Results on the Coherent Interaction of High Energy Electrons and Photons in Oriented Single Crystals

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NA-59 Collaboration

Abstract

The CERN-NA-59 experiment examined a wide range of electromagnetic processes for multi-GeV electrons and photons interacting with oriented single crystals. The various types of crystals and their orientations were used for producing photon beams and for converting and measuring their polarisation.

The radiation emitted by 178 GeV unpolarised electrons incident on a 1.5 cm thick Si crystal oriented in the Coherent Bremsstrahlung (CB) and the String-of-Strings (SOS) modes was used to obtain multi-GeV linearly polarised photon beams.

A new crystal polarimetry technique was established for measuring the linear polarisation of the photon beam. The polarimeter is based on the dependence of the Coherent Pair Production (CPP) cross section in oriented single crystals on the direction of the photon polarisation with respect to the crystal plane. Both a 1 mm thick single crystal of Germanium and a 4 mm thick multi-tile set of synthetic Diamond crystals were used as analyzers of the linear polarisation.

A birefringence phenomenon, the conversion of the linear polarisation of the photon beam into circular polarisation, was observed. This was achieved by letting the linearly polarised photon beam pass through a 10 cm thick Silicon single crystal that acted as a "quarter wave plate" (QWP) as suggested by N. Cabibbo et al.

Key words: Single Crystal, Coherent Bremsstrahlung, Polarised Photons, Polarimetry
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1 Introduction

Interest in polarised particle physics has been increasing in recent years. Significant polarisation effects may appear in the final-state products providing useful tools for particle studies. Photon initiated interactions are attractive probes, however the experimental study of polarisation observables after photonuclear reactions requires intense beams of polarised high energy photons. One compelling motive to generate these intense, highly polarised high energy photon beams comes from the need to investigate the polarised photoproduction mechanisms. For example, the so-called "spin crisis of the nucleon" and its connection to the gluon polarisation has attracted much attention [1,2,3]. For these purposes both linearly and circularly polarised photon

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beam lines with high intensity and energy are required. A well known method to produce circularly polarised photons is from the interaction of longitudinally polarised electrons with crystalline or amorphous media, where the emitted photons are circularly polarised due to conservation of angular momentum [4]. Calculations based on [5,6] show that CB and channeling radiation in crystals by aligned incidence of longitudinally polarised electrons are also circularly polarised. These effects can be used to enhance the number of high energy circularly polarised photons. The real difficulties here are associated with the production of polarised electrons. Currently, the highest energy available for polarised electrons is only 45 GeV [7].

The goals of NA59 collaboration were:

- Production of linearly polarised photon beams by the CB of unpolarised electrons in aligned single crystals oriented in the Point Effect (PE) and Strings-of-Strings (SOS) modes.
- Establishing a new fast polarimetry technique using the aligned crystal method.
- Investigating the birefringent properties of aligned crystals. This involved studying the conversion of linear to circular polarisation by using an aligned single crystal as a quarter-wave plate for photons of energy 100 Gev. The feasibility of producing high energy circularly polarised photon beams starting from an unpolarised electron beam was investigated.

The detailed description of the experimental setup, data analysis and results obtained are given in references [8,9,10]. In this paper we present the main results devoted to the polarisation measurement.

The NA59 experiment was performed in the North Area of the CERN SPS, where unpolarised electron beams with energies above 100 GeV are available. The various data sets were obtained with an electron beam with an energy of 178 GeV and an angular divergence of 48 μrad (σ) and 33 μrad (σ) in the horizontal and vertical planes, respectively.

The experiment was performed in two stages. The linear polarisation of the photon beam was studied in the first stage, see reference [8]. In the second stage [9], the QWP crystal was introduced between the radiator and analyser crystals to investigate the transformation of the linear polarisation of the photon beam into circular polarisation. The linear polarisation measurements are important because the technique of identifying circular polarisation is related to a reduction in linear polarisation and the conservation of polarisation.

We have been working toward testing the conjecture that it is possible to produce circularly polarised photon beams in proton accelerators using the extracted unpolarised high energy secondary electron beams with energies up to 250 GeV (CERN) and 125 GeV (FNAL) [11]. These unpolarised electron beams can produce linearly polarised photons via CB radiation in an aligned single crystal. One can transform the initial linear polarisation of the photons into circular polarisation by using the birefringent properties of aligned crystals. This method was first proposed by Cabibbo and collaborators in the 1960's [12]. The detailed theory of birefringence in aligned crystals is given in [13,14,15].

The theoretical predictions showing the possibility of transforming the linear polarisation of a high energy photon beam into circular polarisation in the 80-110 GeV energy range are presented in [13,15,16]. The calculations of the energy and the orientation dependence of the indices of refraction were performed using the quasi-classical operator method and CPP formulae. In these references, the optimum thickness for a QWP Si crystal was found to be 10 cm. The relevant geometrical parameters involved the photon beam forming an angle of 2.3 mrad with the $\langle 110 \rangle$ axis such that the photon momentum is also directly in the (110) plane of the Si single crystal. In this case the angle between the photon momentum and crystal plane is ψ=0. For this choice of parameters, the fraction of surviving photons is 17-20%.

The production of polarised high energy photon beams enables the development of methods for the determination of the polarisation of the photon beam. Several polarimetry methods for linear and circular polarised photon beams have been developed and used in experiments in the last decades [17]. Historically, pair conversion in single crystals was proposed, and later successfully used as a method to measure linear polarisation for photons in the 1-6 GeV range [18]. It was predicted theoretically and later verified experimentally that the pair production (PP) cross section and the sensitivity to photon polarisation in the single crystals increases with increasing energy. Therefore, at sufficiently high photon energies, a new polarisation technique based on this effect can be constructed. Due to the large analysing power of the crystal this technique become competitive to other techniques such as pair production in amorphous media and photonuclear methods.

The photon polarisation is conveniently expressed using the Stoke's parametrisation with the Landau convention, where the total elliptical polarisation is decomposed into two independent linear components (η_1 and η_3) and a circular component (η_2). The NA-59 collaboration used a new crystal method for measuring the linear polarisation of the photon beam. The polarisation dependence of the PP cross section and the birefringent properties of crystals are key elements of the photon polarisation measurement. The imaginary part of the refraction index is related to the PP cross section. This cross section is sensitive to the relative angle between a crystal plane of a specific symmetry and the plane of linear polarisation of the incident photon. In essence, the two orthogonal directions where these two planes are either parallel or perpendicular to each other yield the greatest difference in the PP cross section. We there-

Table 1
Different types of crystals and their orientations used in the experiment

Crystal Type	Radiation Type	Purpose	Axes, Planes	Orientation	Thickness
Si	CB	Radiator	$\langle 001\rangle$, (110)	θ_0=5mrad, $\psi_{(110)}$=70μrad	1.5cm
Si	CB	Quarter Wave Plate	$\langle 110\rangle$, (110)	θ_0=2.29mrad, $\psi_{(110)}$=0	10cm
Ge	CB	Analyser	$\langle 110\rangle$, (110)	θ_0=3mrad, $\psi_{(110)}$=0	1mm
Diamond	CB	Analyser	$\langle 001\rangle$, (110)	θ_0=6.2mrad, $\psi_{(110)}$=560μrad	4mm
Si	SOS	Radiator	$\langle 001\rangle$, (110)	θ_0=0.3mrad, $\psi_{(110)}$=0	1.5cm
Diamond	SOS	Analyser	$\langle 001\rangle$, (110)	θ_0=6.2mrad, $\psi_{(110)}$=465μrad	4mm

fore studied the pairs created in a second aligned crystal, called the analyser crystal. A method of choosing pairs with particular kinematics to enhance the analysing power was identified. This has been called the "quasi-symmetrical pair selection method (y-cut)" [19] and it has been used for constructing the pair asymmetry (between the parallel and perpendicular configurations) in the PP analysis. As a result of such a cut, although the total number of events decreases, the relative statistical error diminishes. This is because it is inversely correlated with the measured asymmetry. The asymmetry analysis technique is given in reference [8] in detail.

The types and orientations of the single crystals used in the experiment are summarised in Table 1.

2 Experimental Setup

The experimental setup shown in Fig. 1 was used to investigate the linear polarization of CB and birefringence in aligned single crystals [8,9,10]. This setup is ideally suited for detailed studies of the photon radiation and pair production processes in aligned crystals.

The main components of the experimental setup are: three goniometers with crystals mounted inside vacuum chambers, a pair spectrometer, an electron tagging system, a segmented leadglass calorimeter, wire chambers, and plastic scintillators.

In more detail a 1.5 cm thick Si crystal can be rotated in the first goniometer with 2 μrad precision and serves as radiator. The second goniometer needed to control the 10 cm thick Si crystal, that served as a QWP, is located after the He-bag. A multi-tile synthetic diamond and Germanium crystals on the third goniometer can be rotated with 20 μrad precision and are used as the analyzer of the linear polarization of the photon beam.

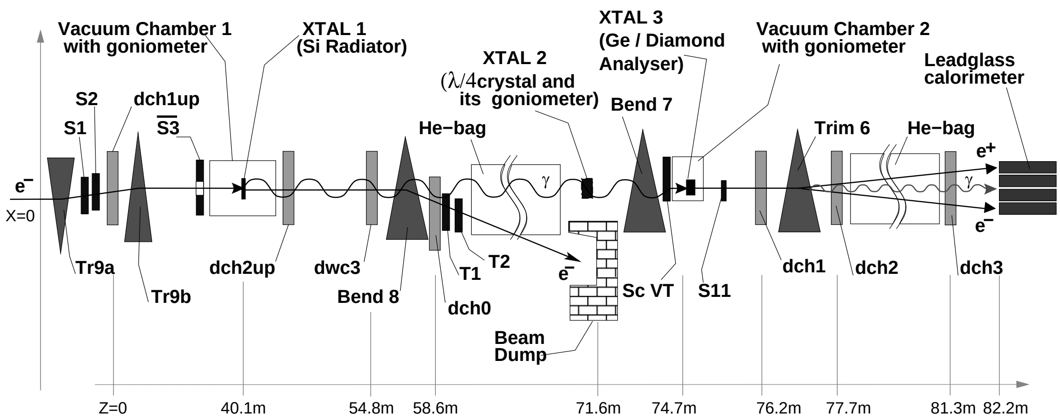

Fig. 1. NA59 experimental setup.

The photon tagging system consists of a dipole magnet B8, chamber dch0, and scintillators T1 and T2. Given the geometrical acceptances and the magnetic field, the system, tags the radiated energy between 10% and 90% of the electron beam energy.

The e^+e^- pair spectrometer consists of dipole magnet Trim 6 and of drift chambers dch1, dch2, and dch3. The drift chambers measure the horizontal and vertical positions of the passing charged particles with 100 μm precision. Together with the magnetic field in the dipole this gives a momentum resolution of $\sigma_p/p^2 = 0.0012$ with p in units of GeV/c. The pair spectrometer enables the measurement of the energy of a high energy photon, E_γ, in a multi-photon environment.

Drift chambers dch1up, dch2up, and delay wire chamber dwc3 define the incident and the exit angle of the electron at the radiator. Signals from the plastic scintillators S1, S2, $\overline{\text{S3}}$, T1, T2, S11 and veto detector ScVT provide several dedicated triggers [8].

The total radiated energy E_{tot} is measured in a 12-segment array of leadglass calorimeter with a thickness of 24.6 radiation lengths and a resolution of $\sigma_E = 0.115\sqrt{E}$ with E in units of GeV. A central element of this leadglass array is used to map and to align the crystals with the electron beam.

A detailed description of the NA59 experimental apparatus can be found in reference [8].

3 Production of Linearly Polarised Photons

CB in oriented single crystals was chosen as a source of the linearly polarised photon beam. The (CB) method is a well established one for obtaining linearly polarised photons starting from unpolarised electrons [20,21]. The relative merits of different single crystals as CB radiators have been investigated in the past [22]. The silicon crystal stands out as a good choice due to its availability, ease of growth, and low mosaic spread.

The NA-59 collaboration chose to use a 1.5 cm thick Si crystal as a radiator to achieve a relatively low photon multiplicity and reasonable photon emission rate. Two types of crystal orientations, those of the PE and the SOS orientations, were examined for producing linearly polarised photons.

In the so-called point effect (PE) orientation of the crystal, the direction of the electron beam has a small angle with respect to a chosen crystallographic plane and a relatively large angle with the crystallographic axes that are in that plane. For the PE orientation of the single crystal essentially one reciprocal lattice vector contributes to the CB cross section [20]. The CB radiation from a crystal aligned in this configuration is more intense than the incoherent bremsstrahlung (ICB) radiation in amorphous media and a high degree of linear polarisation can be achieved. The SOS orientation corresponds to the case where the incident electron momentum lies within a certain crystallographic plane making a relatively small angle with one of the crystal axes in that plane.

In the case of the PE orientation of the radiator crystal, the electron beam makes an angle of 5 mrad to the $\langle 001 \rangle$ crystallographic axis and about 70 μrad from the (110) plane. The resulting photon beam polarisation spectrum was predicted to yield a maximum polarisation of about 55% in the vicinity of 70 GeV and 36% in the vicinity of 100 GeV [8].

In the case of the SOS orientation of the radiator crystal, the electron beam was incident within the (110) plane with an angle of $\theta = 0.3$ mrad to the $\langle 100 \rangle$ axis. This hardens the spectrum and gives the hard photon peak position (relative to the incident beam energy) at $x_{max} = 0.725$. This corresponds to the photon energy $E_\gamma = 125$ GeV. Under this condition the expected linear polarisation of photons in the vicinity of 125 GeV radiation is negligible [10,23,24].

The single photon intensity spectra are presented in figure 2. The left figure represents the MC prediction and the results obtained when the radiator crystal was in the PE orientation [8].

The right figure represents the MC prediction and the experimental results obtained when the radiator crystal was in the SOS orientation [10]. There are

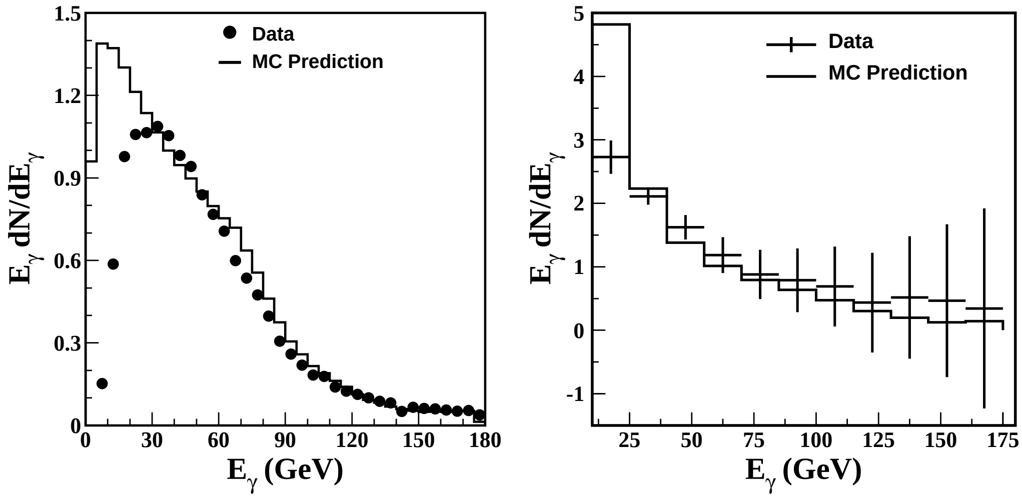

Fig. 2. The photon intensity spectra, $E_\gamma dN/dE_\gamma$, as a function of the energy E_γ of individual photons radiated by an electron beam of 178 GeV in the case of the 1.5 cm Si crystal aligned in the PE (left) and SOS (right) modes.

several consequences for the photon spectrum due to the use of a 1.5 cm thick crystal. The photon multiplicity is above 15 [10] due to the emission of mainly low energy photons from planar channeling (PC) for the chosen orientation of the Si crystal. The most probable radiative energy loss of the 178 GeV electrons is expected to be 80%. The beam energy decreases significantly as the electrons traverse the crystal. The energy of both SOS and PC radiation also decreases in proportion to the decrease in the electron energy. Clearly, many electrons may pass through the crystal without emitting SOS radiation and still lose a large fraction of their energy due to PC and ICB. Hard photons emitted in the first part of the crystal that convert in the later part also do not contribute anymore to the high energy part of the photon spectrum. Consequently, the SOS radiation spectrum does not show a clearly discernable hard photon peak as would be the case for a thin radiator [25]. The measured SOS photon spectrum instead evidences a smoothly decreasing distribution. The low energy region of the photon spectrum is especially saturated, due to the abundant production of low energy photons. Above 25 GeV however, there is satisfactory agreement with the theoretical MC prediction, which includes the effects mentioned above.

It follows from the above discussion that CB in crystals aligned in the PE mode is the more suitable method to increase the intensity of the high energy part of the gamma spectrum (without significant increase of the low energy part) for tagged photon facilities [26].

4 Results on Measured Asymmetry and Linear Polarisation

Two types of analyser crystals (Germanium and multi-tile synthetic diamond), were used in the NA-59 experiment. The selected orientations with respect to the incident photon beam are given in Table 1. These configurations gave an analysing power peaking at 90-100 GeV [8] and around 125 GeV [10] for the PE and the SOS orientations, respectively. The major advantages of using diamond in the analyser role are its high pair yield, high analysing power and radiation hardness. This special multi-tile synthetic large crystal diamond was produced and processed by the South African collaborators [27] and mounted and aligned at the ESRF.

4.1 Linear Polarisation without the Quarter Wave Crystal

The measured asymmetry in the induced polarisation direction (η_3) is presented in figure 3 with and without the y-cut using the Ge(left) and diamond(right) analyser crystals. The solid line represents the MC predictions without any broadening effects considered for the spectrometer. The lower plots represent the increase in the asymmetry due to quasi-symmetrical pair selection together with the statistical error associated with this increase. It thus confirms the non statistical source of the asymmetry increase in the 70-110 GeV range.

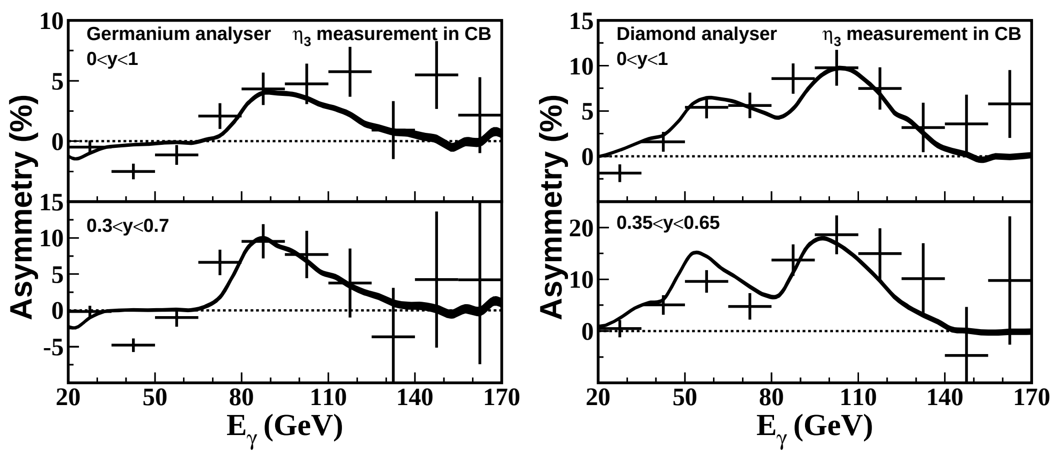

Fig. 3. Asymmetry to determine the η_3 component of the photon polarisation with the Ge (left) and diamond (right) analysers. Measurements without (top) and with (bottom) the quasi-symmetrical pair selection are presented.

Comparing the asymmetry results in figure 3, we conclude that the multi-tile synthetic diamond crystal is a better choice than the Ge crystal as an analyser, since for the same photon polarisation the former yields a larger asymmetry and thus enables a more precise measurement. The diamond analyser also allowed the measurement of the photon polarisation in the 40-70 GeV range, since it has some, albeit small, analysing power at these energies.

It is interesting to note that the measured asymmetry in the induced polarisation direction (η_1) is consistent with zero [8].

From these results it is easy to determine the Stokes parameter η_3 by the formulae (4) from [8] using the known analysing power of the crystals.

The Stokes parameter η_3 determined by the asymmetry in e^-e^+ PP in both Germanium and diamond analysers is presented in figure 4. The solid lines are the MC predictions and the crosses are the experimental data. The data for the η_3 parameter are introduced only in the high energy region due to the geometrical acceptance and smallness of analysing power in the low energy region.

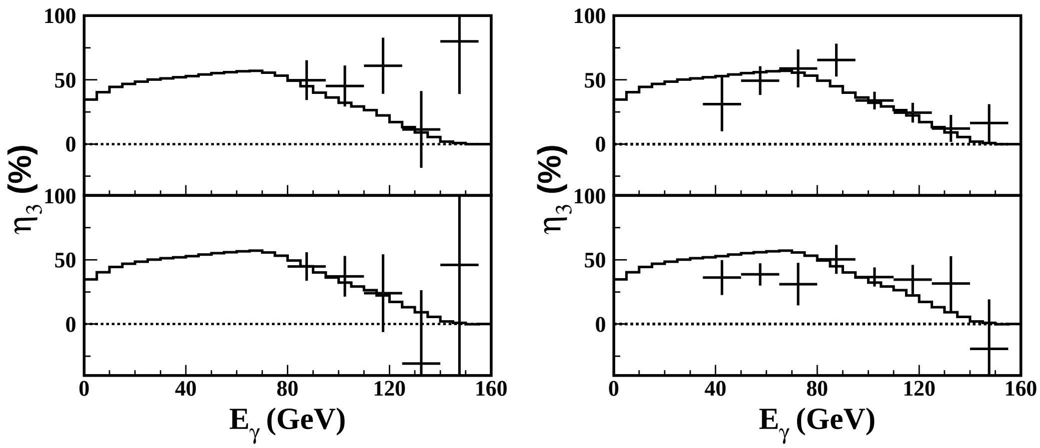

Fig. 4. The η_3 component as a function of photon energy of the photon polarisation with the Ge (left) and diamond (right) analysers. Measurements without (top) and with (bottom) the quasi-symmetrical pair selection are presented.

4.2 Linear Polarisation with the Quarter Wave Crystal

The measured asymmetries (left) in e^-e^+ PP in the Germanium analyser and the Stokes parameters η_1 and η_3 (right) are presented in figure 5. The solid lines are the MC predictions and the crosses are the experimental data. The data for the η_1 and the η_3 parameters are introduced only in the high energy region due to the geometrical acceptance and smallness of analysing power in the low energy region.

In figure 5, we see an interesting increase of up to a factor of seven for the η_1 Stokes parameter in the same energy region. This phenomenon was also predicted by Cabibbo et al [28]. The unpolarised photon beam traversing the aligned crystal becomes linearly polarised. This follows from the fact that the high-energy photons are more strongly affected by the PP process. The cross section for this depends on the polarisation direction of the photons with respect to the plane passing through the crystal axis and the photon momentum (polarisation plane). Thus, the photon beam penetrating the oriented single crystal feels the anisotropy of the medium. For the experimental verification of this phenomenon with photon beams at energies of 9.5 GeV and 16 GeV, see [29,30]. In the high energy region >100 GeV the difference between the PP cross sections parallel and perpendicular to the polarisation plane is large. Since the photon beam can be regarded as a combination of two independent beams polarised parallel and perpendicular with respect to the polarisation plane, one of the components will be absorbed to a greater degree than the other one, and the remaining beam becomes partially linearly polarised.

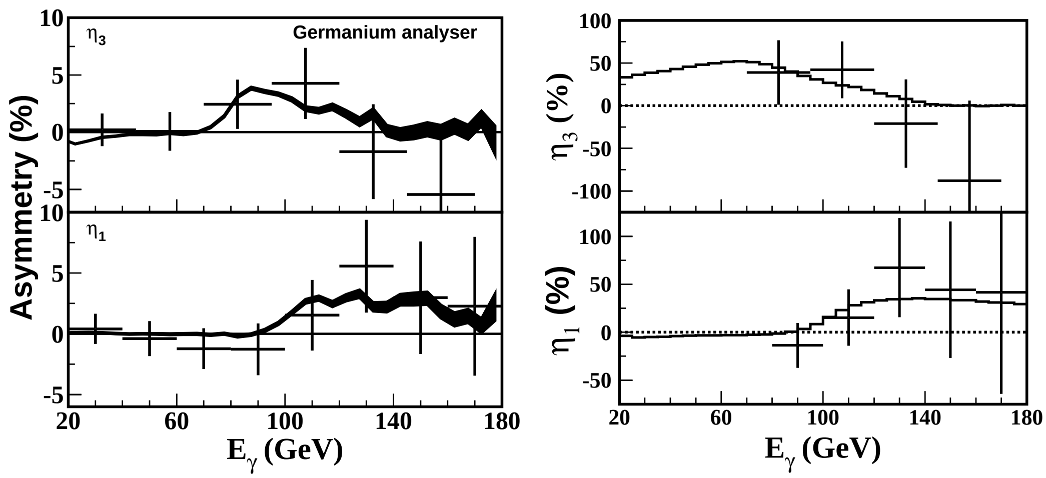

Fig. 5. The measured asymmetry (left) and the Stokes parameters (right) as a function of photon energy with the Ge analyser in presence of QWP. The top figures are for the η_3 component and the bottom figures are for the η_1 component.

4.3 Linear Polarisation in the SOS orientation

The measured asymmetry, the predicted asymmetry and the η_3 component of the linear polarisation are shown in figure 6. One can see that the measured asymmetry is consistent with zero over the whole photon energy range. The null result is expected to be reliable as the correct operation of the polarimeter had been confirmed in the same beam-time in measurements of the polarisation of CB radiation [8]. Note, that the expected asymmetry is small, especially in the high energy range of 120-140 GeV, where the analysing power is large [8]. This corresponds to the expected small linear polarisation in the high energy range, see figure 6 (right).

In contrast to the result of a previous experiment [31], our results are consistent

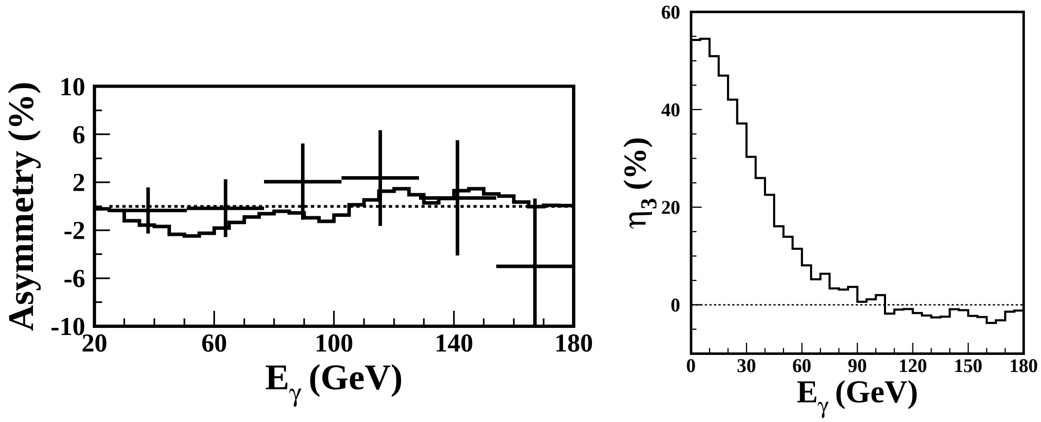

Fig. 6. Asymmetry of the e^+e^- pair production in the aligned diamond crystal (left) and prediction of the η_3 component (right) as a function of the photon energy E_γ. The black crosses are the measurements and the solid line represent the MC prediction.

with calculations that predict negligible polarisation in the high energy photon peak for the SOS orientation. The analysing power of the diamond analyser crystal in the previous experiment's [31] setup peaked in the photon energy range of 20-40 GeV where a high degree of linear polarisation is expected. But in the high energy photon region we expect a small analysing power of about 2-3%, also following from recent calculations [23,24]. The constant asymmetry measured in a previous experiment [31] over the whole range of total radiated energy may therefore not be due to the contribution of the high energy photons.

5 Discussion and Conclusion

The statistical significance of the results was estimated using the F-test [9,10]. These results then show the feasibility of the use of aligned crystals as linearly polarised high energy photon beam sources. The predictability of the photon energy and polarisation is a good asset for designing future beamlines and experiments. These results also establish the applicability of aligned crystals as polarimeters for an accurate measurement of the photon polarisation at high energies. The important aspects are the analyser material selection and utilisation of the quasi-symmetrical pairs. The use of synthetic diamond as the analyser crystal is found to be very promising due to its availability, durability and high analysing power.

Coherence effects in single crystals can be used to transform linear polarisation of high-energy photons into circular polarisation and vice versa. Thus, it seems possible to produce circularly polarised photon beams with energies above 100 GeV at secondary (unpolarised) electron beams at high energy proton accelerators. The birefringent effect becomes more pronounced at higher photon energy, which allows for thinner crystals with higher transmittance.

We did not perform a direct measurement of the circular polarisation of the photon beam. However, realistic theoretical calculations describe the radiated photon spectrum from the aligned radiator and the pair production asymmetries in the aligned analyser both with and without the birefringent Si crystal in the photon beam very well. In view of this good agreement between the theoretical and predicted linear polarisations for each case, the predicted birefringent effect seems to be confirmed by the present measurements.

Summarising the results, we find the weighted average of the Stokes parameter before and after the QWP in the energy region 80-110 GeV η_3=44±11% and η_3=28±7% before and after the QWP crystal, respectively. From these results one can estimate the η_2 component of the photon beam polarisation [9], which is η_2=21±11%. This is consistent with the predicted value of 16% [9]. Given the statistical significance of the data points, we find a confidence limit of 73% for the observation of circular polarisation.

Similar calculations may be done for the Stokes parameter η_1. If we make a weighted average for the asymmetry values between 20 and 100 GeV, where we expect no asymmetry, we obtain a value of 0.19±0.3%. Above 100 GeV we expect a small asymmetry, where we measured (1.4±0.7)%.

We also presented new results regarding the features of high energy photon emission by an electron beam of 178 GeV penetrating a 1.5 cm thick single Si crystal aligned at SOS orientation. This concerns a special case of coherent bremsstrahlung where the electron interacts with the strong fields of successive atomic strings in a plane and for which the largest enhancement of the highest energy photons is expected. Photons in the high energy region show less than 20% linear polarisation at the 90% confidence level.

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References

[1] G. Baum et al., Compass Proposal, CERN/SPSLC 96-14, SPSLC/P297, 1996.

[2] Proposal on Spin Physics Using the RHIC Polarised Collider (RHIC-Spin Collaboration) 1992; update 1993, (unpublished).

[3] V. Ghazikhanian et al., SLAC Proposal E-159/160/161, (2000).

[4] H. Olsen and L.C. Maximon, Phys. Rev. 114 (1959) 887.

[5] I.M. Nadzhafov, Bull. Acad. Sciencis USSR, Phys. Ser. 14 (1976) 2248.

[6] A.B. Apyan, R.O. Avakian, P.O. Bosted, S.M. Darbinian and K.A. Ispirian, Nucl. Instr. and Meth. B145 (1998) 142.

[7] R. Alley et al., Nucl. Instr. and Meth. A365 (1995) 1.

[8] A. Apyan et al., NA59 Collaboration, hep-ex/0306028, 2003.

[9] A. Apyan et al., NA59 Collaboration, hep-ex/0306041, 2003.

[10] A. Apyan et al., NA59 Collaboration, hep-ex/0406026, 2004.

[11] A. Apyan et al., Proposal to the CERN SPS Committee, CERN/SPSC 98-17, SPSC/P308 (1998).

[12] N. Cabibbo et al., Phys. Rev. Lett. 9 (1962) 270.

[13] V.A. Maisheev, hep-ex/9904029, (1999) 11pp.

[14] V.A. Maisheev, V.L. Mikhalev and A.M. Frolov, Sov. Phys. JETP 74 (1992) 740.

[15] V.M. Strakhovenko, Nucl. Instr. and Meth. B 173 (2001) 37.

[16] N.Z. Akopov, A.B. Apyan and S.M. Darbinian, hep-ex/0002041 (2000).

[17] A.P. Potylitsin, High Energy Polarised Photon Beams (In Russian), Energoatomizdat, Moscow, 1987.

[18] G. Barbiellini, G. Bologna, G. Diambrini and G.P. Murtas, Nuovo Cimento 28 (1963) 435.

[19] A.B. Apyan, R.O. Avakian, S.M. Darbinian, K.A. Ispirian, S.P. Taroian, U. Mikkelsen and E. Uggerhoj, Nucl. Instr. and Meth. B 173 (2001) 149.

[20] M.L. Ter-Mikaelian, High Energy Electromagnetic Processes in Condensed Media, Wiley Interscience, New-York, 1972.

[21] G. Diambrini-Palazzi, Rev. Mod. Phys. 40, (1968) 611.

[22] H. Bilokon, G. Bologna, F. Celani, B. D'Ettorre-Piazzoli, R. Falcioni, G. Mannocchi and P. Picchi, Nucl. Instrum. Meth. 204 (1983) 299.

[23] S.M. Darbinian and N.L. Ter-Isaakyan, Nucl. Instr. and Meth. B 187 (2002) 187.

[24] V.M. Strakhovenko, Phys. Rev. A 68, (2003) 042901.

[25] R. Medenwaldt et al., Phys. Lett. B 281, (1992) 153.

[26] N.Z. Akopov, A.B. Apyan, R.O. Avakian, R. Carrigan, S.M. Darbinian, K.A. Ispirian, Yu.V. Kononets and S. Taroyan. Nucl. Instr. and Meth. B 115 (1996) 372.

[27] R.C. Burns et al., J. Crystal Growth 104 (1990) 257.

[28] N. Cabibbo et al., Nuovo Cimento 27 (1963) 979.

[29] C. Berger *et al.*, Phys. Rev. Lett. **25** (1970) 1366.

[30] R.L. Eisele, D. Sherden, R. Siemann, Charles K. Sinclair, D.J. Quinn, J.P. Rutherfoord and M.A. Shupe, Nucl. Instr. and Meth. 113 (1973) 489.

[31] K. Kirsebom *et al.*, Phys. Lett. B 459 (1999) 347.