obviously desirable to obtain an experimental confirmation of the calculated values. One possibility would be to use the inverse phenomenon of coherent pair production in a second crystal, since this process is affected by the photon polarization. However, this would have required lengthy series of measurements, since coherent pair production has a considerably smaller cross-section than CB at a given incident energy. The angles of the electrons and positrons in the normal conversion of a polarized photon also give in principle a determination of the polarization, but the measurement precision which would be needed is completely unattainable in practice.

The simplest means of confirming our polarization values was to make use of the properties of photoproduced ρ mesons. It has been established at lower energies that ρ^0 photoproduction proceeds by an s-channel helicity conserving mechanism⁷⁾ which imposes certain constraints on the production density matrix elements. In particular, the photon polarization determines the distribution of the quantity $\psi = \phi - \Phi$ where ϕ is the azimuthal angle of the ρ decay in the helicity frame, and Φ is the angle between the polarization plane of the incoming photons and the production plane. It is reasonable to assume that a similar SCHC mechanism applies at the present energies.

Accordingly, a set of ρ^0 events from the current experiment was analysed in order to determine the effective polarization of the photons. The distribution in ψ is of the form

$$d\sigma/d\psi = \sigma_0(1 + P \cos 2\psi) .$$

Figure 7a shows the distribution of photon polarization, calculated as in Section 4.1, for a typical data-taking run. For various intervals of the calculated polarization, the ρ data were fitted to the above form of cross-section to obtain 'measured' values of P . The results are shown in Fig. 7b, together with the line indicating $P(\text{measured}) = P(\text{calculated})$. It is clear that to within the statistical errors, the agreement is good. We conclude that the method described here produces photons whose polarization is reliably determined and can be used for physical measurements.

4.3 Discussion

In using a polarized photon beam such as that described above, certain difficulties arise in analysing specific final states which would not arise if the beam were monochromatic, or if the acceptance of the spectrometer were simple and did not have, for example, the problems connected with the vetoing of particles in the horizontal median plane. In order to evaluate physical results, it is normal to run event simulations of a Monte Carlo type, and in order to do this one must know the energy spectrum of the beam, its angular distribution and, when relevant, its polarization properties. For a normal bremsstrahlung beam, the polarization is zero and the energy spectrum is independent of the angular distribution. This greatly simplifies the simulations. However, in the present CB beam these quantities are correlated, making a theoretical simulation of the beam extremely difficult. The solution which was adopted makes use of an experimental trigger which selected unbiased electron-positron pairs (only a small random fraction of which were actually recorded on tape). Since all photons have the same probability of converting in the liquid hydrogen, such data comprise an unbiased sample of the polarized photons incident on the target. The data were therefore separated off and used as the basis for Monte Carlo calculations. This approach has the further merit that any inefficiencies present in the tagging system are also taken automatically into account.

In conclusion, we have constructed and operated a tagged polarized photon beam at high energies. The technique is a simple extension of previously existing techniques, and gives rise to no practical difficulties.

The measured polarizations are consistent with the calculated values. There would appear to be no reason why the method could not be used at higher beam energies. The main points requiring attention are the accuracy required in measuring the trajectories of the incident electrons, and the fact that as the electron energy increases so do the coherent cross-sections. This could eventually give difficulties in constructing a radiator which is sufficiently thin to avoid double bremsstrahlung problems, sufficiently wide to cover the beam, and of sufficient mechanical strength to avoid flexing. Bilokon et al.⁸⁾ have recently given a comparison of many crystalline materials, with the aim of using CB not so much for the generation of polarization as for the enhancement of the upper end of the photon spectrum. Contrary to what they imply, however, the polarizations over the rest of the spectrum are useful, as demonstrated in the present experiment, and will improve as the energy increases.

Maisheev et al.⁹⁾ have operated at Serpukhov a photon beam which is in a number of respects similar to the one described here. They have used a 31 GeV electron beam, and report an enhanced production of photons at high x values and low θ_s values. They attribute this observation to channelling radiation. Using an 80 GeV electron beam, we do not see any indications of such an effect.

Other techniques that have been used for generating high-energy polarized photon beams include the use of back-scattered laser beams, and of selective absorption of one polarization direction from a photon beam by means of graphite crystals. Both these methods give rather low intensities. The virtues of the system described here are that it provides good intensities of usefully polarized photons with no loss of precise tagging information, and that full information is made available on each photon individually. This gives the experimenter complete flexibility as to whether or not a crystal radiator should be used in any given experiment using the tagged photon facility.

The work which made possible the use of polarized photons at the Omega Spectrometer involved the whole of the Omega Photon Group. We should like to thank CERN for the facilities which they provided, and

the SERC (UK) and BMFT (BRD) for their generous funding. We acknowledge with gratitude the work of W. Smith (Daresbury Laboratory) and the late J.G. Rutherglen in the design and construction of the goniometer system.

REFERENCES

- 1) D. Aston et al., Nucl. Instrum. Methods 197 (1982) 278.
- 2) P.J. Bussey et al., Proc. High-Energy Physics with Polarized Beams and Polarized Targets, Lausanne 1980 (eds. C. Joseph and J. Soffer), Birkhauser 1981, p. 478.
- 3) G. Diambrini-Palazzi, Rev. Mod. Phys. 40 (1968) 611.
- 4) U. Timm, Fortschr. Phys. 17 (1969) 767.
- 5) See, for example, P.J. Bussey et al., Nucl. Phys. B154 (1979) 205; and other work referred to in this paper.
- 6) D. Luckey and R.F. Schwitters, Nucl. Instrum. Methods 81 (1970) 164.
- 7) D. Ballam et al., Phys. Rev. 7D (1973) 3150.
- 8) H. Bilokon et al., CERN/EP/82-40, submitted to Nucl. Instrum. Methods.
- 9) V. Maisheev et al., Sov. Phys. JETP 50 (1980) 856.
V. Maisheev et al., Sov. Phys. JETP 52 (1980) 831.

Figure captions

- Fig. 1 : Coherent photon intensity (I) and polarization (P) calculated for an incident electron energy of 80 GeV: (a) energy spectrum for sensitive angle 0.4 mrad relative to 022 planes of silicon, (b) angular distribution, as function of sensitive angle, for $E_Y = 40$ GeV; $\delta\theta = 0$. The intensities are equivalent quanta per incident electron for a 2.2 mm crystal.
- Fig. 2 : Simplified plan of the photon tagging system at the Omega Spectrometer.
- Fig. 3 : Spectra calculated with the application of differing amounts of Gaussian smearing to the sensitive angle distribution. Dashed curve: $\delta\theta = 0.025$ mrad; solid curve: $\delta\theta = 0.06$ mrad.
- Fig. 4 : Spectrum observed during data taking in the counter hodoscope at the rear of the tagging system, normalized to the spectrum observed with an unpolarized photon beam.
- Fig. 5 : Angular distribution of photons produced in energy range 30-35 GeV as a function of sensitive angle, normalized to the incoming electron angular distribution. There are systematic uncertainties of up to 10% in the shape of the latter. The zero of the angle scale is arbitrary.
- Fig. 6 : Probability of obtaining a BV signal, as a function of sensitive angle (with same arbitrary zero as in Fig. 5). The peak indicates the value of plotted sensitive angle corresponding to the true zero of the sensitive angle, at which the electrons are passing parallel to the 022 crystal planes.
- Fig. 7 : a) Distribution of photon polarization values (as calculated) for a typical data-taking run. b) Experimentally measured polarizations compared with the calculated values.

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7a

Fig. 7b