Subproject H7: Two Photon Exchange and Strangeness in the Nucleon


H7.1 Introduction

The A4 collaboration investigates the structure of the nucleon by measuring single spin asymmetries in the cross section of elastic scattering of polarized electrons off unpolarized nucleons. The polarization of the electron beam can be longitudinal as well as transverse giving access to different properties of the nucleon:

- With longitudinal polarization, a parity violating asymmetry can be measured from which the contribution of strange sea quarks to the vector form factors of the nucleon can be derived. Such an observation is of special interest since this is a pure sea quark effect.
- With transverse polarization, an asymmetry can be measured which arises primarily from the interference between one-photon and two-photon exchange amplitudes. This asymmetry allows to access the imaginary part of the two-photon exchange amplitude.

A detailed description of the A4 setup was given in the previous annual report [1]. In the years 2004/2005 the results of the measurements taken so far have been published in three Physical Review Letters (chap. H7.2 and H7.3). The main work in the past two years was spent on modifying the experimental setup in order to be able to put the lead fluoride calorimeter easily under forward angles as well as under backward angles to allow measurements with the same momentum transfers but with different kinematics (chap. H7.4 and H7.5). Furthermore, improvements on the Compton backscattering polarimeter could be achieved (chap. H7.6), the transmission Compton polarimeter was fully operational (chap. H7.7) and theoretical effort was spent on the understanding of the inelastic part of the energy spectra in order to determine the parity violating asymmetry in the range of the Δ(1232) resonance (chap. H7.8).


H7.2 Strangeness in the nucleon

Although there is no net strangeness in the nucleon, $s\bar{s}$ sea quarks can contribute to the properties of the nucleon. To investigate the contribution of strange quarks to the form factors of the nucleon, it is convenient to perform a flavour decomposition to distinguish between the different flavours $f$, omitting the heavy quarks,

$$G_{E,M}^{N} = \sum_{f=u,d,s} q_f G_{E,M}^{N,f} = \frac{2}{3} G_{E,M}^{N,u} - \frac{1}{3} G_{E,M}^{N,d} - \frac{1}{3} G_{E,M}^{N,s}$$  \hspace{1cm} (H7.1)

Using charge symmetry and the universality of the quark distribution, one can relate within the framework of the standard model the strange form factors of the proton $G_{E}^{p}$ and $G_{M}^{p}$ to the parity violating asymmetry $A_{PV}$ in the cross section of the elastic $\vec{e}p$-scattering [1]:

1
\[ A_{PV} = -\frac{G_p Q^2}{4\pi \alpha \sqrt{2}} \times \left[ \rho'_{\text{eq}} \left\{ \left( 1 - 4\varepsilon_{\text{eq}}^2 \right) - \frac{\varepsilon G_E^p G_M^p}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right\} \right. \\
+ \left. \frac{(1 - 4\varepsilon^2) \sqrt{1 - \varepsilon^2} \sqrt{(1 + \tau) G_M^p G_A^p}}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right] \\
+ \rho'_{\text{eq}} \left\{ \frac{\varepsilon G_E^p G_E^p + \tau G_M^p G_M^p}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right\} \]

The kinematic variables are \( \varepsilon = [1 + 2(1 + \tau) \tan^2 \frac{\Theta}{2}]^{-1} \) and \( \tau = \frac{Q^2}{4m_p} \), the standard model parameters \( \alpha, G_p, \tilde{\nu}_2 = \sin \tilde{\theta}_w \) and the electroweak radiative corrections \( \rho'_{\text{eq}} \) and \( \tilde{\rho}'_{\text{eq}} \) can be taken from the PDG [2]. \( G_{E,M}^p \) are the electromagnetic form factors of the proton and the neutron respectively, \( G_E^p \) is the weak axial form factor of the proton. At forward scattering angles one can extract from an experimentally measured asymmetry \( A_{PV} \) a linear combination of the strange form factors \( G_E^p + k \cdot G_M^p \), at backward angles the asymmetry is primarily sensitive to \( G_M^p \).

Figure H7.1: \( G_E^p \) vs. \( G_M^p \) at \( Q^2 = 0.23 \) (GeV/c)\(^2\) (left) and \( Q^2 = 0.11 \) (GeV/c)\(^2\) (right). The thick line shows the linear combination, the grey band gives the possible values within the 1\( \sigma \) range. For the low momentum transfer result for the SAMPLE collaboration is also shown (right, light grey) [5]. The ellipse shows the overlap of the SAMPLE and A4 data within the 1\( \sigma \) range.

The results of two measurements at forward angles \( 30^\circ \leq \theta \leq 40^\circ \) corresponding to the momentum transfers \( Q^2 = 0.23\) (GeV/c)\(^2\) and \( Q^2 = 0.11\) (GeV/c)\(^2\) have been published in 2004 and 2005 [3, 4]. The linear combinations are \( G_E^p + 0.225G_M^p = 0.039 \pm 0.034 \) and \( G_E^p + 0.106G_M^p = 0.071 \pm 0.036 \) respectively. Fig. H7.1 shows the linear combinations of strange electric and magnetic form factor within a 1\( \sigma \) range. For a separate determination of \( G_E^p \) and \( G_M^p \) it is necessary to measure the asymmetry \( A_{PV} \) with different kinematics, but with the same momentum transfer \( Q^2 \). Therefore in the years 2004 and 2005 the lead fluoride calorimeter was prepared for backward angle measurements (chap. H7.4).

**Bibliography**

H7.3 Two Photon Exchange

The electromagnetic interaction in the elastic electron-proton scattering is described in first order by the Born approximation with the exchange of one virtual photon. A process of second order is the exchange of two virtual photons (fig. H7.2). An experimental access to the two-photon exchange amplitude is of interest since only the proton ground state contribution can be calculated strictly within QED, the calculation of the contribution of higher states is model dependent. There are hints that the two-photon amplitude might be underestimated at higher momentum transfers and that this could explain a discrepancy which exists in the determination of the ratio $G_p^E/G_M^p$ between the Rosenbluth separation technique and the polarization transfer experiments [1].

An experimental access to the imaginary part of the two-photon amplitude is possible through the measurement of single spin asymmetries in elastic $ep$-scattering [2]. The scattering amplitude taking into account the exchange of more than one photon can be described by introducing six complex functions $\hat{G}_M, \hat{F}_2, \hat{F}_3, \hat{F}_4, \hat{F}_5$ and $\hat{F}_6$, which depend on $s$ and $Q^2$. In the Born limit the first two functions turn into the well-known electromagnetic form factors, the other ones vanish:

$$\hat{G}_M^{\text{Born}}(s, Q^2) \rightarrow G_M(Q^2)$$
$$\hat{F}_2^{\text{Born}}(s, Q^2) \rightarrow F_2(Q^2)$$
$$\hat{F}_{3,4,5,6}^{\text{Born}} \rightarrow 0$$
The so-called beam normal spin asymmetry \( A_\perp \) is defined as the asymmetry in the cross sections for the electron spin parallel \((\sigma_\parallel)\) and antiparallel \((\sigma_\perp)\) to the polarization normal vector \( \vec{S}_n = (\vec{k} \times \vec{k}')/|\vec{k} \times \vec{k}'| \) (see fig. H7.3):

\[
A_\perp = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}
\] (H7.2)

This asymmetry is related to the imaginary part of two photon exchange processes [2]:

\[
A_\perp = \frac{2m_e}{Q} \sqrt{2\epsilon(1-\epsilon)} \sqrt{1 + \frac{1}{\tau} \left( G_M^2 + \frac{\epsilon}{\tau} G_E^2 \right)^{-1}} \times \left\{ -\tau G_M \text{Im} \left( \hat{F}_3 + \frac{1}{1 + \tau M^2} \hat{F}_3 \right) - G_E \text{Im} \left( \hat{F}_4 + \frac{1}{1 + \tau M^2} \hat{F}_4 \right) \right\}
\]

where \( \nu \) is the energy transfer onto the proton and \( \tau \) and \( \epsilon \) are kinematic parameters as defined in the previous chapter.

In 2005, the results of two measurements at forward angles with momentum transfers of \( Q^2 = 0.23(\text{GeV}/c)^2 \) and \( Q^2 = 0.11(\text{GeV}/c)^2 \) have been published [3]. Fig. H7.4 shows the results together with model calculations from [2]. One can clearly see that the ground state contribution to the asymmetry is small and cannot explain the experimental asymmetries, so inelastic intermediate states play an important role. The calculations for backward angles predict asymmetries of the order of \( 100 \cdot 10^{-6} \) for beam energies between 300 MeV and 420 MeV. With the new setup of the lead fluoride calorimeter, such asymmetries can be measured with a statistic precision of 10% within 50 hours of data taking.

**Bibliography**


Figure H7.4: Values for the beam normal spin asymmetry $A_{\perp}$ determined by the A4 experiment at two momentum transfers together with model calculations from [2]. The dashed-dotted line represents the asymmetry arising only from the ground state contribution, the dashed line shows the asymmetry arising from excited $\pi N$ intermediate states, the solid line is the sum of the two contributions. The ground state contribution is small and can not explain the experimental asymmetries.

H7.4 Rearrangement of the A4 calorimeter for the measurement at backward angles.

Figure H7.5: The new scattering chamber. The electron beam enters from the left. The left picture shows the forward, the right one the backward scattering configuration. For the backward configuration, an elongation of the scattering chamber is necessary so that both the calorimeter and the luminosity monitors point to the target under the correct angles.

With the existing setup of the lead fluoride calorimeter there was no easy way to put it under backward angles. It was not possible to rotate the calorimeter. One could only translate it along the beam axis to set its focus on the target and to remove the scattering chamber. Also the scattering chamber was not movable at all. Fig. H7.5 shows the angular acceptance of the calorimeter and the luminosity monitors for the forward and the backward scattering configuration. One can see that not only the crystals of the calorimeter, but also the luminosity monitors
have to focus under a definite angle on the target. To avoid a mounting of the luminosity monitors to the beamline support during backward measurements, a scattering chamber elongation (fig. H7.5) was needed. Fig. H7.6 presents the new structure resulting from these requirements. The calorimeter and the scattering chamber are both mounted on a support which is rotatable around the target.

Figure H7.6: Rearranged A4 hall. The electron beam enters from the left. The calorimeter is positioned on a rotatable platform. The luminosity monitors (not shown on picture) are mounted on the downstream flange of the scattering chamber.

The setup can now be rearranged for forward or backward scattering measurements within a few days: The cables and the two flanges of the scattering chamber are removed and then the setup is rotated by 180°. After this, the flanges are remounted so that the luminosity monitors are always on the downstream side of the scattering chamber, and the cables are put back. The rotatable support with its ground plate is shown in fig. H7.7. In order to ensure a vibration free, shock free and easy positioning of the calorimeter, it is supported by three hydraulic oil sliding feed. Fig. H7.8 shows the new experimental setup. It ensures an easy and fast rearrangement for measurements at forward and backward angles. The rearrangement started in August 2004 with the dismantling of the old setup, and ended in May 2005 with the cabling of the new experimental setup. First measurements have been taken at the middle of May 2005.
Figure H7.7: Rotatable platform. The platform is mounted on three hydraulic oil sliding feet to avoid vibrations and shocks during rotation and positioning.

Figure H7.8: New experimental setup. An easy and fast rearrangement for measurements at forward and backward angles is ensured.
H7.5 Development of an additional scintillator trigger system

After turning the A4-detector to backward angles, first measurements showed that the elastic events in the energy spectrum were not separated from background events, in contrast to the forward angles measurements, where a clean separation is possible. Hence it was necessary to install an additional detector system to separate the elastic events (charged particles) from the inelastic events (mostly $\gamma$'s). This new trigger system should work for all 1022 detector crystals and electronic modules.

In the first half of 2005 tests were performed to determine the best material for the detector. Tests with isobutan gas (Cherenkov radiator) resulted in too low efficiency. Tests with aerogel Cherenkov radiators and plastic scintillators yielded sufficient energy resolution and efficiency. Due to the low costs the plastic material, EJ-204 from Eljen Technologies was chosen. The photomultiplier tubes we use are fast 12-stage XP-2262B from Photonis. However, the corresponding passive bases (VD122K) had linearity breakdown effects at high beam currents and rates. Because of this, we developed in cooperation with the electronic workshop a complementary 12-stage active base. Fig. H7.9 shows a single scintillation trigger detector as it is now used in the A4-experiment.

Since the elastic rates at backward angles are at around 1 kHz per crystal only (at a beam current of 20 $\mu$A and an energy of 315 MeV), it was sufficient to install a setup with 72 scintillators for the 1022 calorimeter channels. Each scintillator covers two rows of seven crystals each. Fig. H7.10 shows the final setup with the 72 scintillators and the steel support that was placed around the target chamber in the experimental hall 4. To fit all scintillator modules into the available space between target chamber and the calorimeter, they are arranged in two mutually interspaced rings at 5 and 10 cm distance in front of the PbF$_2$ crystals.

For the signal analysis and trigger generation, we developed an electronic upgrade to the existing data acquisition electronics (Medusa). Fig. H7.11 demonstrates the working principle of the newly installed system: The PM signals are guided from experimental hall 4 via fast cable (LL1030AF, Elspec) to the electronics in experimental hall 3. The signals are splitted and feeded into CFD discriminators to obtain a low and a high threshold. This is done using a passive y-circuit with an impedance of 50 $\Omega$. For the discrimination we used 10 VME based constant fraction discriminators (CAEN V812, 16-channel). The discriminator signal outputs (ECL) then have to be linked (logic AND), time adjusted and distributed to the data acquisition electronics of the 14 corresponding detector channels. For this purpose, we developed a multi layer printed circuit board (scintillator trigger card) with fast LVDS-gates and programmable delay gates, which can be manipulated via VME-access by standard output-modules. This has to be done in order to center the scintillation trigger signal properly into the ordinary Medusa event trigger gate which has a width of 20 ns. Each logical output signal is then used as address bit for the corresponding medusa histogramming memory. This was possible, because
(for future developments) in the original setup of the Medusa readout electronics 16 address-to-memory-bits were installed, though only 15 used bits have been used so far. The global trigger to memorize an event is still set by the Medusa electronics, while the new scintillator signal determines one of two possible memory locations. For the proper connection of the 15 address bits from the Medusa electronics and the new additional bit from the scintillation trigger, 1022 additional printed circuit boards (trigger connect) have been attached to the existing histogramming modules.

Fig. H7.12 shows the energy spectrum of a single channel of the PbF$_2$ calorimeter. The dotted line shows the spectrum without scintillation trigger, the solid line the spectrum with scintillation trigger bit set. In the spectrum with scintillation trigger bit one can identify the elastic
rate and holding it at constant level by increasing the corresponding high voltage. At present, calibrated approximately once per day. The calibration is done by measuring the scintillation procedures and data acquisition of the polarimeter have been introduced. We have investigated significantly improved. We received three heatable getter sorption pumps from MIT Bates under the linear polarizing prism. It is located underneath a vacuum window placed under 45° the middle of 2004 the vacuum conditions inside the polarimeter beamline have been significantly the suitability of different materials for our photon detector and have implemented a routine we were able to reach a pressure of $4 \cdot 10^{-8}$ mbar, ten times better than before. During two test-beamtimes in June and August 2005, several improvements on the photon detector calibration procedures and data acquisition of the polarimeter have been introduced. We have investigated the suitability of different materials for our photon detector and have implemented a routine procedure for proper energy calibration of our detector system.

H7.6 Technical innovations on the A4-Compton-Backscattering-Polarimeter

In early 2004, efforts to measure and optimize the laser polarization state have been made. In the middle of 2004 the vacuum conditions inside the polarimeter beamline have been significantly improved. We received three heatable getter sorption pumps from MIT Bates under the same coorporation agreement as the vacuum chambers and dipole stands. With these pumps we were able to reach a pressure of $4 \cdot 10^{-8}$ mbar, ten times better than before. During two test-beamtimes in June and August 2005, several improvements on the photon detector calibration procedures and data acquisition of the polarimeter have been introduced. We have investigated the suitability of different materials for our photon detector and have implemented a routine procedure for proper energy calibration of our detector system.

H7.6.0.1 Polarization state of the laser light

The Stokes parameter measurement device consists of a rotating quarter waveplate and a fixed linear polarizing prism. It is located underneath a vacuum window placed under 45° for this purpose, where a parasitic reflection of 0.6% of the intensity per surface occurs. This extracted light is intensity modulated at multiples of the waveplate rotation frequency when passing

![Figure H7.12: Example of an energy spectrum of a single channel of the PbF$_2$ calorimeter at 315 MeV. The dotted line shows the spectrum without scintillation trigger, the solid line the spectrum with scintillation trigger bit set. In the solid spectrum the elastic peak can be seen around the ADC channel 47.](image-url)
through this apparatus; the modulation amplitudes indicate the polarization state of the light. The device has been commissioned in early 2004. The system has been shown to work, but further analysis are needed and underway to ensure the reliability of the data, which indicate an unexpectedly high degree of unpolarized light at the moment. The electronics of the device has been constantly improved, including better ADC hardware which is now used for all sensors in the Compton polarimeter. The optical system has been reconfigured for single-line operation (only at 514.5nm) to simplify the realization of the necessary state of polarization and the data analysis of both the backscattered photon spectra and the Stokes parameter measurements. The best polarization/power achievement so far was 35W intra-cavity power at a circular polarization of V/I=0.92 in August 2005. We are planning to perform quantitative measurements of parasitic birefringence in the optical elements of the laser system, because this leads to a reduction of available laser intensity.

Figure H7.13: Result of a Stokes parameter measurement. The left side shows the transmitted intensity, normalized to the over all laser intensity shown below. On the right side, the resulting polarization ellipse is displayed.

**H7.6.0.2 Photon detector calibration procedure**

The photon detector of the backscattering polarimeter has to detect photons in an energy range of up to 30 MeV with good energy resolution. Unfortunately there are no monoenergetic photon sources available in the energy range between about 5 and 30 MeV. Therefore we had been using radioactive sources (photons of up to 4.4 MeV) and the high energy edge of the bremsstrahlung spectrum (about 855 MeV) for energy calibration. We solved this inconvenience by using the movable fibre detector as a tagger, giving access to monoenergetic photons with a spectral width of about 0.8 MeV per fibre, which was determined from GEANT4 simulations. Using this tagging technique the available photon energies range from about 6 MeV to about 50 MeV which fits perfectly our needs. The tagging range is determined by moving a 20µm thin tungsten wire (the same as is used in the wire scanners along the MAMI beamline), which is attached at a fixed distance from the fibres, through the electron beam. Electrons scattered off the wire produce electromagnetic showers in the beampipe. These are detected by a
lead glass detector. This procedure gives the tagging energy range of the fibres as a function of their position.

**H7.6.0.3 Choosing a compact photon detector material**

Due to the high light yield we had first chosen NaI(Tl) as material for our photon detector. Unfortunately our detector has to be placed directly on the beam axis of the chicane in the experimental hall 3 and we suspect low energy pile-up and also low energy background from the beamline and experimental hall 4 to degrade energy resolution. During the last beamtimes we found that a more compact detector material provides better energy resolution in the case of our special application. With a BaF$_2$ crystal borrowed from the TAPS-collaboration, we achieved at least the same energy resolution (about 40\% for 25MeV photons) as with a large (4”x12”) NaI(Tl) detector. In the near future we will perform tests with a new grade of PbWO$_4$ that will be cooled down to −30\°C. Later we will build a very compact photon calorimeter consisting of four 20x20x200mm$^3$ LYSO-crystals.

![Figure H7.14: Measured asymmetry in the spectrum of backscattered photons. The asymmetry is plotted against runnumber (a run corresponds to 5 minutes of data taking)](image)

**H7.6.0.4 Latest asymmetry measurements**

As an example for the already achievable statistical error of our asymmetry measurements with backscattered photons, Fig. H7.14 shows the combined results from nearly 10 hours of data taking with the polarimeter. For each run the asymmetry in the Compton spectrum has been calculated. The average value is indicated by the green and red lines. These two colors represent different states of the GVZ, which is a half waveplate at the polarized source that exchanges the meanings of the polarization states of the electron beam. This serves as a check for systematic errors. The grey vertical bands correspond to background runs without the laser. It should be possible to improve the mean statistical error of about 5.1\% by an increase in the intracavity laser power and by further optimization of beam overlap. Note the luminosity stability of the polarimeter. Before taking the last six runs there was a series of test measurements with different trigger conditions not included in this plot, resulting in a five hour interruption of the regular measurements. The asymmetries and their errors have not changed during this period. In order to extract the electron beam polarization, further calibration, analysis procedures, and GEANT4 simulations will be developed and introduced in 2006.
H7.7 The A4 Transmission Compton Polarimeter

During the period under report the transmission Compton polarimeter (TCP) was used as monitor for the longitudinal polarization and to check the spin angle of the beam electrons. The polarimeter measures an asymmetry in the transmission of polarized bremsstrahlung through a magnet for the “+” and “-” helicity, here called TCP asymmetry. This asymmetry is proportional to the longitudinal component of the polarization of the electron beam.

The spin angle was determined by rotating the electron spin at a given beam energy by means of the Wien filter and by measuring the TCP asymmetry for each rotation angle. A sinusoidal function was fitted to the measured curve (see fig. H7.15), and from the fit the spin angle for the known Wien filter setting during data taking could be calculated (if necessary with a correction for the beam energy).

![Figure H7.15: Result of the spin rotation at 315.24 MeV together with a cosine fit. The Wien filter high voltage is proportional to the spin rotation angle.](image)

Problems caused by a deteriorated electrical isolation of the polarimeter parts became more and more relevant. We interpret this as a radiation damage of the signal cables. Because of the strongly reduced isolation resistances (around 10 kΩ) together with high feedback resistances (of the order of 100 MΩ) the offset voltage of the amplifiers which is varying in time affects strongly the signal amplitudes of the amplifier output. This changes the signal pedestals as well as the effective gain factors (via current losses). To solve these problems we will remove the polarimeter before the next beam time in order to inspect it and to replace the signal cables with more radiation hard ones (with mineral isolation).

Figure H7.16 shows the polarimeter asymmetry as a function of the number of the data taking run for a beam time at 315 MeV. Signal instabilities that result in larger uncertainties in the TCP asymmetries are subject to investigation. One can clearly observe the change of sign for the runs from approx. 34000-35000, where a halfwave plate in the laser optics of the electron source was inserted, reversing the meaning of “+” and “-” helicity.

H7.8 Simulation of the detector response

A study of the A4 detector response has been undertaken by means of Monte Carlo simulations. The result of this investigation provides on the one hand a better understanding of the
energy loss. The distribution of the beam electron energy depends on the position in the target.

Thus there are three random variables to be generated: the position of the scattering centre, the

amount to very small angles compared to the scattering angle covered by the detector and the

For the event generator one has to sample the differential cross sections of the processes to be

The implementation of an event generator producing a sample of primary particles coming out of the target and

the reproduction of the response of the experimental apparatus to those events.

Event generator

For the event generator one has to sample the differential cross sections of the processes to be simulated. Since these cross sections depend on the energy of the beam electrons just before the scattering process, one has to take into account the energy straggling of beam electrons along their passage through the target up to the interaction point. The angular deviations of the beam electron momenta from their original direction are not taken into account, because they amount to very small angles compared to the scattering angle covered by the detector and they modify the cross sections only to a very small extent as compared to the modifications due to energy loss. The distribution of the beam electron energy depends on the position in the target along the beam line, i.e. on the thickness of the target layer the electrons have to pass through. Therefore the energy and angle distribution of the scattered particles depend on this position. Thus there are three random variables to be generated: the position of the scattering centre, the scattering angle and the energy of the scattered particle.
Energy straggling. At the beam energies of the experiment (855 MeV, 570 MeV and 315 MeV), considering the total length of the target (10 cm at forward angle and 23 cm at backward angle) and focusing the interest on large energy losses (of the order of 10 MeV or more), the relevant contributions to the energy straggling come from bremsstrahlung. Hence the treatment of the energy straggling as done by Mo and Tsai [1] can be applied.

Elastic scattering. Convoluting the energy straggling function with the Rosenbluth differential cross section for the elastic electron proton scattering has two effects on the energy spectrum. The peak of the elastic events is modified and a radiative tail appears at lower energies. Furthermore one has to consider the radiative corrections [1] to the elastic scattering cross section, which also give a modification of the elastic peak and a contribution to the radiative tail (fig. H7.17).

Inelastic scattering. For the measurement of the parity violation in the \( \Delta(1232) \) resonance, one needs to detect the electrons scattered in the processes \( ep \rightarrow eN\pi \). These events have been included in the event generator by sampling the inclusive cross section for the single pion electroproduction from the proton. Such a cross section has been calculated using the program MAID [2] (fig. H7.18).

Response of the apparatus

The way primary particles enter into the experimental energy spectrum is determined by several statistical effects. They have to travel from the scattering centre to the detector passing through different material layers. They deposit their energy in the PbF\(_2\) crystals developing electromagnetic showers. All charged particles in the shower with enough velocity generate Cherenkov light. The Cherenkov photons propagate through the crystals and are detected by the photomultipliers. The number of photoelectrons generated at the PMT cathode is finally proportional to the digitised signal, i.e. the energy measurement. All these processes must be taken into account for obtaining the simulation of the energy spectrum from the generated events. For this purpose the GEANT4 simulation package has been used.
Figure H7.18: Sum of the differential cross sections of the processes $ep \rightarrow ep\pi^0$ and $ep \rightarrow en\pi^+$ calculated using the program MAID [2]. The beam energy is 855 MeV and the polar scattering angle 30°. The dashed red line is the cross section including radiative corrections [1]. The solid blue line is the uncorrected one.

The passage of primary particle through the material layers and the deposition of energy in the crystals by formation of electromagnetic showers has been simulated by tracking all particles and their secondaries.

For taking into account the production, propagation and detection of Cherenkov light, a different strategy has been developed and adopted, because tracking all Cherenkov photons is very time consuming and does not allow having a sufficient statistics in the simulation. A relative small sample of events was simulated tracking all Cherenkov photons and simulating their detection according to the quantum efficiency of the phototubes. For each event the direction and the energy of the primary electron were chosen randomly. For each crystal and event the number of detected photons against the deposited energy was entered in a scatter plot (Figure H7.8-(a)) and the following basic approach was adopted:

1. the number of photoelectrons emitted at the photo-cathode of a photomultiplier in one event is a gaussian distributed variable;
2. the mean value and the variance of such a distribution are linear functions of the deposited energy in the corresponding crystal during that event.

This second statement is also statistically well motivated by the simulation result shown in Figure H7.8.

The complete simulation of the energy spectrum is obtained by fully tracking the particles in the electromagnetic shower for each event, that is with GEANT4, in order to calculate the deposited energy in each crystal. With this value the mean and the variance of the number of photoelectrons are calculated for each crystal, and a random variable is sampled accordingly to simulate the "signal" of each photomultiplier. From these numbers the maximum is found to identify to which crystal the event belongs to. The signals from the 9 neighbouring crystals about the selected one are summed and this final value is histogrammed.

**Comparison with the experiment.** The result of the simulation of one single event is entered in a histogram having the same number of bins as the ADC channels in the experiment. The bin is calculated linearly from the simulated signal knowing the position of the elastic peak (at forward angle) and the ADC offset. The histograms corresponding to different processes
Figure H7.19: Result of the simulation of about 10000 events tracking all Cherenkov photons. The primary electron energy was varied between 100 MeV and 1000 MeV, its direction was chosen randomly in order to hit uniformly the surface of a crystal. (a) Plot of the number of photoelectrons $N_{\text{pe}}$ vs. the deposited energy $E_d$ in one crystal. (b) Plot of the sample variance of $N_{\text{pe}}$ vs. $E_d$, considering the linear fit in (a) as the mean value of $N_{\text{pe}}$ at a given $E_d$.

are scaled by a factor $L \Delta \sigma / N$, where $L$ is the luminosity of the experiment, $\Delta t$ the measuring time, $\sigma$ the total cross section used in the event generator and $N$ the number of simulated events.

Results and Outlook

Figure H7.20: Result of simulation for forward scattering angle at the beam energy of 855 MeV (a) and for backward angle at 315 MeV (b). The red histogram is the experimental spectrum. In the case of backward scattering the spectrum is obtained from the coincidence between calorimeter and scintillator. The black histogram is the simulated spectrum (sum of all contributions). The yellow region represents the elastic events with the corresponding radiative tail. The green region is given by the inelastic events.

The simulation of the energy spectrum has been performed for the forward scattering configuration at the beam energy of 855 MeV and for the backward scattering at 315 MeV. The comparison with the experimental spectra are shown in Figure H7.8. The response of the detector is well reproduced by the simulation. First of all, the energy resolution of the detector at both kinematics is in agreement with the simulation. Secondly, the linearity of the detector is proven, since the position of the simulated elastic peak at backward angle agrees with the
experiment without changing the binning function from the forward angle case. Furthermore, the contribution from the elastic scattering are quantitatively well understood.

The inelastic part of the spectrum remains to be investigated. The experience of the backward scattering experiment has taught that the contribution of photons (or neutral particles in general) to the energy spectrum is large. Presently an event generator for the process $ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$ is being implemented for estimating which is the contribution of photons to the spectrum.

Bibliography


H7 Subproject H7

Publications in Journals

F. Maas et al.
Measurement of the strange quark contribution to the nucleon from factors at $Q^2 = 0.23 \text{ (GeV/c)}^2$.

F. Maas et al.
Evidence for strange quark contributions to the nucleon’s form factors at $Q^2 = 0.108 \text{ (GeV/c)}^2$.
Phys.Rev.Lett.94:152001,2005

F. Maas et al.
Measurement of the transverse beam spin asymmetry in elastic electron proton scattering and the inelastic contribution to the imaginary part of the two-photon exchange amplitude

S. Kox, D. Lhuillier, F. Maas, J. Van de Wiele
From parity violation to hadronic structure and more. Proceedings, 2nd workshop, PAVI 2004, Grenoble, France, June 8-11, 2004
Berlin, Springer, 2005

H7 Dissertations

Sebastian Baunack
Einzelspin-Asymmetrien in der elastischen Elektron-Proton-Streuung und die Beiträge der Strange-Quarks zu den Formfaktoren des Nukleons (Dezember 2005)
H7  Diploma Theses

M. Sikora
Aufbau und Inbetriebnahme eines Natriumiodid-Detektors für das A4-Comptonpolarimeter (Juni 2004)

B. Gläser
Entwicklung und Realisierung eines experimentellen Aufbaus für die Messung der paritätsverletzenden Asymmetrie in Elektron-Proton-Streuung unter Rückwärtswinkeln (Januar 2005)

Conference Proceedings

S. Baunack
Transverse spin asymmetry at the A4 experiment

S. Baunack
Single spin asymmetries from the Mainz A4 experiment
Proc. of the 10th International Conference on Structure of Baryons (Baryons 2004), Palaiseau (2004)

L. Capozza

J. Diefenbach
Stabilization system of the laser system of the A4 Compton backscattering polarimeter

B. Gläser
Redesign of the A4 calorimeter for the measurement at backward angles

D. v. Harrach
Strangeness of the nucleon
Prog.Part.Nucl.Phys.55:308-319,2005

Y. Imai
Progress report on the A4 Compton backscattering polarimeter

Y. Imai
The Compton backscattering polarimeter of the A4 experiment
Prog.Part.Nucl.Phys.55:332-335,2005

Y. Imai
The Compton Backscattering Polarimeter of the A4 Experiment
World Scientific, p.926-929, 2005

J. Lee
Electron beam line design of A4 Compton backscattering polarimeter

F. Maas
Recent perspectives in parity violating electron scattering

F. Maas
The Mainz A4 parity violating experiment (Single spin asymmetries in elastic scattering)
World Scientific, p.970-974, 2005

F. Maas
The Mainz A4 parity violation experiment (single spin asymmetries in elastic scattering)
F. Maas  
Parity violating electron scattering at the MAMI facility in Mainz  

F. Maas  
Parity violating electron scattering and the strangeness content of the nucleon  
Strbske Pleso 2004, Deep inelastic scattering, 1134-1139

C. Weinrich  
The transmission Compton polarimeter of the A4 experiment  

**H7 Invited Talks at External Institutions**

F. Maas:  
The Proton in View of Parity Violation and Two-Photon Exchange  
Laboratory for Nuclear Science, MIT, Cambridge, Massachusetts, February 2004

F. Maas:  
The A4 Parity Violation Experiment  
Kolloquium an der Universität Basel, Basel, Schweiz, November 11, 2004

F. Maas:  
Parity Violating Electron Scattering  
Jefferson Lab, Newport News, Virginia, June 21, 2005

**H7 Invited Talks and Contributions at International Conferences**

**DPG-Frühjahrstagung, Köln, March 2004**

J. Diefenbach:  
Stabilization of the laser system of the A4 Compton-Backscattering-Polarimeter

J. H. Lee: Electron beam line design of the A4 Compton backscattering polarimeter

Ch. Weinrich:  
Report on the A4 transmission Compton polarimeter
DIS 2004 - XII International Conference on Deep Inelastic Scattering, Štrbské Plesko, Slovakia, April 2004

F. Maas:
Parity violating electron scattering

PAVI04 - From Parity Violation to Hadronic Structure and more, Grenoble, France, June 2004

S. Baunack (plenary talk):
Transverse spin asymmetry (experiment)

Y. Imai:
Progress report on the A4 Compton backscattering polarimeter

C. Weinrich:
The Transmission Compton Polarimeter of the A4 Experiment at MAMI

F. Maas (plenary talk):
The PVA4 experiment

SPIN-PRAHA-2004, Symmetries and spin, Prague, Czech Republic, July 2004

F. Maas (Overview talk):
Parity Violating Electron Scattering

F. Maas (plenary talk):
The Mainz A4 Parity Violation experiment


F. Maas (plenary talk):
New Results from the A4 Parity Experiment

19th European Few-Body conference, Groningen, Netherlands, August 2004

F. Maas (plenary talk):
Recent developments in parity violation experiments

International School of Lepton Scattering and the Structure of Hadrons and Nuclei, Erice, Italy, September 2004

D. v. Harrach (plenary talk):
Strangeness of the Nucleon

Y. Imai:
The A4 Compton backscattering polarimeter
PESP 2004, Polarized Electron Sources and Polarimeters, Mainz, October 2004

Y. Imai:
The Compton Backscattering Polarimeter of the A4 experiment at Mainz

F. Maas:
The A4-Parity Violation Experiment at MAMI

10th International Baryons Conference, Palaiseau, France, October 2004

S. Baunack:
Single Spin Asymmetries from the Mainz A4 Experiment

International Workshop on Two-Photon Physics, ETC Trento, Italy, May 2005

F. Maas (plenary talk):
Two-Photon Physics in Elastic Electron Scattering: Experimental Status

Third Asia-Pacific Conference on Few-Body Problems in Physics, Nakhon Ratchasima, Thailand, July 2005

F. Maas (plenary talk):
Parity Violating Electron Scattering

Nucleon05 Workshop, Frascati, Italy, October 2005

F. Maas (plenary talk):
Two-Photon Physics in Elastic Electron Scattering: Experimental Status