CLAS-NOTE 98-018

Workshop on "Polarized Photon Polarimetry"

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Tagged linearly-polarized photons from a coherent bremsstrahlung (C.B.) source will be available for use in experiments in Hall B at Jefferson Lab by mid-1999. Currently approved experiments require knowledge of the degree of polarization with high accuracy in the full range of available energies. Calculation of the degree of polarization requires careful measurements of the photon spectra. Cross checks of calculations with direct measurements of the polarization are also necessary. The review of available polarimetry techniques and their consideration for Jefferson Lab was the main focus of the workshop. This document summarizes the current status of the available techniques and preliminary recommendations for Hall B.

I. THE WORKSHOP

The Workshop on Polarized Photon Polarimetry was held June 2–3, 1998 at Jefferson Lab. We kept involvement limited to those who have been involved with the plan to implement a linearly-polarized photon beam at Jefferson Lab and those who are planning to use this beam during the first round of Hall B experiments. A list of attendees is attached in appendix A.

The format of the first day was a presentation format with talks on various topics related to linearly-polarized photons, their planned use in experiments in Hall B, and techniques for determining the degree of polarization. The second day we broke up into working groups for discussions. A tour of Hall B was arranged to help participants visualize where and how polarimetry devices would fit into the existing beam line. Each working group was charged with the responsibility of writing a brief report expounding the virtues and shortcomings of the selected technique, carefully taking into consideration experimental requirements and currently available space. We convened as a whole the afternoon of day two. Each group presented a brief report and preliminary recommendations. Written reports were later turned in to the organizers. This report carries the conclusions and recommendations of these working groups.

II. THE PROGRAM

Tuesday, June 2, 1998:

8:30 – 8:40	Opening	William Briscoe (GWU)
8:40 – 9:15	A Coherent Bremsstrahlung Facility (CBF)	Kalvir Dhuga (GWU)
9:15 – 10:00	Physics with Linearly Polarized Photons with the CBF	Philip Cole (UTEP)
10:00 – 10:45	Survey of Methods of Measuring Linear Polarization of Photons	Leonard Maximon (GWU)
10:45 – 11:00	Break	
11:00 – 12:00	Triplet Production Polarimeter at SAL	Robert Pywell (SAL), and Gerald Feldman (GWU)
12:00 – 13:00	Lunch	
13:00 – 14:00	Linearly Polarized Photons at Mainz	Jürgen Ahrens (Mainz)
14:00 – 15:00	Production of Linearly Polarized Photons and Polarization Measurements by a Pair Polarimeter	Toshimi Suda (Tohoku)
15:00 – 15:30	Measurement of the Photon Beam Polarization at the Yerevan Electron Synchrotron	Robert Avakian (Yerevan)

15:30 – 15:45	Break	
15:45 – 16:15	Calculation of γ Beam Polarization from an Oriented Crystal	Richard Jones (UCONN)
16:15 – 16:45	Microstrip Detector Technology	Branislav Vlahovic (NCCU)
16:45 – 17:15	Polarimeter for High Energy Photons	Bogdan Wojtsekhowski (TJNAF)
17:15 – 17:45	Measuring Photon Polarization via Coherent Pair Production	David Tedeschi (USC)

Wednesday, June 3, 1998:

9:00 – 10:30	Working Group Meetings: Pair Production Technique Triplet Production Technique Calculational Methods	Coordinators: Samuel Danagoulian (NC A&T SU) Gerald Feldman (GWU) Jürgen Ahrens (Mainz), and Leonard Maximon (GWU)
10:30 – 10:45	Break	
10:45 – 12:00	Working Group Meetings (continued)	
12:00 – 13:00	Lunch	
13:00 – 14:00	Tour of Hall B	
14:00 – 16:00	Working Group Presentations	

Tuesday, June 9, 1998: Jlab Seminar

Attenuation through Carbon Technique Polarimeter at SLAC	Charles Sinclair (TJNAF)

III. REPORTS OF THE WORKING GROUPS

The responsibilities of the working groups for a particular technique were to study and evaluate the effectiveness of the method, its feasibility, limitations, cost, location of the detector in the Hall B beamline, and other general considerations. After the workshop, the coordinators of the working groups presented the organizers with a written report with their conclusions and recommendations for each of the methods of polarimetry that are being considered. These reports, and relevant publications, are included in appendices B–D.

Appendix B:	Report of Working Group on Calculational Methods
Appendix C:	Report of Working Group on Triplet Photoproduction Technique
Appendix D:	Report of Working Group on Pair Production Technique (a) Coherent Pair Production (b) Incoherent Pair Production
Appendix E:	Attenuation through Carbon Technique Polarimeter at SLAC

IV. PHYSICS REQUIREMENTS

Presently approved experiments utilizing linearly polarized photons in Hall B require a knowledge of the degree of polarization with an accuracy of 5%, at least in the region of the main peak of the coherent radiation spectrum. However, there are several new ideas for experiments being considered which will need an accuracy of 1–2%. Therefore, we consider an accuracy of 5% as a guideline for the polarimetry technique that will be adopted in Hall B, with focus on the possibility of achieving a 1–2% level of accuracy.

In the long run we will probably rely on continuous monitoring of the photon spectrum intensity and calculating the degree of linear polarization. These calculations must first be verified for the energy ranges considered in Hall B, for which purpose at least one of the three polarimetry techniques should be employed.

V. CONSIDERATIONS AND STATUS OF THE TECHNIQUES

There are several considerations which need to be taken into account in the analysis of each proposed technique:

(a) expected level of systematics;

(b) previous experience with a particular technique;

(c) status of necessary hardware;

(d) manpower and resources needed for implementation and operation.

Based on the reports of the working groups, the following are the observations made for the three different techniques being considered:

(a) Expected Level of Systematics:

The systematics in the calculational method has two sources: accuracy of the measurement of coherent and incoherent radiation spectra and the accuracy of their calculation/analysis. Recent advances made by the Mainz group have demonstrated that the systematics in the calculation of the photon polarization in the region of the main peak of the coherent spectrum is about 5%. At the same time, this uncertainty can be large, as much as 50%, for the part of the spectrum which is outside the main peak.

An understanding of the systematics of the triplet production technique requires detailed experimental study. The effect of detector acceptance on the analyzing power is expected to be large and this may require a further upgrade of the existing detector system. Additional theoretical study needs to be done to ensure the reliability of the code being used for the calculation of the analyzing power.

The systematics of the coherent pair production technique arises mainly from uncertainties in the crystal structure. Because of this and other effects, such as multiple scattering in the target, this method needs to be calibrated at existing facilities, such as LEGS and GRAAL. Also, it is important to know the acceptance of the existing pair spectrometer in Hall B for controlling the systematics. The systematic errors become large at energies below 2 GeV, where the analyzing power is dropping.

The systematics in the incoherent pair production technique is the smallest amongst the three polarimetry methods. The analyzing power can be calculated exactly, and has a small and slow energy dependence.

(b) Previous Experience with a Particular Technique:

The calculational method for measurement of the polarization has been used a long time ago at DESY and at the Yerevan Electron Synchrotron for photons in the few GeV energy range. More recently at Mainz, this method has been used in the energy range $E_\gamma \sim 400$ MeV, where practically all aspects of the method were carefully investigated. However, in the energy range above 400 MeV the demonstrated accuracy is only 10–20%, which is not sufficient for the proposed physics requirements in Hall B.

The triplet production method has been tested in Japan at low photon energies with modest results. This method was not used in an actual experiment and the existing setup was not used for any measurement of nonzero polarization.

The coherent pair production method has been used extensively at DESY and at Yerevan. However, the accuracy achieved in measurement of the polarization is not sufficient for Hall B physics.

The incoherent pair production method has been used only in the energy range below $E_\gamma = 500$ MeV, where the coherent pair production technique cannot be used. Previously used schemes of pair detection should be replaced with a new proposed technique if this method is to be applied in the photon energy range that is considered in Hall B.

(c) Status of Necessary Hardware:

The application of the calculational method in Hall B needs some additional hardware, *e.g.,* scintillation counters and associated electronics, but that is a very small cost compared to what the other methods will require. Comparison of this method with experiment at energies above 400 MeV is absolutely necessary for completing the program.

The setup for the triplet production technique already exists at SAL and is ready for testing at LEGS with $E_\gamma \sim 470$ MeV. Some upgrade of the vacuum chamber and the detection system was recommended at the workshop.

Coherent pair production systems have been used in the past. However, the main part of the detection hardware needs to be built from scratch for Hall B. The system needs a remotely controlled goniometer as well as an upgrade of the existing pair spectrometer when systematics below 5% are required. [The estimated cost for such an upgrade is about $50k (for an additional 50 scintillator counters with fast electronics).]

The modified incoherent pair production technique reported at the workshop will use microstrip silicon detectors, which are widely used in high energy physics. Presently, one set of detectors and the associated electronics for a prototype polarimeter is already in-house and is undergoing testing. As in the case of the coherent pair production method, an upgrade of the existing pair spectrometer will also be required for this method for achieving systematic uncertainties below 5%.

(d) Manpower and Resources Needed for Implementation and Operation:

In order to implement the calculational method of polarization measurement, a team, which includes experts of the Hall B tagger system, is being formed under the leading efforts of GWU.

Developers of the existing triplet polarimeter, Robert Pywell (SAL) and Gerald Feldman (GWU), have offered to have the system brought to CEBAF from SAL at no cost to Jefferson Lab, *i.e.*, it would be the contribution of SAL to Hall B, with some of the costs included in the GWU MRI Grant and in Gerald Feldman's young investigator award. The triplet setup needs to be tested with linearly-polarized photons at the LEGS and GRAAL facilities before it can be considered as a viable option for Hall B. Necessary preparation for such tests at the LEGS facility are currently underway.

The coherent pair production technique will require on the order of $65k for a new goniometer and for test preparations at LEGS. The core group for developing this technique for Hall B has not yet been formed.

Developers of the incoherent pair production polarimeter have recently completed a Jlab technical note (TN-98-039, see appendix D) with a full description of the calculations. The microstrip detectors and electronics for a stand-alone system have already been purchased from commercial suppliers and will be tested with the help of experts from CERN in December, 1998. The tests with a linearly-polarized photon beam (E_γ=20 MeV) at TUNL/Duke University will follow in January, 1999. The cost of beamline components is of the order of $10k, so the major cost for Hall B will be in the future upgrade of the pair spectrometer detector.

Construction of the carbon attenuation polarimeter requires a large amount of expensive material and in view of the requirement for high precision (1–2%), we find that the systematics and expense of this technique do not make it an attractive option for Hall B.

VI. PROPOSED PROGRAM OF DEVELOPMENT

Based on the analysis of the working groups' reports and additional information from polarimeter developers, we propose the following scenario:

A. The calculational method for the determination of the degree of polarization should be implemented. Because the calculations require detailed information about coherent and incoherent radiation spectra, the necessary analysis as to how such a measurement will be organized and what equipment will be used, needs to be carried out. In addition, some modifications to the currently used data acquisition system may be necessary.

B. The development of each of the three proposed polarimeters should proceed before a final decision is made about which device will be incorporated in the beamline in Hall B. The developers of the polarimeters should provide their test results to Hall B management and to the collaboration before March 1, 1999.

C. It will be useful to form a special working group for polarized photon instrumentation in the Hall B collaboration.

Appendix A

List of Participants

Workshop on "Polarized Photon Polarimetry" – List of Participants

Abdellah Ahmidouch	North Carolina A&T State University
Jürgen Ahrens	Institut für Kernphysik, University Mainz
Juhachi Asai	Saskatchewan Accelerator Laboratory
Robert Avakian	Yerevan Physics Institute
William Briscoe	The George Washington University
Philip Cole	University of Texas at El Paso
Hall Crannell	The Catholic University of America
Samuel Danagoulian	North Carolina A&T State University
Kalvir Dhuga	The George Washington University
Chaden Djalali	University of South Carolina
Gerald Feldman	The George Washington University
Arne Freyberger	Thomas Jefferson National Accelerator Facility
Matthieu Guillo	University of South Carolina
Richard Jones	University of Connecticut
Mahbub Khandaker	Norfolk State University / Jefferson Lab.
Franz Klein	Thomas Jefferson National Accelerator Facility
Leonard Maximon	The George Washington University
James McCann	Carnegie Mellon University
James Mueller	University of Pittsburgh
Robert Pywell	Saskatchewan Accelerator Laboratory
Sebastian Simionatto	The George Washington University
Daniel Sober	The Catholic University of America
Elio Soldi	North Carolina Central University
Igor Strakovsky	The George Washington University
Toshimi Suda	Tohoku University
Kazunori Takahashi	Tohoku University
David Tedeschi	University of South Carolina
Branislav Vlahovic	North Carolina Central University
Bogdan Wojtsekhowski	Thomas Jefferson National Accelerator Facility
Amrit Yegneswaran	Thomas Jefferson National Accelerator Facility

Appendix B

Report of Working Group on Calculational Methods

Working Group on Calculations

Coordinators: Jürgen Ahrens (Mainz) and Leonard Maximon (GWU)

The state of the art of today's techniques requires that we ascertain the degree of polarization of the photons as precisely as possible. A relative precision of 5% or better seems to be a good guideline, and methods that cannot fulfill this requirement should not be considered. The production process, which in our case is coherent bremsstrahlung, and the polarimetry of the photons will be discussed in the following. The A2 collaboration at MAMI has already developed the technique of coherent tagged bremsstrahlung into a useful tool [1–3].

I. THE PRODUCTION PROCESS – COHERENT BREMSSTRAHLUNG

The most important part, of course, is the production process, which is coherent bremsstrahlung. This, as well as the incoherent bremsstrahlung background, needs to be calculated reliably in order to enable us to draw conclusions concerning systematic errors, *e.g.*, when extrapolating to energies where no checks of the calculations have been made.

In the experiment we will always use collimated photon beams, a bremsstrahlung tagger and realistic electron beams. This means that we will not know precisely which kinematic cuts the experiment makes and thus we will not be able simply to calculate the effects. Thus we need to measure a quantity that reflects the real experimental conditions.

The properties of interest in an experiment with coherent bremsstrahlung are the photon spectrum after collimation and the degree of linear polarization of those photons.

The quantities and parameters to be used in the following are:

k: photon energy
E_0: energy of the incoming electron
x: fractional photon energy $= k/E_0$
x_d: fractional photon energy at the discontinuity
$I(x)$: photon intensity spectrum
I_i: incoherent part of I – ordinary bremsstrahlung
I_c: coherent part of I
I_{rel}: relative intensity spectrum. $I_{rel} = (I_c + I_i)/I_i$
F: another relative intensity spectrum. $F = I_c/(I_c + I_i) = 1 - 1/I_{rel}$
$P_\gamma(x)$: degree of linear polarization of the photons
$PHI(x, x_d)$: function linking P_γ to F. $P_\gamma = PHI(x, x_d) \times F(x) \quad (x < x_d)$

A. Photon spectrum

From a crystal we have a coherent and an incoherent intensity spectrum, I_c and I_i. Their relation is given by the bremsstrahlung effect and by experimental conditions such as collimation. The uncollimated total spectrum $(I_c + I_i)_u$ is measured with the tagger. It carries information about the crystal orientation, crystal quality, electron beam divergence, multiple scattering of the electrons before the process, *etc.*. The collimated total spectrum is different from the latter because the angular distributions of the coherent and the incoherent photons are different. Tight collimation reduces the incoherent effect. A device has to be found (a pair detector, a pair spectrometer, or a total absorbing calorimeter, *etc.*) that will measure reliably the collimated photon spectrum. In order to deduce a relative quantity like $I_{rel} = (I_c + I_i)/I_i$, I_i has to be measured separately. This can be done either by choosing a crystal orientation that yields no coherent effect in the energy range of interest or by just using an equivalent carbon (graphite) radiator. Normalization of $(I_c + I_i)$ and I_i needs to be done precisely. Thus, the quantity (electron current)×(target thickness) needs to be determined. The most elegant way of doing this is to measure the yields from some effect that is not influenced by the crystal lattice. The number of Møller electrons from the radiator might be a suitable quantity. This would require the detection in coincidence of electron pairs whose sum energy corresponds to the incoming electron energy. This would then result in finding where I_{rel} has the value 1 or $F(x) = 1 - 1/I_{rel}$ has the value 0. *Note*: there is a background effect to the Møller scattering, which is electron pair production. This effect is certainly influenced by the lattice. The measured relative intensity spectrum needs to be in agreement with the corresponding uncollimated spectrum as measured with the tagger ladder such that the discontinuities are found at the same x_d values. The calculation of the relative intensity spectrum can be used in a fitting procedure to determine reasonable parameters for the electron beam divergence, the change of electron beam direction during the experiment, the multiple scattering, the structure of the crystal, *etc.*.

B. Degree of Polarization

The degree of linear polarization, P_γ, needs to be known to run an experiment since any asymmetry measured will be P_γ times the analyzing power of the reaction under investigation. P_γ is influenced by the amount of coherent to incoherent effect, as given by $F(x)$, and by the coherent effect itself. According to Timm [4] there is a function PHI which factorizes the latter effect such that $P_\gamma(x) = PHI(x, x_d) \times F(x)$. Thus, if $F(x)$ is known, $P_\gamma(x)$ could be deduced. The calculation of the relative intensity spectrum (see above) has yielded a set of parameters describing the experimental conditions. A full calculation then has to be made using these parameters to determine $P_\gamma(x)$. A comparison needs to be made of the thus found P_γ values with those obtained with the factorization using PHI. The difference between these two approaches is given by the fact that in the factorization no further integration over angles is applied, which should still lead to a reasonably precise result, since PHI is a function that varies slowly with x_d. A polarimeter reaction needs to be found that enables one to check the whole procedure experimentally.

II. POLARIMETRY – POLARIMETER REACTIONS

As a polarimeter reaction, any reaction of which the analyzing power is known well enough would, of course, do. A good example is coherent π^0 production on a spin zero nucleus, which can only be obtained through magnetic transitions and thus has intrinsically an analyzing power of 100%. ^{4}He is a very good choice of nucleus since all excited states are in the continuum that starts roughly 20 MeV above the ground state. This makes it easy to use this reaction as an analyzer at energies around the $\Delta(1232)$ resonance. Other reactions, such as triplet production, pair production (in amorphous targets or in thin crystals), or attenuation in thick crystals, would need to be calculated reliably or calibrated to be of use. Another possibility is to use a reaction that can be measured easily with the equipment at hand and have it calibrated by colleagues who use photon beams with a well known degree of polarization, such as those who use backscattered laser photons. A possible simple reaction would be single π^0 production on the proton, which has a high analyzing power in certain kinematic regions. Of course, on-line polarimetry would be ideal, but it seems that it is hard to get and probably not necessary if the factorization scheme of Timm can be shown to be reliable.

REFERENCES

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[2] A. Kraus *et al., Phys. Rev. Lett.* **79**, 3834 (1997).
[3] F. Rambo *et al., Phys. Rev.* **C58**, 489 (1998).
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Appendix C

Report of Working Group on Triplet Photoproduction Technique

Report of the Working Group on Triplet Photoproduction

Coordinators: Gerald Feldman (GWU) and Robert Pywell (SAL)

I. INTRODUCTION

A recommendation is presented to pursue the prospect of using triplet photoproduction to measure the photon beam polarization in Hall B at CEBAF. The intention is to exploit the existing SAL triplet polarimeter which has already been tested in Saskatoon and which can be easily adapted for use at CEBAF with minor modifications. The main practical advantages are that, given the fact that the device already exists, very minimal cost and very short time scale would be involved in order to bring the device into Hall B for an in-beam test. In addition, the device is compact enough that it might easily be transported to a facility that can produce photons with known polarization where its operation characteristics might be checked.

II. GENERAL CONSIDERATIONS

The process of triplet photoproduction involves pair production in the Coulomb field of an atomic electron. While the pair is highly energetic and extremely forward-peaked, the recoil electron comes off at large angles ($\theta_r > 15^\circ$) with relatively low energy ($E_r < 10$ MeV). The angle and energy of the recoil is nearly independent of the incident photon energy. Detecting the "triplet" (both particles of the pair, plus the recoil) provides a unique experimental signature for the process, leading to a substantial reduction in background compared to pair production. The passage of a pair (electron and positron) in a thin plastic scintillator downstream from the target is identified by a *double* minimum-ionizing peak in the energy spectrum. The recoil electron can be detected over a polar angular range of $\theta_r = 15^\circ - 35^\circ$ in a straightforward manner using ΔE-E telescopes (plastic scintillators or solid-state detectors). Placing four recoil detectors at fixed azimuthal angles ($\phi = 0^\circ, 90^\circ, 180^\circ, 270^\circ$) gives a measure of the azimuthal asymmetry of the recoil electron, which in turn is sensitive to the linear polarization of the incident photon.

The differential cross section can be expressed as a function of the azimuthal angle ϕ:

$$d\sigma/d\phi = (\sigma/2\pi)[1 - P\lambda\cos(2\phi)]$$

where σ is the total cross section, P is the photon polarization, and λ is the analyzing power. The experimental asymmetry Σ is related to P and λ by $\Sigma = P\lambda$. The value of λ at a given photon energy must be determined by a calculation. Endo and Kobayashi have developed a computer code (TPP) which performs a numerical integration over the experimentally accessible kinematical region using a Monte Carlo technique. Typical input parameters include the photon energy and polarization, the polar angle region covered by the pair detector, and the polar angle region of the recoil detectors. The program output includes the azimuthal angular distribution of the recoils, which yields σ and λ when fitted with the expression above.

One shortcoming of the above procedure is the reliance on a theoretical calculation for the analyzing power. We propose to calibrate the triplet polarimeter at LEGS using a 450 MeV photon beam of known polarization ($P \sim 96\%$). This would check the calculation at that energy. The possibility of calibrating at higher energies (perhaps at GRAAL) is also being considered.

III. DESIGN OF POLARIMETER

The triplet polarimeter, in the configuration used at SAL, is depicted in Fig. 1 and consists of 3 primary parts – the production target, the in-beam counters for detecting the pairs, and the recoil detectors. The defining collimator, sweep magnet, and main shielding wall with clean-up collimator were part of the method used in the SAL test for producing polarized photons and were not strictly part of the polarimeter. In the SAL test the beam spot on the target was defined by the defining collimator with diameter 6.3 mm. The target used in the SAL test was LiH, which is the lowest-Z material that could be made into a solid target. Since the principal background comes from pair production, whose cross section goes as Z^2, while the triplet production cross section is proportional to the number of electrons, Z, a low-Z target is desirable for background reduction.

Just in front of the target is a veto scintillator and a clean-up collimator of diameter 12.7 mm. The veto counter allowed rejection of events caused by charged particles coming along with the beam. The recoil detectors consist of four plastic scintillator paddles (3 mm thick) which subtend the polar angle range $\theta_r = 15^\circ - 42^\circ$. These paddles proved to be too thick in the SAL test measurement, since it was evident in the data that low-energy electrons ($E_r \sim 1$ MeV) were being stopped in the paddles. This made the results dependent on the gains and thresholds of the recoil detectors, which would introduce a systematic error in the asymmetry. Several improvements are envisioned that will significantly enhance the recoil detection. First, the detectors will be limited to $\theta_r < 35°$ to kinematically exclude low-energy ($E_r < 2.5$ MeV) recoils. Second, two paddles will be used and a coincidence requirement will be imposed. In addition, the front paddle will be made thinner (1–2 mm thick). This guarantees that the recoil electron passes cleanly through the front paddle, giving a better recoil signal and helping reduce background. Third, the target and recoil detectors may be placed in a vacuum box in order to eliminate multiple scattering in air.

The pair detectors consist of two plastic scintillator paddles that sit in the beam. The hardware trigger condition requiring a coincidence of ***both*** pair paddles ***in addition*** to the recoil detector limits the event rate. For a total photon rate of ~5 MHz, the event rate in the SAL test run was ~300 Hz. The free-running scaler rates in the pair paddles were 100 kHz (front) and 200 kHz (back), while the recoil detector rates were a modest 3 kHz. The trigger condition also included a coincident hit in the tagger focal plane, and an anti-coincidence with a veto paddle immediately preceding the target.

The SAL polarimeter in its present form is ~1.2 m long and could fit easily at the front of the alcove in the downstream end of Hall B. In this position, it could serve as an on-line downstream device and acquire polarimetry data continuously without affecting the running of CLAS.

IV. DATA ANALYSIS

The analysis of the triplet data is quite straightforward. The energy spectra from the two pair paddles (see Fig. 2) shows two peaks, representing the passage of one electron or two. A cut on the double minimum-ionizing peak in both spectra identifies the events in which a pair was unambiguously detected. The separation between the single and double minimum-ionizing peaks is seen to be quite good when viewed in a two-dimensional plot of paddle #1 vs. paddle #2 (bottom panel of Fig. 2). The energy spectra for the four recoil detectors are shown in Fig. 3 and should show (with thinner paddles) a clean minimum-ionizing peak due to passage of the recoil electron. Integrating these spectra gives the yields for the $\phi = 0°, 90°, 180°, 270°$ detectors. Summing the 90° and 270° (top and bottom) detectors together gives the vertical yield N_V while summing the 0° and 180° (right and left) detectors together gives the horizontal yield N_H. The measured asymmetry is then determined by the ratio of the difference over the sum:

$$\Sigma = (N_H - N_V)/(N_H + N_V).$$

The asymmetry Σ and the known analyzing power λ (obtained from calculation) allow the photon polarization to be deduced. Instrumental asymmetry may be checked with an unpolarized photon beam.

V. SPECIAL CONSIDERATIONS

The detection of the recoil electrons at moderately low energies could pose a problem due to multiple scattering either in the target or in the air. By putting the triplet production target in a vacuum along with the recoil detectors, the latter problem would be eliminated if necessary. For a 2 mm thick lithium metal target, the standard deviation of the multiple scattering angle for a 2.5 MeV electron is ~ 7° and for a 4.0 MeV electron is ~ 4.5°. The angular extent of the recoil paddles is $\theta_r = 15° - 35°$ and $\phi_r = \pm 22°$, so the multiple scattering angle is substantially smaller than the angular size of the recoil detectors. To quantify the effect of multiple scattering in the target on the measured asymmetry, a Monte Carlo simulation of the triplet production process is being developed. The number of radiation lengths of air between the target and the recoil detectors is about 10% of the number of radiation lengths in the target. This suggests that a vacuum chamber may not be necessary but a complete simulation will check this. To insure clean detection of the recoil electrons, a double detector system (ΔE-E) will be used. Furthermore, by restricting the recoil detectors to relatively forward angles ($\theta_r < 35°$), the lowest-energy recoil will be ~2.5 MeV, which can penetrate the first (thin) ΔE with little difficulty.

Since the triplet production cross section varies as Z (compared to pair production, which is Z^2), the count rate is not substantial. Much of the cross section occurs in the region of low-energy recoils ($E_r < 1$ MeV) which are not easily detectable – in fact, these are purposely excluded by requiring $\theta_r < 35°$ to avoid such experimental problems. Based on experience from the test run at SAL, it is possible to accumulate ~10,000 counts per recoil detector in 40 minutes across the entire focal plane of the SAL tagger. This assumes a total photon rate of ~5 MHz, comparable to rates presently being run in Hall B. In order to achieve that level of statistics for each T-counter, it would require running 60 times longer (or 40 hours). This would be possible to achieve during an experiment if the polarimeter was continuously running as a downstream beam-line device. Every two days, high statistics asymmetry information would be available for each T-counter. With yields of ~10,000 counts in the recoil detectors, the uncertainty in the measured asymmetry would be ±5% assuming conservative estimates of $P \sim 50\%$ and $\lambda \sim 20\%$. Relative variations of the beam polarization on a shorter time scale could be monitored by summing groups of T-counters. If the two-day readings show a constant polarization with time, then many such sets could be summed together to give a precise determination of the asymmetry.

It should be noted that the analyzing power λ can be enhanced by restricting the opening angle of the detected pairs, which in turn tends to reduce the cross section σ. This can be seen in Fig. 4, where σ and λ and the figure of merit ($\sigma\lambda^2$) are plotted as a function of the recoil electron angle (in radians) for three photon energies (1, 3, and 5 GeV) and three pair detector sizes (θ_{det} = 2.5, 5.0, and 7.5 mrad). As the collimation of the pairs gets tighter, the analyzing power increases, but the cross section drops. This trend is also apparent in Fig. 5, where σ and λ are plotted as a function of the pair detector size (polar angle), integrated over a recoil electron acceptance range of $\theta_r = 15^\circ - 35^\circ$ as in the modified version of the SAL polarimeter. Thus, a compromise must be reached between λ and σ. In Fig. 6, these quantities are plotted as a function of photon energy for three pair detector sizes. Since these values are a function of both photon energy and pair opening angle, the collimation for the pairs may not be optimal across the entire tagger focal plane. However, since the polarization from coherent bremsstrahlung is highly structured, the collimation appropriate for the particular photon energy range of interest can be selected.

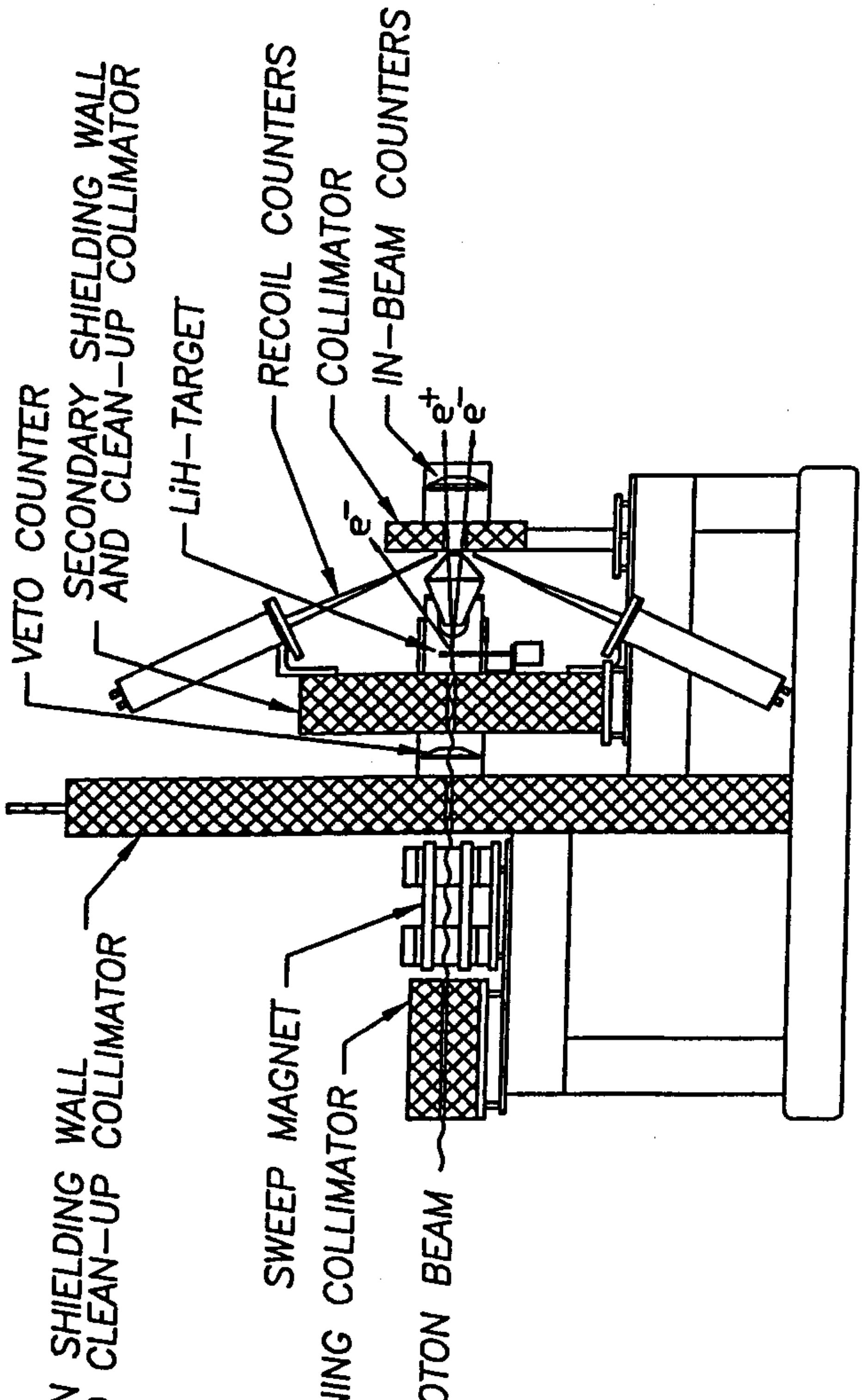
A remaining question relates to the effect on λ of finite beam spot size. For the envisioned coherent bremsstrahlung facility, a 2 mm beam collimator will be located ~20 m downstream from the diamond radiator. The alcove at the back of Hall B is ~30 m away from the collimator, giving a beam spot of ~5 mm. To first-order, the recoils will not be affected very much due to the fact that *both* the left and right (or top and bottom) detectors are added to give the horizontal (or vertical) yields for the asymmetry. While one side may get more counts, the other side will get correspondingly less, but the sum will be approximately unchanged. For the pairs, the effect of finite beam size is comparable to allowing a larger polar angle for the detected pair. From Fig. 4, it is clear that while λ does in fact decrease with larger pair acceptance, the variation is slow at larger polar angles. Thus, a choice of pair detector size that reduces this sensitivity (*i.e.*, where λ is relatively flat) would be advisable. The Monte Carlo code being developed for triplet photoproduction will address this particular question more quantitatively.

VI. SUMMARY

The idea of pursuing the triplet photoproduction technique using a slightly modified version of the existing SAL polarimeter seems like an attractive option. The low cost (mostly borne by SAL) and the short time scale required to make the modifications are the main practical advantages. The device is technically simple and is virtually maintenance-free. The analysis of the triplet data is rather straightforward.

The disadvantages of this method have been carefully considered, and all of them appear to be solvable. The experimental difficulty of detecting the low-energy recoils can be handled by utilizing a vacuum box and a ΔE-E telescope with a thin ΔE detector. The low count rate allows good statistics (±5% uncertainty in the asymmetry) to be collected on the order of days (not hours), but for periodic checks this could be acceptable. In particular, as an on-line device, data could be acquired simultaneously with the physics data. The dependence on a calculated value of λ can be checked at LEGS at 450 MeV and possibly at GRAAL at 1.5 GeV. Once the validity of the calculation has been established, the measured asymmetry at any energy can be combined with the calculated value of λ to give the photon beam polarization.

Overall, the recommended plan can be implemented expeditiously and shows reasonable promise of success.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AND CLEAN-UP COLLIMATOR
SWEEP MAGNET
DEFINING COLLIMATOR
PHOTON BEAM
VETO COUNTER
SECONDARY SHIELDING WALL
AND CLEAN-UP COLLIMATOR
LiH-TARGET
RECOIL COUNTERS
COLLIMATOR
IN-BEAM COUNTERS
e+ e- e-
e-

Fig. 1

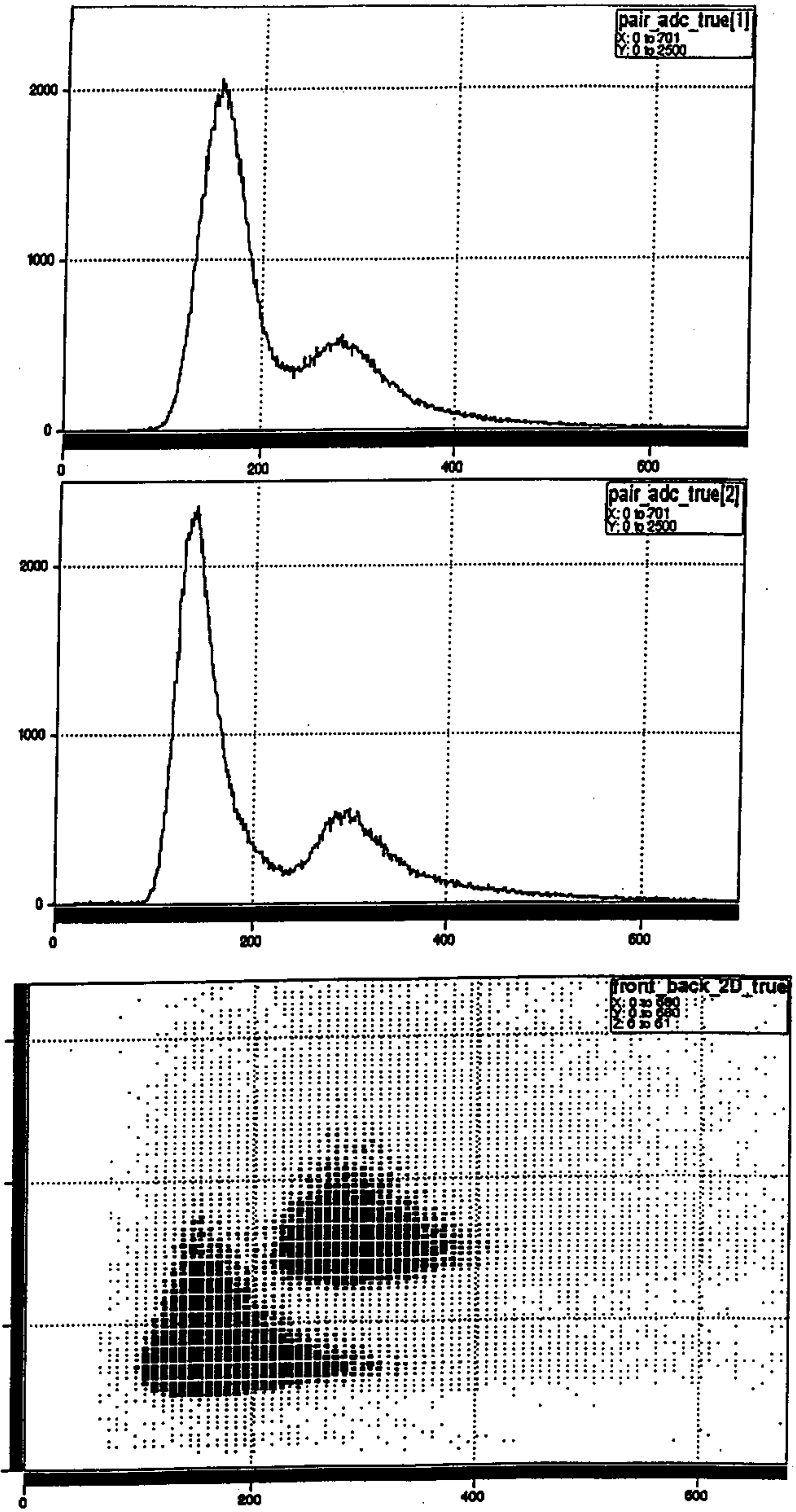

pair_adc_true[1]
X: 0 to 701
Y: 0 to 2500
0
1000
2000
0
200
400
600
pair_adc_true[2]
X: 0 to 701
Y: 0 to 2500
0
1000
2000
0
200
400
600
front_back_2D_true
X: 0 to 680
Y: 0 to 680
Z: 0 to 61
0
200
400
600
0
200
400
600

Fig. 2

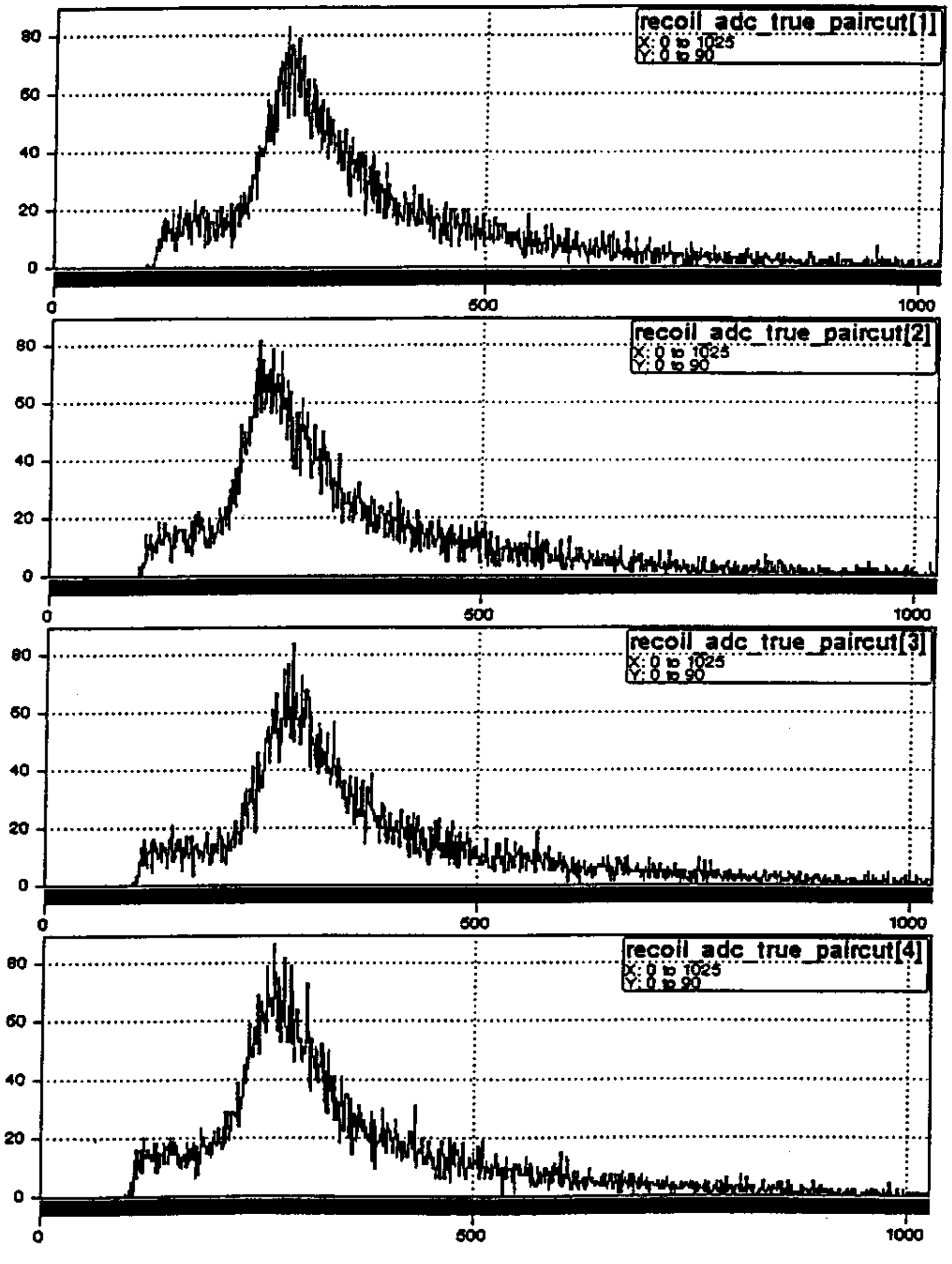

recoil_adc_true_paircut[1]
X: 0 to 1025
Y: 0 to 90
recoil_adc_true_paircut[2]
X: 0 to 1025
Y: 0 to 90
recoil_adc_true_paircut[3]
X: 0 to 1025
Y: 0 to 90
recoil_adc_true_paircut[4]
X: 0 to 1025
Y: 0 to 90
0
20
40
60
80
0
500
1000

Fig. 3

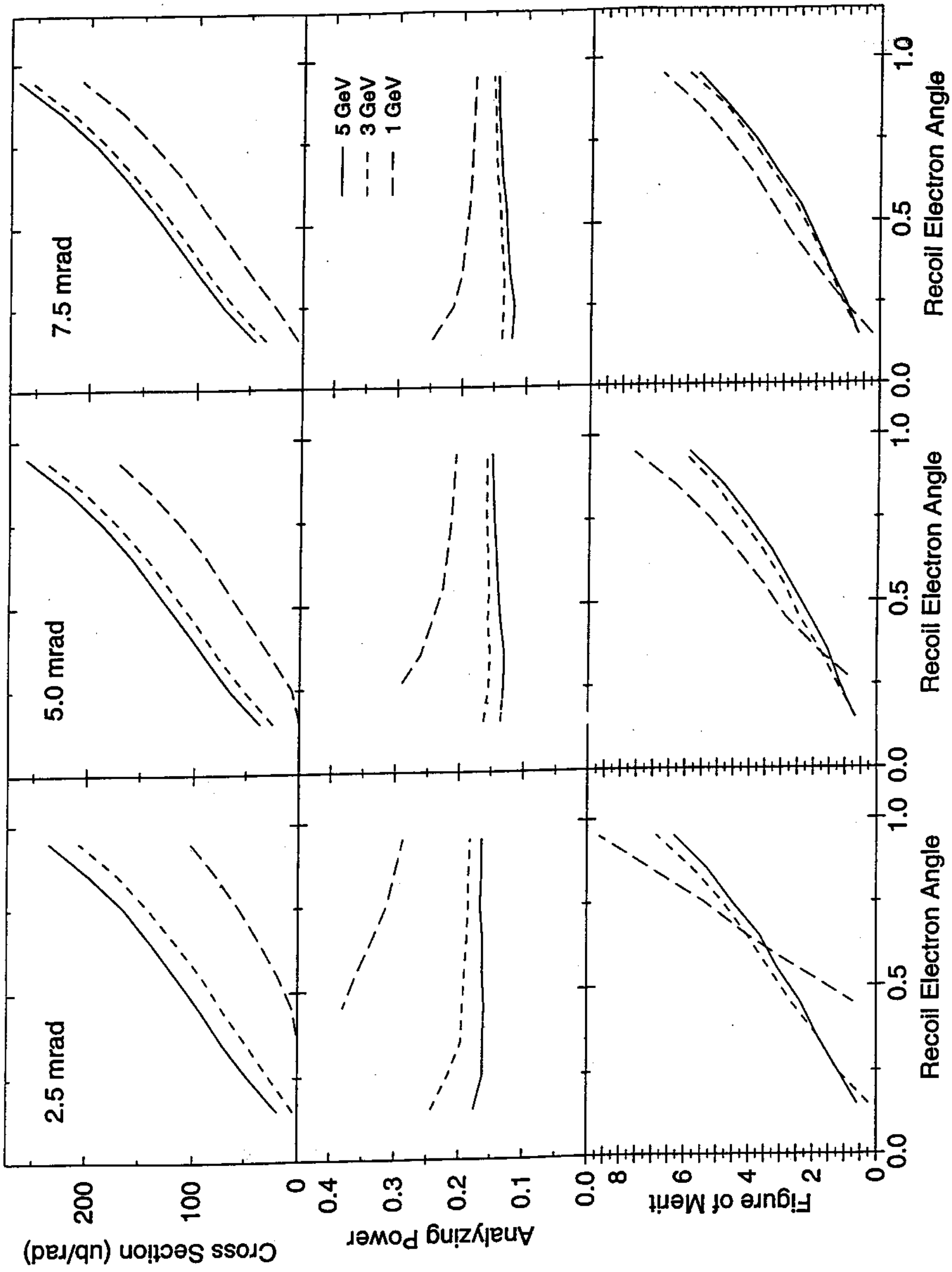

2.5 mrad
5.0 mrad
7.5 mrad
5 GeV
3 GeV
1 GeV
Cross Section (ub/rad)
200
100
0
Analyzing Power
0.4
0.3
0.2
0.1
0.0
Figure of Merit
8
6
4
2
0
Recoil Electron Angle
0.0
0.5
1.0

Fig. 4

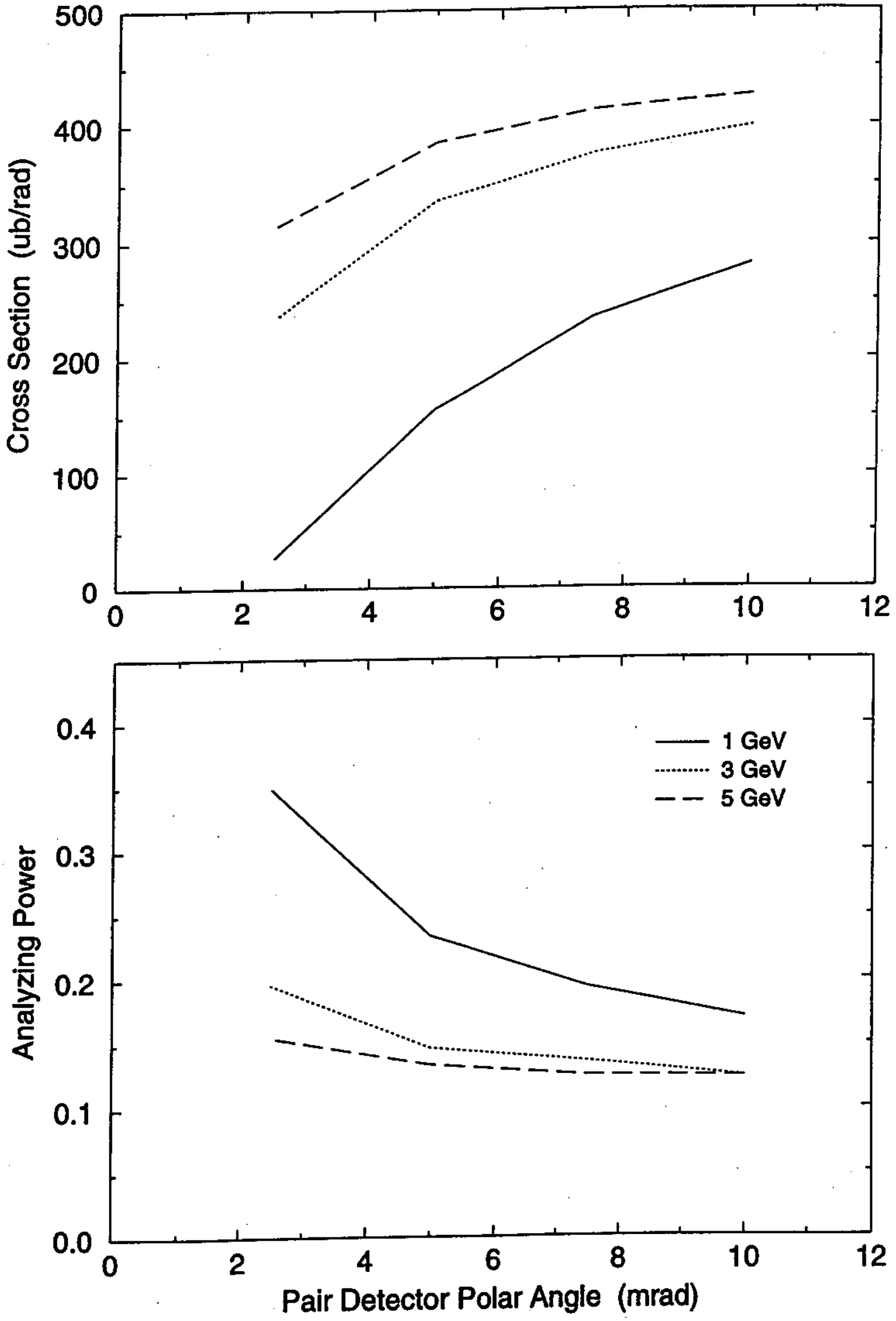
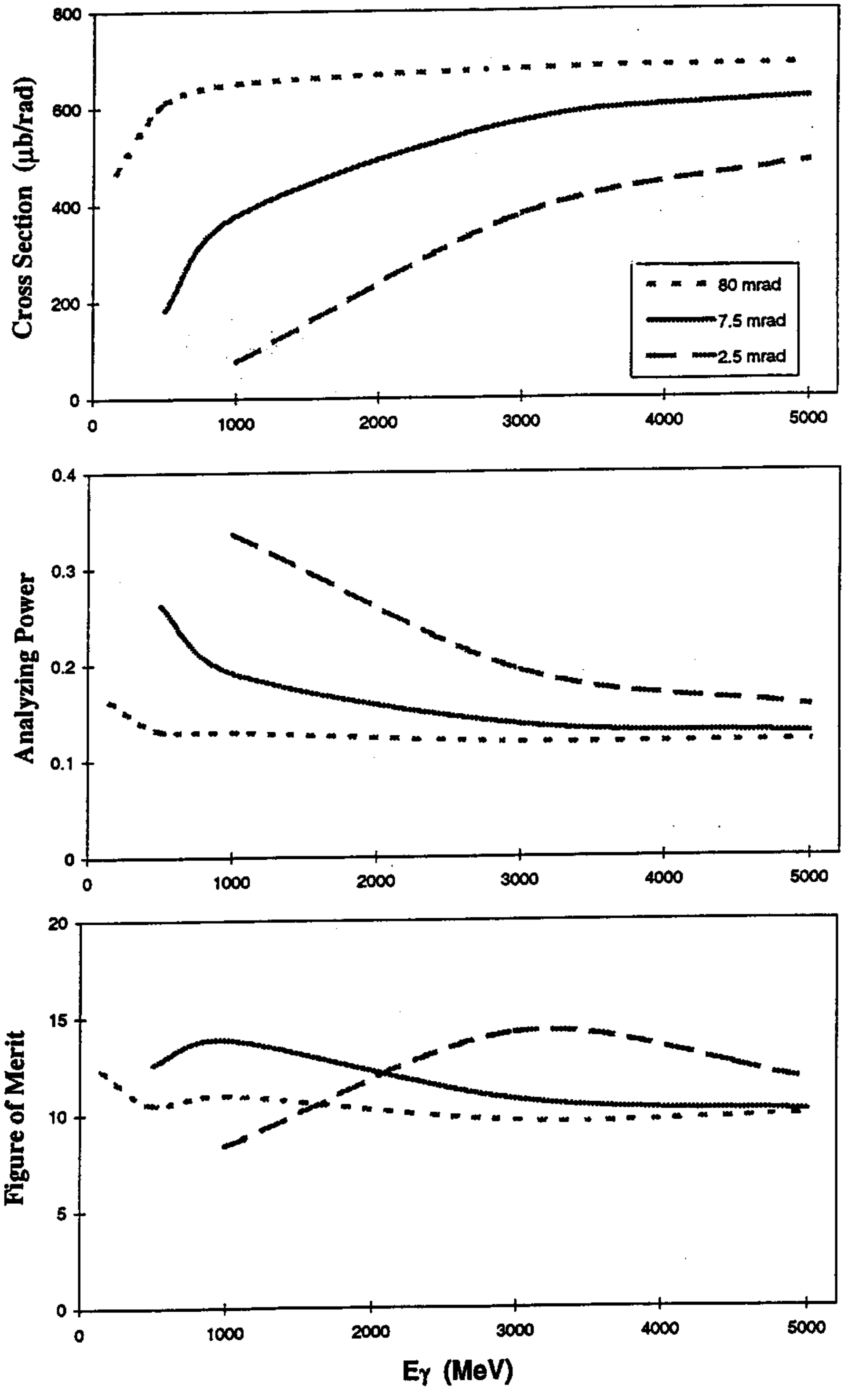

Cross Section (ub/rad)
500
400
300
200
100
0
0
2
4
6
8
10
12
Analyzing Power
0.4
0.3
0.2
0.1
0.0
1 GeV
3 GeV
5 GeV
Pair Detector Polar Angle (mrad)

Fig. 5



800
600
400
200
0
Cross Section (μb/rad)
80 mrad
7.5 mrad
2.5 mrad
0
1000
2000
3000
4000
5000
0.4
0.3
0.2
0.1
0
Analyzing Power
0
1000
2000
3000
4000
5000
20
15
10
5
0
Figure of Merit
0
1000
2000
3000
4000
5000
Eγ (MeV)

Fig. 6

Appendix D

Report of Working Group on Pair Production Technique

Polarized Photon Polarimetry

Thomas Jefferson National Accelerator Facility
June 2–3, 1998

Working group: *"Pair Production Technique"*
Coordinator: S. Danagoulian (NC A&T SU)

Two methods of pair production have been discussed in the group meeting:

- Coherent pair production using a crystalline target.
- Incoherent pair production in the amorphous target, the azimuthal asymmetry of production.

Existing equipments:

- Coherent pair production:
  - DESY; E_γ=(1–3) GeV.
  - Yerevan; E_γ=(0.6–3) GeV.
- Incoherent pair production:
  - Frascati; E_γ <0.5 GeV.
  - Tohoku (Japan); E_γ <0.5 GeV.

Below a comparative characteristics of both methods are presented.

I. COHERENT PAIR PRODUCTION

Presented by R. Avakian (Yerevan Physics Institute).

- Collaboration: Yerevan Physics Institute, University of South Carolina, Jefferson Lab.
- Method: measurement of the number of coherent e^+e^- pairs produced in the monocrystal when the polarization vector of the photon is parallel and perpendicular to the electric vector of the crystalline lattice. The method was applied successfully at DESY, and at Yerevan.
- Target: oriented monocrystal of diamond, thickness < 1 mm, mounted on the goniometric system with three axes of rotation. Angular accuracy $\sim 10^{-4}$ rad..
- Detector: detection system of pair spectrometer.
- Energy interval: 0.5 GeV – tagger/beam-dump.
- Analyzing power: (5–15)% at E_γ=(0.5–2) GeV and higher at higher energies.
- Efficiency: $\sim 10^{-3}$.
- Accuracy: $< 5\%$ (the systematic error due to the angular accuracy of the crystal orientation $< 1\%$).
- Data acquisition time: parasitic mode, $\sim$ 2 hours.
- Availability: high precision goniometer and crystalline targets are available. Goniometer needs upgrade.
- Reproducibility: at the level of 100%.
- Required space: < 0.5 m.
- Required equipment: pair spectrometer with energy resolution (1–2)%.
- Time schedule: design of the vacuum chamber by 9/1/98, installation and commissioning, end of 1999.

Polarized Photon Polarimetry

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- Required space: < 0.5 m.
- Required equipment: pair spectrometer with energy resolution (1–2)%.
- Time schedule: design of the vacuum chamber by 9/1/98, installation and commissioning, end of 1999.

The second polarimeter based on the measurement of the azimuthal asymmetry of pair production in the amorphous target is in the testing stage of the project. The calculations, including analytical and Monte Carlo simulation, have been accomplished demonstrating high analyzing power in the energy region starting at relatively low energy of photons. The detection system based on high resolution microstrip detectors have been studied in details. The design of the polarimeter is in progress.

- Advantages:
  - High analyzing power, almost independent of the photon energy.
  - May be used in parasitic mode.
  - Does not need absolute normalization.
  - The quality of the target material is not an issue.
- Disadvantages:
  - The method has never been tested before.
  - Sensitive to the multiple scattering of produced pairs in the remaining thickness of the target.
  - Complicated and expensive readout system of the microstrip detectors.
  - The microstrip detector must be homogenous at the level of a few percent.
  - Microstip detector ageing (loss of homogeneity with time).
  - The polarimeter must be constructed from scratch and tested.

Both polarimeters need an energy measurement of the pairs at the level of (1–2)%. High energy resolution is necessary for reduction of accidentals. Thus, for any of these methods the construction of a high resolution pair spectrometer is important.

MEASUREMENT OF THE PHOTON BEAM POLARIZATION AT THE YEREVAN ELECTRON SYNCHROTRON

R.O.Avakian, *A.A.Armaganian*, *L.G.Arutiunian*, *G.A.Vartapetian*,
A.G.Iskandarian, *R.M.Mirzoian* and *G.M.Elbakian*.

Izv. Akad. Nauk Arm. SSR, Fizika, 9, 252-255, 1974

As it has been reported earlier [1] a quasimonochromatic photon beam was produced at Yerevan Synchrotron with the help of coherent bremsstrahlung of 4.5GeV electrons on diamond crystal.

Fig.1 shows the bremsstrahlung spectrum from diamond target. The photon peak energy is 1.5 Gev. The inverse lattice vector $[2\bar{2}0]$, gives the main contribution into the cross section.

In this work it has been carried out the measurement of the polarization of the 1.5Gev photons in the spectrum with the above given parameters. The polarization has been measured by the method proposed in the work [2,3]. The method is based on the fact that in the case of the coherent electron-positron pair production in single crystal there is an asymmetry depending on the direction of photon polarization with respect to the plane $[[110], \vec{k}]$.In the case of completely polarized photons the asymmetry depends on primary photon energy k and on the photon angle of entrance into crystal. It is defined as

$$R = \frac{d\sigma_{\perp} - d\sigma_{\parallel}}{d\sigma_{\perp} + d\sigma_{\parallel}} \qquad (1)$$

where $d\sigma_{\perp}$ and $d\sigma_{\parallel}$ are the theoretical differential cross sections of electron-positron pair production by photons the polarization vector of wich is perpendicular to the chosen plane $[[110], \vec{k}]$ and lies in it.

In the experiment it is necessary to achieve such conditiens for which R is maximal. The experimental arrangement is described in the work [1] with such a modification that now a diamond crystal placed in a goniometer is in the pair spectrometer magnet. The goniometer allowed to rotate the crystallic convertor around the horizontal and vertical axis with an accuracy ±0.12 mrad and rotate 90^0 around the beam axis with acueracy

$\pm 1^0$.It was measured the numbers of symmetrical ($y = E_\pm/k = 0.5, E_\pm$ is the positron or electron energy) pairs $N_\|$ and $N_\perp$ when the photon polarization vector $\vec{\varepsilon}$ lies in the plane [[110], $\vec{k}$] and is perpendicular to it. We measured also the corresponding values $N'_\|$ and $N'_\perp$ for the same angle of photon entrance into the crystal. The measurements were corried for entrance angles when R is maximal. The polar angle Θ (the angle between the axis [110] and $\vec{k}$) was equal to 71mrad, while the azimuthal angle $\alpha = 0$.

Having four experimentally measured magnitudes $N_\|$, $N_\perp$, $N'_\|$ and $N'_\perp$ one can determine the degree of polarization by three different methods:

$$P_1 = \frac{1}{R}\frac{N_\| - N_\perp}{N_\| + N_\perp}, \tag{2}$$

$$P_2 = \frac{N_\|/\sigma_1^\| - N'_\|/\sigma_{min}^\|}{RN_\|/\sigma_{min}^\| - R_{min}N_\|/\sigma_1^\|} \tag{3}$$

$$P_3 = \frac{1}{R_0}\frac{(N_\| - N'_\|) - (N_\perp - N'_\perp)}{(N_\| - N'_\|) + (N_\perp - N'_\perp)} \tag{4}$$

were the following notations are used: R is the theoretical asymmetry for the given orientation of the diamond convertor at the first main maximum with main contribution from the first inverse lattice plane $n_3 = 1$, $\Theta = 71$ mrad; R_{min} is the theoretical asymmetry at the minimum of the first peak for the angle $\Theta = 71$ mrad when the first inverse lattice plane does not given any contribution into the cross section; R_0 is the theoretical asymmetry without taking into account the noncoherent part of the cross section of electron-positron pair production by polarized photons; $\sigma_1^\|$, $\sigma_{min}^\|$ are the cross section of electron-positron pair production by photons polarized parallelly at the maximum and minimum.

Experimental measurements	Theoretical values
$N_\| = 9100$	R=0.083
$N'_\| = 7760$	$R_{min} = 0.002$
$N_\perp = 8000$	$R_0 = 0.66$
$N'_\perp = 7640$	$\sigma_1^\| = 14.07$
	$\sigma_{min}^\| = 11.03$

The results of the experimentally measured and theoretical values used for the determination of the polarization are given in the Table. The experimental results are given in Fig.2. The polarization values, calculated with the help of the above given formulae are:

$$P_1 = 0.775 \pm 0.076,$$
$$P_2 = 0.931 \pm 0.122,$$
$$P_3 = 0.873 \pm 0.096.$$

The averag value of polarization is equal to 0.859 ± 0.098. This value is in good agreement with the result of the work[4]

Yerevan Physics Institute

References

[1] R.O.Avakian et al, Izv. AN Arm SSR, 6, (1971).

[2] G. Barbiellini et al. Nuovo Cim., 28, 435 (1963).

[3] L. Criegee et al. Phys. Rev. Lett, 16, 1031(1966).

[4] V.G.Gorbienko et al, Yadernaya Fizika 4, 793 (1973).

Figure Captions

Fig.1. The 4.5 GeV electron bremsstrahlung spectrum produced $6.4 \cdot 10^{-4}$ rad. length thick diamond crystal.

Fig.2. The dependence of the symmetrical electron-positron pair production on the photon entrance angle at energy 1.5 GeV. The solid curve ($\sigma^{||}$) and the dashed curve ($\sigma^{\perp}$ are the e^+e^- pair production cross sections by photons polarized parallely and perpendicularly to the plane $[[110], \vec{k}]$.

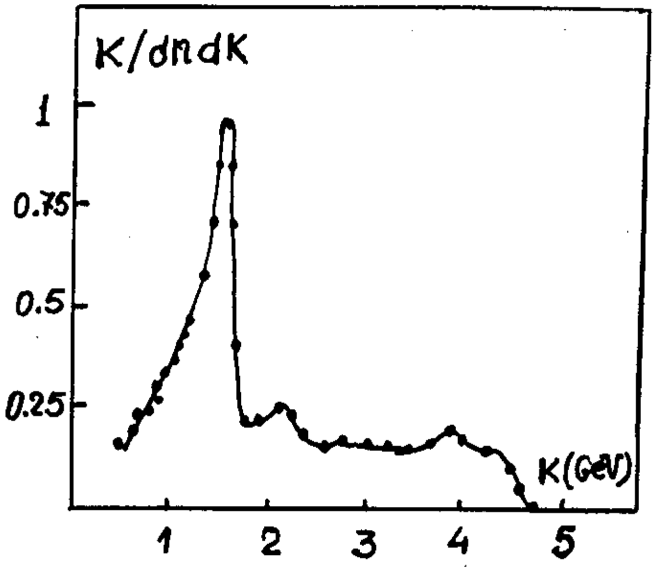

K/dndK
1
0.75
0.5
0.25
K(GeV)
1
2
3
4
5

Fig. 1

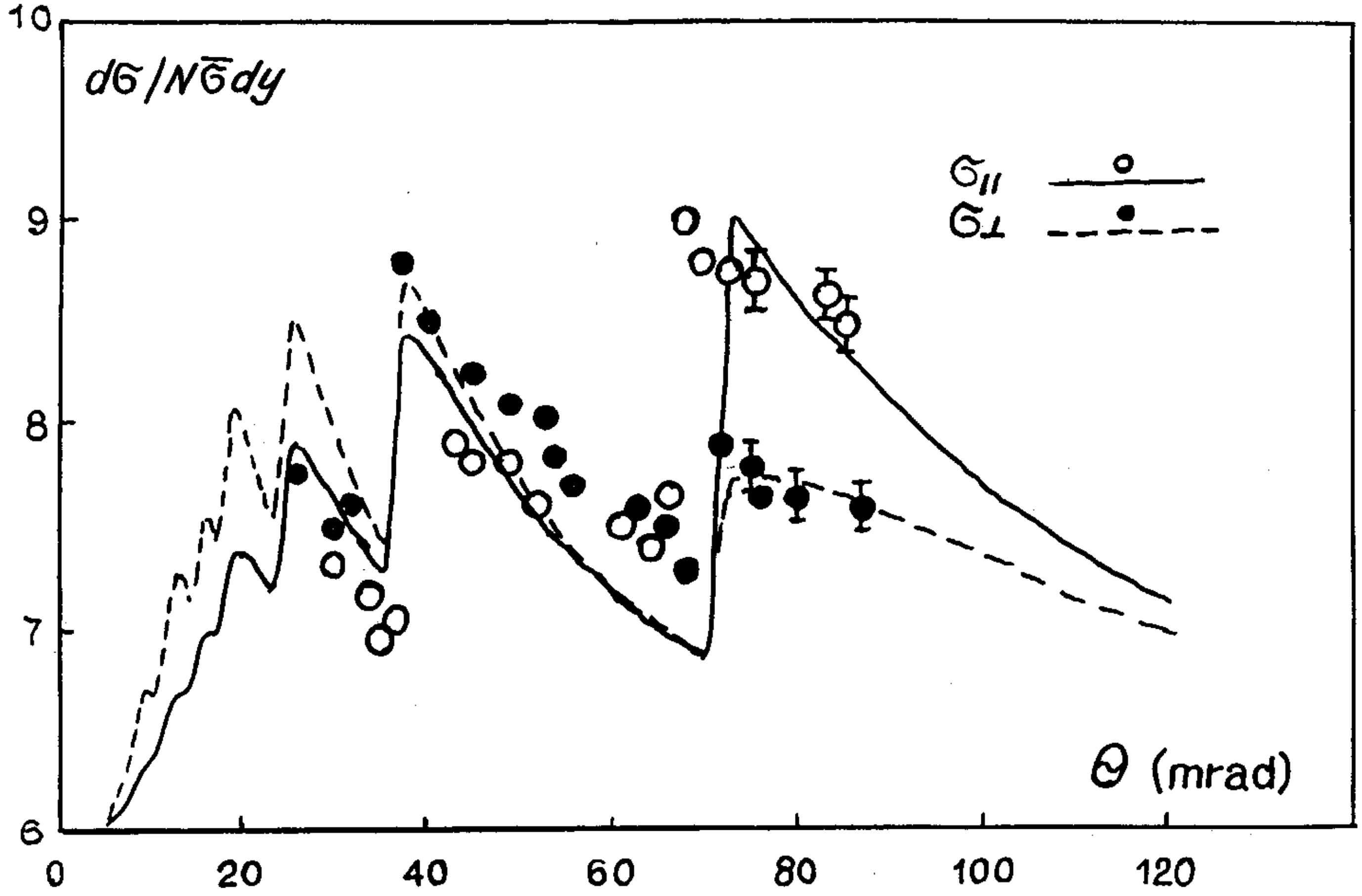
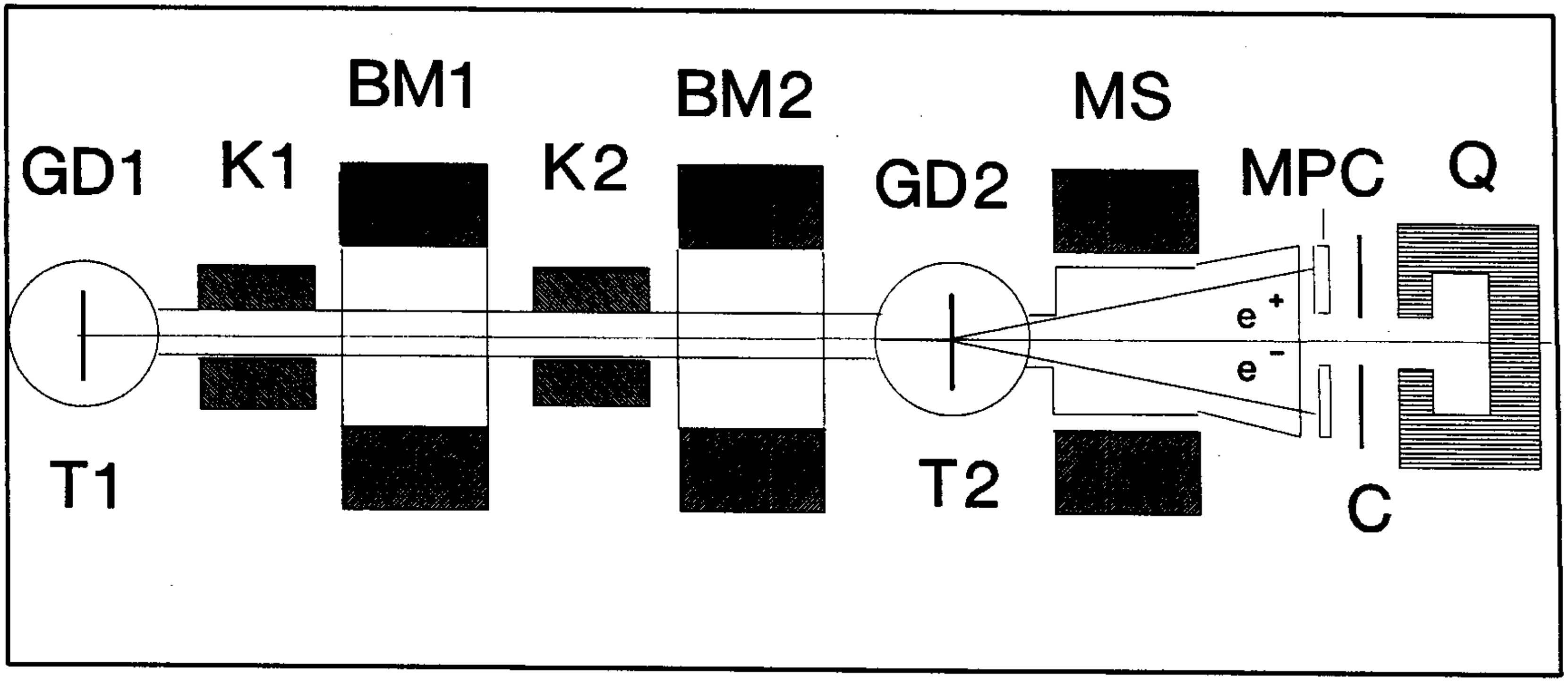
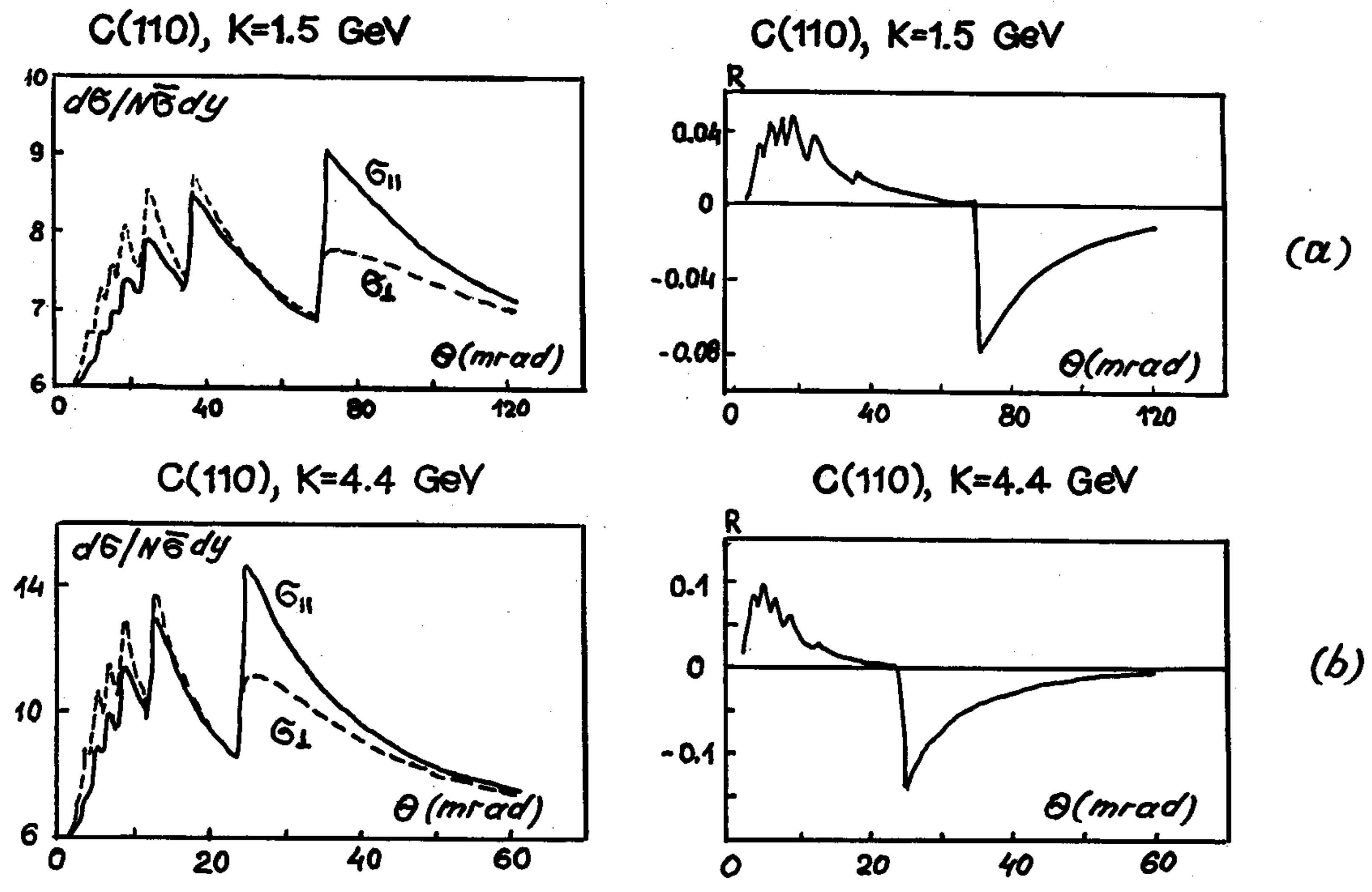

dσ/Nσdy
σ∥ ○
σ⊥ ●
θ (mrad)
10
9
8
7
6
0
20
40
60
80
100
120

Fig. 2

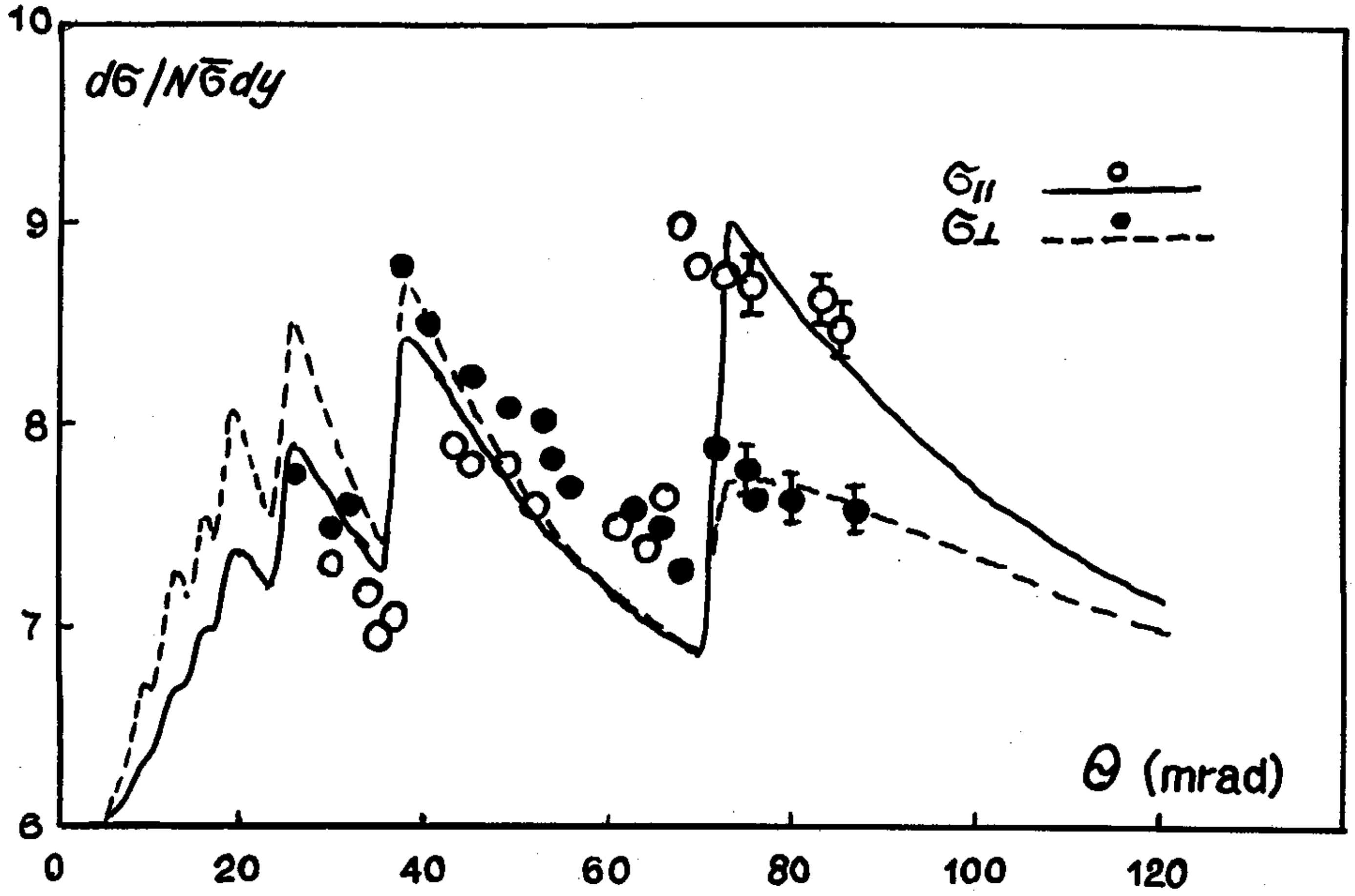


Experimental layout: T- crystal target; GD- goniometric device; K- collimator; BM - bending magnet; MS - magnet spectrometer; Q - quantometer.



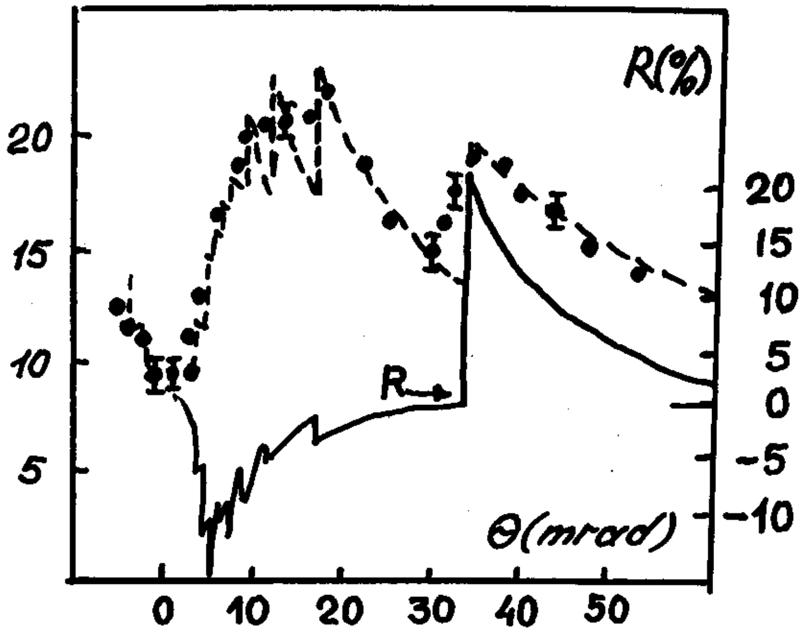
e^+e^- pair production from $K = 1.5$ GeV (α) and $K = 4,4$ GeV (b) linearly polarized photons in a diamond crystal. θ - angle between the photon and the crystal axis [110]. $R = (\sigma_{\perp} - \sigma_{\parallel})/(\sigma_{\perp} + \sigma_{\parallel})$

R. Avakian et al.
Izv. AN Arm SSR, 9, 252 (1974)

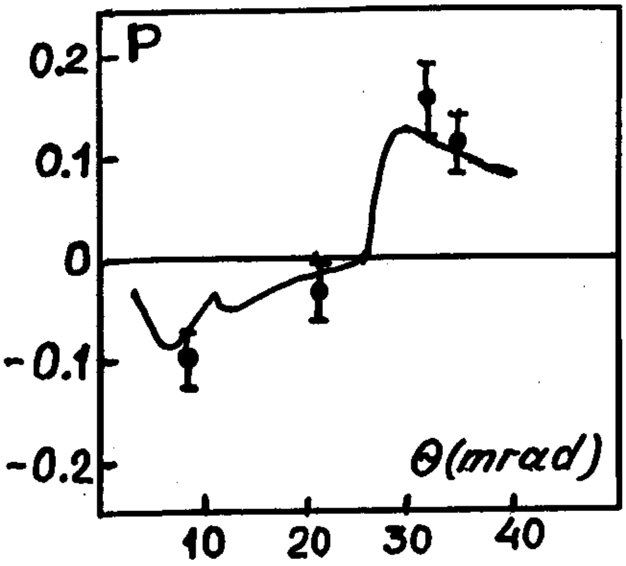


e^+e^- - pair production from K = 1.5 GeV linearli polarized photons in a diamond. θ - angle between the primary photon and the crystal axis [110].

R. Avakian et al.
Izv. AN Arm SSR, 10, 423 (1975)



e^+e^--pair production from K = 4.4 GeV nonpolarized photons in a diamond.



Polarization of photons K = 4.4 GeV

Polarimeter for high energy photons

Bogdan Wojtsekhowski[#],
Branislav Vlahovic[*], and Samuel Danagulian[%]

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* *NC Central University, Durham, NC*
% *A&T State University, NC*

Abstract. The physics program at TJNAF includes fundamental experiments with polarized photon beam in few GeV energy range. Development of the Polarimeter for use in Hall B experiments is the subject of present Technical Note. We have proposed to take advantage of the recent progress in silicon micro strip detectors for measurement of the geometry and angle correlation in electron positron pair production from an amorphous converter. A detailed analysis of the setup including MC simulation shows an experimental asymmetry $\sigma_{\parallel} / \sigma_{\perp} \sim 1.7$ in a wide range of the photon energies.

Introduction

The angle correlation in e^+e^-pair production by linear polarized photon was proposed for photon polarization measurements by Yang /1/ and Berlin & Madansky /2/. Accurate QED calculations with analysis of the possible experimental setup were done by L. Maximon and H. Olsen /3/. The effect was used succesfully for measurement of the beam polarization /4/. The limitation of the method at photon energy above 100 MeV arises from the small value of an angle between pair components. The realizations of the method /4,5/ were done by using a magnetic field for separation of the electrons and the positrons which caused considerable loss of analyzing power. Our proposal has the advantage of larger analyzing power and simplicity of setup.

The kinematics of the process is shown on Figure 1. The positron and electron have small angles ϑ_+, ϑ_- relatively to the direction of momentum of incident photon. The azimuth angles are φ_+, φ_-. They are the angles between photon polarization plane $(\vec{k}, \vec{x})$ and plane defined by momentum of the photon and momentum of outgoing particle (a positron or an electron). The opening angle between these planes is φ_{+-}. The angle $\omega_{\pm}$ between polarization plane and vector PN represents experimentally the most accessible parameter. Vector PN connects the crossing points of the positron and electron in the detector plane, which is perpendicular to the photon momentum.

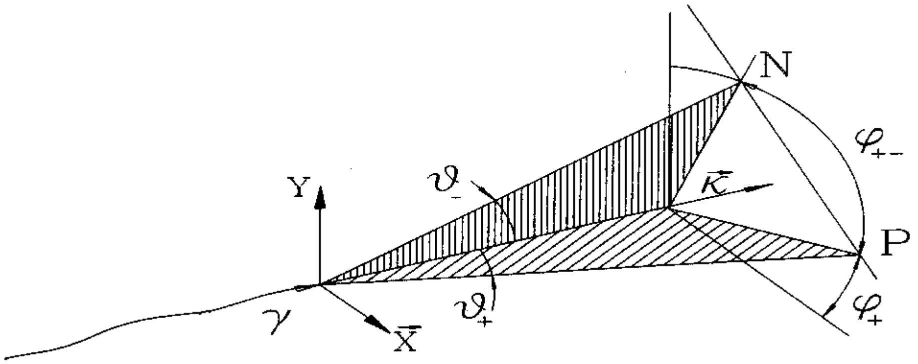

Figure 1. Kinematics of the pair production.

Because of the vector nature of the photon, the cross section of the $\gamma \to e^+e^-$ reaction has the following form:

$$d\sigma = \sigma_{sym} + \sigma_{asym} = \sigma_{unp} + P_\gamma \sigma_{pol} \cos(2\varphi_+ - 2\vartheta); \tag{1}$$

where σ_{sym} represents the part of cross section independent of the azimuth angle, σ_{sym} is corresponding to the unpolarized photon cross section σ_{unp}; σ_{asym} is azimuth dependent part of the cross section which is proportional to the beam polarization degree P_γ, σ_{pol}, and $\cos(2\varphi_+ - 2\vartheta)$; here ϑ is an angle shift which as well as σ_{pol} depends on the dynamics of electron-positron pair production. In the Born approximation for the ultra relativistic limit angle $\vartheta = 0$. The σ_{pol} is a slow smooth function of the photon energy and energy sharing between positron and electron. The main term of σ_{pol} is proportional to $E_+ \cdot E_- / E_\gamma^2$. In article /3/ an existence was found of important dependence of the σ_{pol} on the angle between photon-positron plane and photon-electron plane φ_{+-}. The asymmetry was defined by Maximon as $R = \dfrac{\sigma(\varphi_1 = 0)}{\sigma(\varphi_1 = \pi/2)}$ (where φ_1 is the same as our φ_+) is less then 1 for the complanar pair events, when angle φ_{+-} between γ-e$^+$ and γ-e$^-$ planes is close to π, and larger then 1 for events with $\varphi_{+-} < \pi - 0.034$ (exact value of the cut depends on the target charge Z).

The development of the silicon micro strip detectors for use in the vertex detectors of high energy physics experiments has advanced dramatically during the last few years. The most important features of these detectors are the capability to detect two tracks separated by a very small distance (~ 100 microns) and very good position resolution (~ a few microns). Because the typical opening angle in e^+e^- pair is about 1/γ and available space for Polarimeter is about 1 meter, the distance e^+e^- is about a fraction of mm. It means that at the photon energies of our interest, up to 6 GeV, most of pairs have a distance e^+e^- larger then the micro strip detector limitation.

Analysis of the cross section formula

We used the following expression for the pair production cross section /5/:

$$\frac{\partial^3\sigma_e}{\partial E_-\partial\Omega_-\partial\Omega_+}=\frac{\overline{\Phi}}{4\pi^2}\cdot\frac{\left[1-F(q)\right]^2}{\delta\cdot q^4}\cdot X_e; \tag{2}$$

where X_e is $\mathrm{X}_\parallel$ or $\mathrm{X}_\perp$, so that σ_e is the cross section for photon polarization vector $\vec{e}$ parallel or perpendicular to the direction of the axis x, which is indicated with suffixes $_\parallel$ and $_\perp$ respectively.

$$X_\parallel+X_\perp=\frac{4}{k\delta\Delta_+\Delta_-}\left\{\left(E_+^2+E_-^2\right)\times\left[\left(\xi_++\xi_-\right)^2+\left(\eta_++\eta_-\right)^2\right]+2E_+E_-\frac{\left(\Delta_+-\Delta_-\right)^2}{\Delta_+\Delta_-}\right\}; \tag{3}$$

$$X_\parallel-X_\perp=\frac{-4}{k\delta}2E_+E_-\left[\left(\frac{\xi_+}{\Delta_+}+\frac{\xi_-}{\Delta_-}\right)^2-\left(\frac{\eta_+}{\Delta_+}+\frac{\eta_-}{\Delta_-}\right)^2\right]; \tag{4}$$

where $\overline{\Phi}=\alpha r_0^2Z^2$; k is the photon energy; E_+ and E_- are energies of the positron and the electron; $\partial\Omega_+$ and $\partial\Omega_-$ are the elements of solid angles for the direction of a positron and an electron; Z is the charge of the target nuclei; α is fine structure constant; r_0 is the electron classical radius; $F(q)$ is the atomic form factor, $F(q)=1/\left[1+\left(111qZ^{-\frac{1}{3}}\right)^2\right]$; δ is the minimum momentum transfer, $\delta=k/\left(2E_+E_-\right)$; q^2 is the square of momentum transfer to the nuclei,

$$q^2=\left(\xi_++\xi_-\right)^2+\left(\eta_++\eta_-\right)^2+\delta^2\Delta_+\Delta_-+\left(\Delta_+-\Delta_-\right)\left(\frac{\Delta_+}{4E_+^2}-\frac{\Delta_-}{4E_-^2}\right); \tag{5}$$

where we used the combinations $\Delta_\pm=1+\xi_\pm^2+\eta_\pm^2$; the reduced plane angles $\xi_\pm$ and $\eta_\pm$ are defined as: $\xi_\pm=E_\pm x_\pm/L$ and $\eta_\pm=E_\pm y_\pm/L$; $x_\pm$ is the x coordinates of the positron (electron) on the detector plane; $y_\pm$ is the y coordinates of the positron (electron) on the detector plane; L is the distance between the target and the detector. The rest mass of the electron is used as a unit of the energy and momentum in this formula.

The asymmetry term is presented in Eq.4. In terms of angles φ_+, φ_- and $\delta_\pm^2 = \xi_\pm^2 + \eta_\pm^2$, it has the following form:

$$\mathrm{X}_{\shortparallel} - \mathrm{X}_\perp = \frac{4}{k\delta} 2E_+E_- \left[\left(\frac{\delta_+ \sin\varphi_+}{\Delta_+} + \frac{\delta_- \sin\varphi_-}{\Delta_-} \right)^2 - \left(\frac{\delta_+ \cos\varphi_+}{\Delta_+} + \frac{\delta_- \cos\varphi_-}{\Delta_-} \right)^2 \right]; \quad (6)$$

or $\sigma_{asym} \sim -\rho_+^2\left(\sin^2\varphi_+ - \cos^2\varphi_+\right) - \rho_-^2\left(\sin^2\varphi_- - \cos^2\varphi_-\right) -$

$$-2\rho_+\rho_-\left(\sin\varphi_+\sin\varphi_- - \cos\varphi_+\cos\varphi_-\right) = \rho_+^2\cos 2\varphi_+ + \rho_-^2\cos 2\varphi_- + 2\rho_+\rho_-\cos(\varphi_+ + \varphi_-) =$$
$$= \rho_+^2\cos 2\varphi_+ + \rho_-^2\cos 2(\varphi_+ - \varphi_{+-}) + 2\rho_+\rho_-\cos(2\varphi_+ - \varphi_{+-}); \quad (7)$$

where $\rho_\pm = \delta_\pm / \Delta_\pm$, $\varphi_{+-} = \varphi_+ - \varphi_-$. Because q^2 has dependence of $\cos\varphi_{+-}$, but not of individual angles φ_+ and φ_-, the terms in Eq.7, which are proportional to $\sin 2\varphi_{+-}$ and to $\sin\varphi_{+-}$, will not contribute into the cross section after integration over φ_{+-} from 0 to 2π. As a result , the expected $\cos 2\varphi_+$ dependence of asymmetry term become obvious.

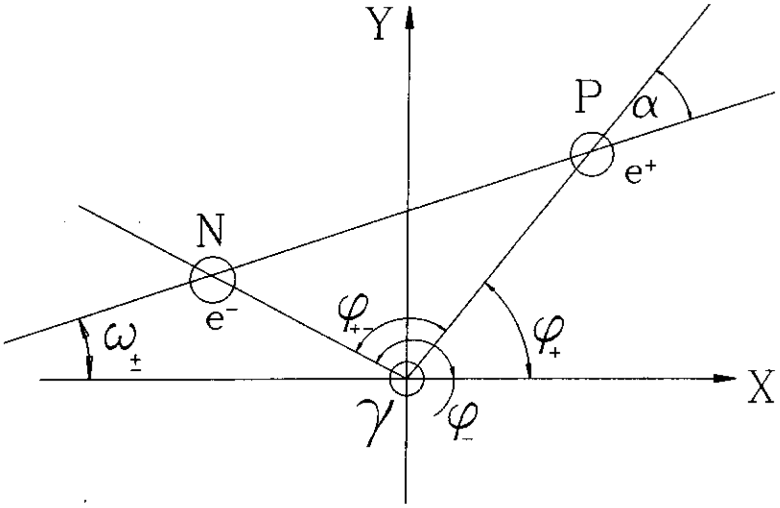

Figure 2. The event pattern on the micro strip detector plane.

Let us express the cross section as a function of angle $\omega_\pm$ (see Fig. 2).
By using expressions $\varphi_+ = \omega_\pm + \alpha$ and $\varphi_- = \omega_\pm + \alpha - \varphi_{+-}$ we can rewrite Eq.7 as:

$$\sigma_{asym} \sim \rho_+^2\cos 2(\omega_\pm + \alpha) + \rho_-^2\cos 2(\omega_\pm + \alpha - \varphi_{+-}) + 2\rho_+\rho_-\cos(2\omega_\pm + 2\alpha - \varphi_{+-}); \quad (8)$$

In our case of ϑ_+, $\vartheta_+ \ll 1$ the angle α can be found from an expression $\sin\alpha \approx \dfrac{\vartheta_-\sin\varphi_{+-}}{\sqrt{\vartheta_+^2 + \vartheta_-^2 - 2\vartheta_+\vartheta_-\cos\varphi_{+-}}}$.

When doing integration of σ_{asym} over φ_{+-} , we must use the expression of α from φ_{+-}. The α is an odd function of φ_{+-}. It is easy to see that the terms with $\sin 2\omega_{\pm}$ will not contribute to the result after integration over φ_{+-} because they are proportional to $\sin 2\alpha$, to $\sin 2(\alpha - \varphi_{+-})$, and to $\sin(2\alpha - \varphi_{+-})$. As result the σ_{asym} is proportional to the cos of angle $2\omega_{\pm}$ like it was for angle $2\varphi_{+}$. Numerical integration shows that the asymmetry in terms of $\omega_{\pm}$ is considerably larger than in terms of φ_{+}. It is also important to note that asymmetry does not depend on possible beam profile deformation.

Calculations of the cross section and asymmetry

For the analysis of the expected asymmetry we wrote a code which provides three dimensional integration of the cross section of Eq. 2-8 over electron and positron solid angles for fixed energy sharing between $e^{+}e^{-}$.

As the first test we used the code to reproduce the total cross section of the pair production. The results become correct after we fixed the wrong sign in article /5/ in the expression of the q^{2} and in the expression for $X_{\parallel} - X_{\perp}$. In the second test we compared our results for the asymmetry with analytical calculation /3/. It was done for 2 GeV photons, equal energies positrons and electrons, for the case of complete screening of the copper nuclei ($Z = 29$), at φ_{+-} angle integrated between 0 and $\pi - 4\cdot\beta$ or $\Delta\varphi/\beta = 4$ (see Fig. 4 in /3/). Maximon's result is $R = \dfrac{\sigma(\varphi_1 = 0)}{\sigma(\varphi_1 = \pi/2)} \approx 1.45$ (reading from Fig. 4 in /3/). Our result (in terms of φ_{+-} angle) for the same conditions is 1.443.

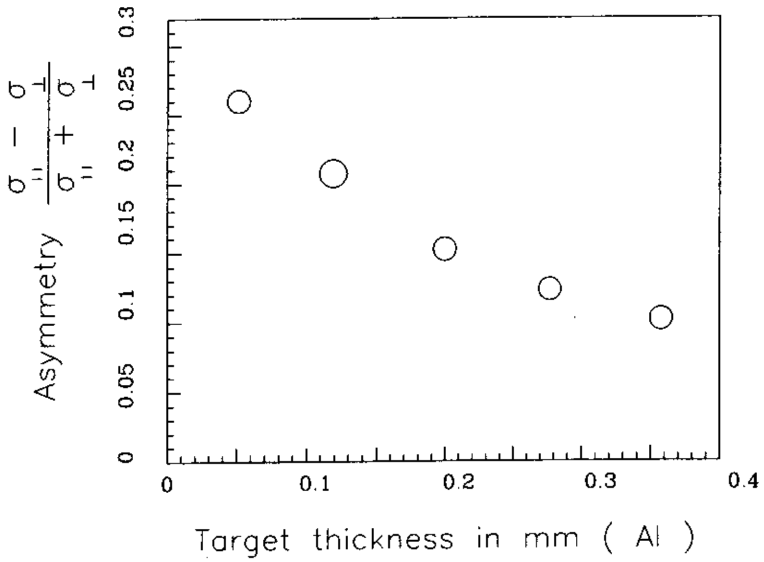

Figure 3. Effect of multiple scattering in the production target on polarization asymmetry.

The Monte Carlo simulation of the experiment was also done. It includes photon beam production, collimation, multiple scattering in the pair production target, alignment of the detectors, and detector position resolution. The output ntuple file was analyzed like it will be done for actual experimental data. This code allowed us to investigate all possible effects on analyzing power. The calculations of the asymmetry for 1 GeV photons, at equal energy positrons and electrons, are presented on Fig. 3. The analyzing power found from MC calculations for thin production target agrees strongly with the results of the analytical integration.

E_γ, GeV	0.5	1.0	2.0	4.0
$\sigma_{total} \cdot \frac{dE_{e^-} = mc^2}{E_\gamma \cdot \overline{\Phi}}$	$1.1*10^{-2}$	$6.0*10^{-3}$	$3.14*10^{-3}$	$1.60*10^{-3}$
For $d_{\min} = 0.0\ mm$ $\sigma_{\det} \cdot \frac{dE_{e^-} = mc^2}{E_\gamma \cdot \overline{\Phi}}$	$7.1*10^{-3}$	$5.2*10^{-3}$	$2.99*10^{-3}$	$1.56*10^{-3}$
For $d_{\min} = 0.5\ mm$ $\sigma_{\det} \cdot \frac{dE_{e^-} = mc^2}{E_\gamma \cdot \overline{\Phi}}$	$6.9*10^{-3}$	$4.9*10^{-3}$	$2.32*10^{-3}$	$0.69*10^{-3}$
$A = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$ for the angle $\omega_\pm$	0.291	0.289	0.282	0.241

Table 1. Asymmetry and effective cross section.

As it was explained in /3/, the light target provides larger analyzing power, so we did our calculation for Carbon which is the most practical light converter. We assumed a 10x10 mm size of the micro strip detectors and an 80 cm distance from the production target to the detector plane. The photon energy dependence for the cross section and asymmetry are presented in Table 1. Shown are total cross section σ_{total}, cross section integrated over detector area σ_{det} and asymmetry. The σ_{det} is calculated for all events (d_{min} = 0.0 mm) and for events with distance between positron and electron larger than 0.5 mm (d_{min} = 0.5 mm).

Scheme of the Polarimeter

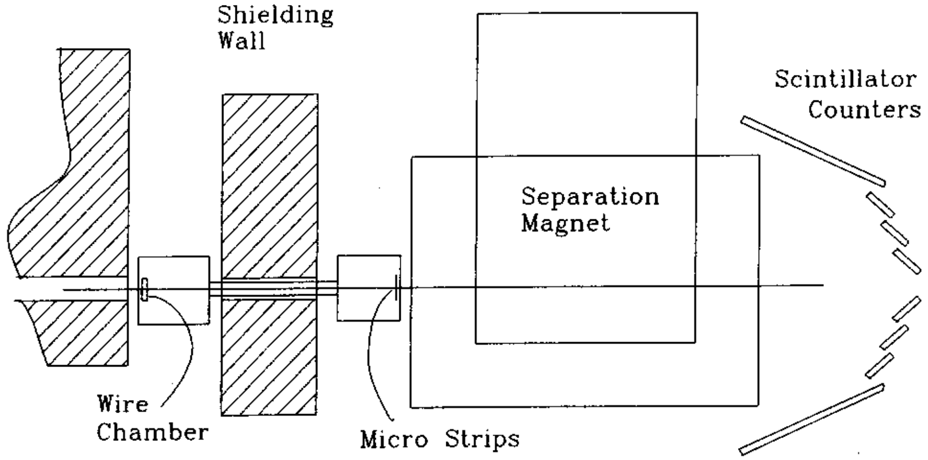

Figure 4. Layout of the photon Polarimeter

The Polarimeter needs a space of ~ 100 cm on the beam line. The distance from the conversion point of the photon to the detector of the electron/positron is about 80 cm.

The wire chamber is used as an active converter with a thickness of about 0.01% of the radiation length. It has an active area of about 20x20 mm. The gas windows are made from mylar film 5 microns thick. The field electrodes are located outside of an active area. The total thickness of the detector is 2 cm. The sensitive thickness will be about 1 cm of ethane gas at STP. The time resolution can be better than 50 nanoseconds.

The micro strip detectors have three layers for reconstruction of the coordinates of two particles. The size of the micro strip sensitive area is 10 x 10 mm. The inter strips distance is 50 microns which allows position resolution (sigma) of about 5 microns and two track separation of about 100 microns. The strips are connected to the flash ADC.

The μ metal shield between production target and the micro strip detectors protects pair components from the effect of the magnetic field.

The pair spectrometer used in our setup is an existing pair spectrometer located in the beam dump tunnel of Hall B.

Design considerations

The accuracy of the measurements of the angle correlation is limited by multiple scattering of the electron and positron in the pair production target. The opening angle between pair components is about $1/\gamma \sim 10^{-4}$. It requires us to keep the converter thickness ~ 0.01 % of the radiation length. This limitation is independent of the beam energy because multiple scattering is also inversely proportional to initial energy:

$$\theta_{+-} \approx \frac{mc^2}{E_\gamma} \quad \textit{must be} \gg \textit{than} \quad \theta_{mult} \sim \frac{14}{E_{+(-)}}\sqrt{t}\,; \tag{9}$$

where θ_{+-} is a pair opening angle, t is the target thickness in units of radiation length, $E_{+(-)} \sim E_\gamma / 2$ is the pair particle energy in MeV.

Analyzing power has a smooth maximum at equal energy of the positrons and the electrons. For minimization of the systematic uncertainty in the value of analyzing power some care must be taken in measurement of the energy acceptance of the pair detector. If $\Delta_{\min} \cdot E_\gamma$ is a minimum and $\Delta_{\max} \cdot E_\gamma$ is a maximum energies of the detected pair components, then the average analyzing power A_{aver} relates to maximum one $A_{1/2}$ (at $E_{+(-)} = E_\gamma / 2$) as $2 \cdot (\Delta_{\max} + \Delta_{\min}) - 4/3 \cdot (\Delta^2_{\max} + \Delta^2_{\min} + \Delta_{\max}\Delta_{\min}) = 1 - 4/3 \cdot (\delta^2_{\max} + {}$ ${} + \delta_{\max}\delta_{\min} + \delta^2_{\min})$, where $\delta_{\min(\max)} = 1/2 - \Delta_{\min(\max)}$. To get the systematic error of P_γ on the level 1%, one needs to know the value of $\delta_{\min(\max)}$ (which is about 0.1) with accuracy of about 0.01.

Counting rate considerations

The low thickness of the production target limits the counting rate, however it is already very large for conventional DAQ. The expected beam intensity is 10^7 per second of tagged photons. It will produce ~ 1 kHz of e^+e^- pairs to be detected in the active converter. The rate on the micro strip detectors and pair spectrometer (PS) will be 10 times higher because of larger thickness of the micro strip detectors (total ~ 0.5 mm). Because of limited acceptance of the PS, the actual rate of PS trigger will be a bit less.

The DAQ of the Polarimeter will use trigger based on coincidence of the PS trigger and signal from production target-active converter, which is a fast proportional chamber. The use of the active chamber allows us to reduce trigger rate to ~ 1 kHz. This data will be recorded for off line analysis. After the cut on minimum distance between positron and electron and software cut on the flat part of the pair spectrometer acceptance (assume 20%) we are expecting ~ 20 Hz of useful events. The expected asymmetry for these events is about R ~ 1.7. For the fit of the data to expected $\cos 2\omega_\pm$ dependence it is convenient to bin the histogram on the equal intervals of $\cos 2\omega_\pm$, so the asymmetry value can be extracted directly from the linear fit. The statistical uncertainty of the polarization is: $\sigma_{P_\gamma} = \dfrac{2}{\left(\dfrac{R-1}{R+1}\right) \cdot \sqrt{N_{events}}} \sim \dfrac{7.7}{\sqrt{N_{events}}}$. Our Polarimeter allows to measure polarization degree and also to find the direction of the polarization plane.

For the estimation of the time needed for ±0.05 accurate polarization measurement, let us assume that in every 1% energy interval the photon intensity is 10^5 per second. The polarization will be measured simultaneously in ~ 20% photon energy interval. The time of the measurement will be about 6 hours.

Conclusion

The proposed scheme of the photon Polarimeter provides a large analyzing power compact device which can work continuously during the experiment. The space on the beam line required is about 1 meter upstream of the CLAS pair spectrometer. The detectors used in proposed Polarimeter are well developed and can be constructed quickly. We also expressed asymmetry in terms of $\omega_{\pm}$, which has advantage that it does not depend on possible detector and beam asymmetries, and as was shown by numerical integration is larger than when it is expressed in terms of φ_{+}.

Additional analysis needs to be done on the intensity of the soft component of the photon spectra, which can give an increase of the detectors counting rate. The MC of the pair spectrometer acceptance needs to be done for more accurate calculation of the measurement time.

Acknowledgments

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Appendix E

Attenuation through Carbon Technique Polarimeter at SLAC

A Polarized Photon Beam Produced by Coherent Pair Production in Oriented Graphite

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Abstract

Attenuation by coherent pair production in highly oriented, compression annealed, pyrolytic graphite has been used to polarize 16-GeV bremsstrahlung beam. The polarizer consists of 61 cm of graphite crystals whose reciprocal lattice vectors are oriented at 10.5 mrad to the normal to the beam direction, and can be rotated by 90° about the beam line to rotate the plane of polarization. A functionally identical assembly of length 30.5 cm was used as an analyzer to measure the polarization of the beam with the SLAC pair polarimeter. The beam produced intensities greater than 4×10^8 equivalent quanta per beam pulse and had a measured polarization of (0.225 ± 0.020).

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