MEASUREMENT OF THE NEUTRON ELECTRIC FORM FACTOR AT $Q^2 = 1.58 \ (\text{GeV}/c)^2$

Relatrice: prof.ssa Giuseppina Orlandini

Correlatore: prof. Peter Grabmayr

Laureanda: Sara Caliari

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1 INTRODUCTION

A particle accelerator is a device whose purpose is to accelerate beams of charged particles. The values of kinetic energy the particles can now reach are included between one MeV and a few TeV.

Particle accelerators exist in many shapes and sizes, but they all have a source that generates charged particles and they all use electric fields to accelerate charged particles through an evacuated region of space, such as a vacuum tube. A good vacuum is necessary to improve the beam quality.

The first accelerators were built at the beginning of the 1930s. In particular, in 1932 the two scientists John Douglas Cockcroft and Ernest Walton realised the first nuclear transformation initiated by a proton. Using an electric system that could deliver a voltage of 800 kV they accelerated a beam of protons and aimed it at a target of lithium. The resultant emission of alpha particles, that is, positively charged particles consisting of two protons and two neutrons, indicated not only that some protons had succeeded in penetrating the nuclei of the lithium atoms but also that they had somehow combined with the lithium atoms and had been transformed into something new.

For their pioneering work on the transmutation of atomic nuclei by artificially accelerated atomic particles, Walton and Cockcroft shared the 1951 Nobel Prize in Physics.

Physicists use accelerators in research on the nucleus and its constituents, however accelerators are also used for radioisotope production, industrial radiography, radiation therapy, sterilization of biological materials, and a certain form of radiocarbon dating.

In this thesis I want to tell about my experience at the institute for nuclear physics of the Johannes Gutenberg University in Mainz, Germany. Centre of the research activities is the Mainzer Microtron MAMI, an electron accelerator with energies up to 1508 MeV.

My experience lasted about three weeks: from the fourth to the twenty-first of July. I was there with a friend and colleague of mine, Andrea Dalla Riva. In three weeks time we learnt how typical accelerators and detectors for nuclear physics experiments look like and work and we participated to data taking of an important nuclear physics experiment.

In particular, the current thesis is divided in this way:

- the second chapter is about the MAMI accelerator itself and the three spectrometres facilities of the A1 collaboration;
- the third chapter discusses the experiment and the theory relating to it;
1 INTRODUCTION

- the fourth and last chapter describes what Andrea and I exactly did at Mainz to help people working and what we learnt.

This thesis includes the photographs taken by Andrea and me and the graphs we realized with ROOT.
2 THE MAINZ MICROTRON MAMI AND THE A1 COLLABORATION

2.1 Introduction

The Mainz Microtron MAMI is a particle accelerator in which electrons are accelerated to relativistic velocities up to 1.5 GeV energy. It consists of three race track microtrons with a 3.5 MeV injector linac, followed by a Harmonic Double Sided Microtron (HDSM) as the fourth and last stage. [1]

The last stage was finished in 2006.

During the construction of the accelerator many areas have been established to accommodate experimental equipment. Each experimental area is operated by a collaboration, which is responsible for the equipment as well as the experimental program. Currently the following collaborations are active at the MAMI: collaboration A1 performs high precision electro-production experiments using a three spectrometer setup, collaboration A2 is a nuclear physics research group that is devoted to experiments using tagged Bremsstrahlung photons and collaboration A4 performs parity violating electron scattering experiments on the proton.

In this chapter I will summarize the main points of MAMI’s history, I will describe the principle of the accelerator system and at last I will concentrate on the A1 spectrometer hall: the hall were the experiment I was involved in took place.

As Andrea and I helped A1 Collaboration members to dismount some of the A1 hall facilities at the end of the experiment, I will include some of the pictures we took in the appropriate section. In this way it should be easier and more interesting for the reader to understand what I am talking about.
2.2 The MAMI accelerator

2.2.1 History

The most important steps in MAMI history include[2]:

- the project studies about Microtrons between 1972 and 1975;
- the first 14 MeV beam of MAMI A1 in 1979;
- the first 183 MeV beam of MAMI A2 in 1983;
The development of the 855 MeV MAMI B and the 3.5 MeV injector linac between 1983 and 1990;

the first 855 MeV beam of MAMI B in 1990;

the approval of the 1.5 GeV HDSM as a forth stage of the MAMI (design by Kaiser et al) in 1999;

improved polarised electron source with $P_e=80\%$ in 2001;

the first 1.5 GeV beam of MAMI C in 2006.

Starting on 10th of August 1990 (first 855 MeV from MAMI B), MAMI accumulated till today almost 100000 hours of operation time.

2.2.2 The injector linac

The 3,5 MeV injector linac replaced a 2.1 MeV Van de Graaff for getting higher reliability, improved beam dynamics in the first RTM\textsuperscript{1} by increased and more stable input energy, as well as an easier access and a better vacuum to launch a beam of polarized electrons.\textsuperscript{3}

The linac is a particle accelerator that imparts a series of increases in energy to particles as they pass through a sequence of alternating electric fields set up in a linear structure.

It consists of a hollow pipe vacuum chamber. The chamber is composed of "drift tubes" positioned at appropriate intervals to shield the particles during the half-cycle when the field is in the wrong direction for acceleration. Every time the particles cross the gaps they are repelled by an electrode and are attracted by another one. In this way they are accelerated.

As the source operates at precise frequency, the length of the electrodes must be dimensioned according to particle velocity. In particular, we have shorter electrodes near the source and longer electrodes near the end of the linac.

The scheme of a general linac is given in Fig. 2.2.

![Figure 2.2: Scheme of a linear accelerator.](image)

The output energy of the injector linac is about 3,5 MeV.

\textsuperscript{1}Race Track Microtron
Using the relativistic expression of the energy, that is $E = mc^2$, we have that an electron at the end of the injector linac has already reached the speed of about 0.99c.

The principal setup of the injector linac for the MAMI is shown in Fig. 2.

---

### 2.2.3 The Race Track Microtrons

The linear accelerator is very simple, and does not require any magnet. The problem is it has to be very long to reach high beam energies. In order to accelerate particles to high energies circular accelerators are used.

The principle of the race track microtron is illustrated below. The electron beam from the source is deflected into a semicircular path by a magnet, then it travels through good vacuum towards another magnet which deflects the beam trajectory another time. At this point the beam is accelerated by a linear accelerator near the edge of the gap between the magnets and is emitted toward the first magnet. The electron is sent to the linear accelerator after every revolution until the increased radius of the particle paths makes further acceleration impossible.

Electrons always have to pass the linac in phase, otherwise they are repelled. This leads to a relation between path length, magnetic field and energy gain.

On the other hand, electrons have to enter the race track microtrons in the right phase.

---

Mainz RTM 1 (or MAMI A1) input and output energies are 3.97 MeV and 14.86 MeV, while Mainz RTM 2 (MAMI A2) values are 14.86 MeV and 180 MeV and Mainz RTM 3 (MAMI B) values are 180 MeV and 855.1 MeV.\[4\]

---

\[m\] is the relativistic mass, that is $\gamma m_0$, where $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$, $v$ is the particle velocity, $c$ is the speed of light in vacuum and $m_0$ is the rest mass of the particle.
2.2.4 The Harmonic Double Sized Microtron

The Mainz Harmonic Double Sized Microtron (MAMI C) is the fourth and last stage of the MAMI.

It consists mainly of two pairs of 90° bending magnets and two linear accelerators. Special features of the HDSM are the operation of the two linacs at different frequencies, 2.45GHz and 4.90GHz, for higher longitudinal stability, and a relatively strong field gradient in the bending magnets for the compensation of vertical edge defocusing.\[5\]

The Mainz HDSM input energy is 855.1 MeV, while the output energy is 1508 MeV.

2.3 The Three Spectrometer Setup of the A1 Collaboration

2.3.1 The hall

The A1 collaboration works with three high-resolution magnetic spectrometers, named A, B and C, which are located in an experimental hall 30 m × 20 m wide and 17.4 m high (from the floor to the crane hook).
The spectrometers A and C both consist of a quadrupole, a sextupole and two dipole magnets, while the spectrometer B consists of a single dipole magnet. Spectrometer C is essentially a scaled-down version of spectrometer A.

The magnets induce the deflection of the particles, according to the Lorentz force law.

The bending radius of particle tracks is related to the magnetic field strength and the momentum component of the particle perpendicular to magnetic field.

Moreover, each spectrometer is equipped with a position sensitive detector system consisting of four planes of vertical drift chambers, two planes of plastic scintillators and a threshold gas Cherenkov detector.

The detector systems are mounted on top of each spectrometer inside heavy shieldings consisting of 40 cm thick Boron carbide loaded concrete walls covered with a 5 cm thick lead layer on the inside. They weight about 110 tons each.

All trigger detectors are time calibrated and controlled during runtime by means of a UV laser monitoring system.

The spectrometers themselves are placed on a turntable and can be rotated around a common pivot.
The incoming beam is guided in a vacuum pipe, 3 cm in diameter, 3 m above the floor into a cylindrical scattering chamber placed on top of the central pivot. The scattering chamber contains a vertically movable target ladder for mounting solid targets or cryogenic target systems or a high-pressure, low-temperature gas target. The beam leaves the scattering area again in a vacuum pipe which opens conically to a diameter of 1 m.

Spectrometers A and C cover angular ranges between 18° and 160° on the left and right side, respectively, relative to the incoming beam. In normal position, spectrometer B can rotate
between 7° and 62° on the right side. After removal of the exit beam pipe, it can be rotated to
the left side covering angles between 7° and 90°. Spectrometer B can also be moved vertically by
10° by means of a mechanical driving system, allowing to perform out-of-plane experiments. [6]

Each of the spectrometers can optionally be used for the detection of positively or negatively
charged particles and can be used alone, or with the others for coincident experiments. Moreover, if needed, the three spectrometer setup can be complemented by additionally magnetic or
nonmagnetic devices, like, for instance, a neutron detector or a proton polarimeter as happened
in the past.

![Figure 2.10: Schematic drawing of the three spectrometer facilities.](image)

### 2.3.2 The magnet-optical design

The essential properties of magnetic spectrometers are the momentum resolving power \( R \), the
solid angle \( \Delta \Omega \) and the momentum acceptance \( \Delta p/p \).

As I have said before, spectrometers A and C are QSDD-spectrometers, which means that
their optical system consists of a quadrupole (Q), a sextupole (S), a dipole (D) and another
dipole (D).

The first quadrupole is used to obtain a large solid angle by providing transverse focusing.
The two dipole generate the dispersion and the focusing. The pole faces of the dipole magnets
are inclined, which introduces additional quadrupole strength. The sextupole magnet is mainly
used to correct for spherical aberrations in the non dispersive plane. [7]

Spectrometers A and C reach maximum momenta of 735 MeV/c and 550 MeV/c respectively.
They are characterized by having bigger solid angle and momentum acceptance than spectrom-
eter B.
Spectrometer B consists of one dipole magnet only. Its field has a gradient which provides transverse focusing and the entrance and exit pole faces are inclined to provide quadrupole and sextupole strength. It has a better momentum resolution than the other two spectrometers. Moreover, spectrometer B reaches extremely small scattering angles: it is able to detect particles with scattering angles as small as 7° with respect to the electron beam.

The design parameters of the three spectrometers are summerized in the table below:
### 2.3.3 The Vertical Drift Chambers

The focal plane coordinates are determined in each spectrometer by a package of vertical drift chambers (VCD).

Figure 2.13 schematically illustrates the basic operation of a drift chamber.

<table>
<thead>
<tr>
<th>Spectrometer Configuration</th>
<th>A (QSDD)</th>
<th>B (D+)</th>
<th>C (QSDD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum momentum [MeV/c]</td>
<td>735</td>
<td>870</td>
<td>551</td>
</tr>
<tr>
<td>Max. momentum (centr. traj.) [MeV/c]</td>
<td>665</td>
<td>810</td>
<td>490</td>
</tr>
<tr>
<td>Maximum induction [T]</td>
<td>1.51</td>
<td>1.50</td>
<td>1.40</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>20</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Horizontal angular acceptance [mrad]</td>
<td>± 100</td>
<td>± 20</td>
<td>± 100</td>
</tr>
<tr>
<td>Vertical angular acceptance [mrad]</td>
<td>± 70</td>
<td>± 70</td>
<td>± 70</td>
</tr>
<tr>
<td>Solid angle [msr]</td>
<td>28</td>
<td>5.6</td>
<td>28</td>
</tr>
<tr>
<td>Data taking power [msr]</td>
<td>8.5</td>
<td>1.2</td>
<td>10.1</td>
</tr>
<tr>
<td>Long-target acceptance [mm]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Scattering angle range [°]</td>
<td>18 – 160</td>
<td>7 – 62</td>
<td>18 – 160</td>
</tr>
<tr>
<td>Length of central trajectory [m]</td>
<td>10.76</td>
<td>12.03</td>
<td>8.53</td>
</tr>
<tr>
<td>Angle of image plane [°]</td>
<td>45.0</td>
<td>46.7</td>
<td>45.3</td>
</tr>
<tr>
<td>Length of image plane [m]</td>
<td>1.73</td>
<td>1.77</td>
<td>1.63</td>
</tr>
<tr>
<td>Dispersion to magnification [cm/%]</td>
<td>10.62</td>
<td>9.64</td>
<td>8.38</td>
</tr>
<tr>
<td>Momentum resolution [cm/MeV]</td>
<td>≤ 10^{-4}</td>
<td>≤ 10^{-4}</td>
<td>≤ 10^{-4}</td>
</tr>
<tr>
<td>Angular resolution at target [mrad]</td>
<td>≤ 3</td>
<td>≤ 3</td>
<td>≤ 3</td>
</tr>
<tr>
<td>Position resolution at target [mm]</td>
<td>3 – 5</td>
<td>≤ 1</td>
<td>3 – 5</td>
</tr>
</tbody>
</table>

* clamshell dipole
The basic VDC consists of a plane of equally spaced anode wires centred between two cathode planes. In order to produce a suitable drift field, potential wires are introduced between neighbouring anode wires.

The signal and potential wires have diameters of 15 and 50 $\mu m$, respectively. The high voltage is set to a value typically between 5.6 and 6.5 kV. The distance between a signal wire and its adjacent potential wire is 2.5 mm. The distance L between wires plane and cathode foils is 12 mm.

The VDC is based on the fact that spatial information can be obtained by measuring the drift time of the electrons coming from an ionizing event.

The VDC is filled with equal parts of argon and isobutane and a 1.5% admixture of pure ethanol to minimize aging.

A particle traversing the chamber liberates electrons in the gas which then begin drifting towards the anode. The distance from the sensing wire to the origin of the electrons is $z = \int v(t)dt$. In practice, it would be highly desirable to have a constant drift velocity and hence a linear relationship between time and distance.

Each package of VDC consists of four planes, two perpendicular to the dispersive plane, called x-planes, to determine the momentum and the out-of-plane angle of the reconstructed particle, and two at an angle of 40° relative to the x wires, called s-planes.

With this detector the resolution achieved is of [8]:

- $dx < 100 \mu m$ for the dispersive coordinate;
- $dy < 200 \mu m$ for the nondispersive coordinate;
- $d\theta < 0.3$ mrad for the dispersive angle;
- $d\phi < 1$ mrad for the nondispersive angle;

The single plane efficiency is better than 99%, leading to an overall efficiency of better than 99.9%. 

Figure 2.13: Basic operation principle of the drift chamber.

The electrical field distribution is schematically shown in the right quarter of the figure.
2.3.4 Scintillation Detectors

On all the three spectrometers, the scintillator detector system is set up by two thin segmented planes of plastic scintillator material. In particular, the two scintillator planes of spectrometers A and C each consist of 15 individual detectors, while the ones of spectrometer B consist of 14 individual detectors. The thickness of the bottom layer is 3 mm and it is made of NE 102A, while the thickness of the top layer is 1 cm and it is made of NE 3 Pilot U.

Scintillator detectors are fast instruments in the sense that their response and recovery times are short relative to other types of detectors.

The main purpose of the scintillation detector system is the determination of the time when a particle hits the detector system, which is needed for the coincidence with the other spectrometers and as a time reference for the drift chambers, and the discrimination of particles due to their specific energy loss in the scintillator. The bottom layer is used as timing detector for low-energy protons and deuterons, while the higher layer provides informations about positrons and positive pions.

The scintillators also help to discriminate against neutrons.

As radiation passes through the scintillation detector, it excites the atoms and molecules making the scintillator causing light to be emitted. This light is transmitted to the photomultipliers, where it is converted into photoelectrons which are then further amplified by an electron multiplier system. The resulting current signal is then analyzed by an electronics system.

The scintillators are read out by photomultipliers from both sides.

---

3Nuclear Enterprises
2.3.5 Cherenkov detectors

If a charged particle in a material medium with refractive index $n$ moves faster than the speed of light in the same medium, it emits a characteristic electromagnetic radiation, called Cherenkov radiation. A particle emitting Cherenkov radiation must therefore have a velocity

$$v_{\text{particle}} > c/n.$$  

Cherenkov radiation is emitted because the charged particle polarizes the atoms along its track so that they become electric dipoles. The time variation of the dipole field leads to emission of electromagnetic radiation. [9]

The Cherenkov counters are part of the trigger system of the three spectrometers and are necessary to discriminate between electrons and charged pions.

Cherenkov radiation is generated in the radiator gas $(\text{CF}_2\text{Cl})_2$ by electrons or positrons with energies larger than 10 MeV. The Cherenkov threshold for pions lies at an energy of 2.7 GeV.

Therefore, in the momentum range of interest, the Cherenkov counters give a signal if an electron passes the detector, while a charged pion gives no signal. In this way electrons and pions are distinguishable.

On the other hand it is sometimes useful to have a good electron identification if there is a lot of background.

![Figure 2.15: Schematic drawing of the detector system of spectrometer A. The particles enter from below.](image-url)
Figure 2.16: The detector system of spectrometer A.
3 THE EXPERIMENT

3.1 Introduction

The three spectrometer setup of the A1 Collaboration was built to perform high precision electro-production experiments.

Till now, A1 collaboration members have already performed a lot of experiments: they have, for example, investigated the virtual Compton scattering reaction, the pion production at threshold and the nucleon-nucleon correlations.

The experiment I have taken part in was about the measurement of the electric form factor of the neutron. Many experiments have been already performed with this purpose, but uncertainties were too large for precise comparison with theory.

In this chapter I will discuss the importance of nucleon form factors study, I will present the Rosenbluth separation method with its advantages and disadvantages and I will compare it with another method to measure form factors, based on double polarization. I will then dedicate myself to the experiment I was involved in.

3.2 Importance of the electric and magnetic form factors

All observed subatomic particles are hadrons except for the gauge bosons of the fundamental interactions and the leptons. The characterization of the structure of the nucleon is therefore a defining problem of hadronic physics.

The measurements of e.m. form factors are a rich source of information on the structure of the nucleon. In particular, in the Breit frame the nucleon charge operator depends only on the electric form factor, whereas the electromagnetic three-current operator depends only on the magnetic form factor. This suggest to interpret the Fourier transforms of $G_E (G_M)$ as the nucleon charge (magnetization) densities.\[10\]

The investigation of the spatial distributions of the charge and magnetism carried by nuclei started in the early nineteen fifties and was profoundly affected by the work of the American scientist Hofstadter with his team at the Stanford University High Energy Physics Laboratory.\[13\]

It had been known for more than twenty years that the proton could not be just a mathematical point charge and point magnetic moment.

The first form factor measurements of the proton were reported in 1955\[14\], while the first measurement of the neutron magnetic form factor was reported in 1958\[15\].
Simultaneously much theoretical work concerning the nucleus and its constituent was realized. The prevailing model of the proton at that time was developed by Rosenbluth and was that of a neutral core surrounded by a positively charged meson cloud. This model was then known as the weak meson coupling model.\[10\]

Following the early results obtained at the Stanford University High Energy Physics Laboratory, many other experiments on the nucleus were performed. The quality of the data has been greatly improved in the last one or two decade, thanks to the new generation of electron accelerators. The Mainz Microtron MAMI and the continuous Electron Beam Accelerator Facility (CEBAF) of the Jefferson Lab (JLab) are two of the most recent accelerators, and they combine high-current with high-polarization electron beams to investigate the structure of the nucleons with high precision. By performing double-polarization experiments, they found out that there was something wrong in the results of the Rosenbluth separation methods, or at least the results obtained from the Rosenbluth separation methods were not compatible with the new results from the new accelerators.

### 3.3 Rosenbluth form factor separation method

The Rosenbluth method had been the only technique available to measure the nucleon electric and magnetic form factors until the 1990s. It required measuring the cross section for eN scattering at a number of electron scattering angles, for a given value of $Q^2$ ($Q^2 = -q^2$, with $q$ being the momentum transfer). This was obtained by varying both the beam energy and the electron scattering angle.

The reduced cross section in Born approximation, and thus for single-photon exchange, written in terms of electric and magnetic form factors takes the following form:

$$
\frac{(d\sigma/d\Omega)}{\text{reduced}} = \frac{\epsilon (1 + \tau)}{\tau} \frac{(d\sigma/d\Omega)}{\text{exp}} / \frac{(d\sigma/d\Omega)}{\text{Mott}} = G^2_M + \frac{\epsilon}{\tau} G^2_E,
$$

(3.1)

where $(d\sigma/d\Omega)_{\text{exp}}$ is the measured cross section, $\tau = Q^2/4M^2$, with $M$ being the nucleon mass, and $\epsilon = [1+2(1+\tau)\tan^2\theta_e]^{-1}$, with $\theta_e$ being the laboratory scattering angle.

This formula depends on the square of the electric and magnetic form factors.

A fit to several measured reduced cross section values at the same $Q^2$, but for a range of $\epsilon$ values, gives independently $\frac{1}{\tau}G^2_E$ as the slope and $G^2_M$ as the intercept.

#### 3.3.1 Proton form factors

The results of various analyses from unpolarized experiments on proton form factor measurements with Rosenbluth separation method lead to a simple scaling law, that is:

$$
G_{E_p}(Q^2) = G_{M_p}(Q^2)/\mu_p = G_D(Q^2),
$$

(3.2)
with $\mu_p = 2.79$ and $G_D$ the dipole form factor given by:

$$G_D = \frac{1}{(1 + Q^2/0.71 \text{GeV}^2)^2}$$  \hspace{1cm} (3.3)

However, from the Rosenbluth formula, one sees that for large $Q^2$ values it is difficult to obtain $G_E^2$ by Rosenbluth separation because the electric contribution to the $ep$ scattering cross section is kinematically suppressed relative to the magnetic contribution as $\frac{1}{r}$ decreases. Moreover, even at small $Q^2$, $G_M^2 \sim \mu_p^2 G_E^2$, hence the contribution of $G_E^2$ to the cross section is reduced by a factor of 7.80.

### 3.3.2 Neutron form factors

Rosenbluth formula for the neutron is:

$$G_{M_n}(Q^2)/\mu_n = G_D(Q^2),$$

with $\mu_n = -1.91$.

$$G_{E_n}(Q^2) = -a \frac{\mu_n}{1 + b\tau} G_{E_p}(Q^2),$$

with $a$ and $b$ being constants.

The measurement of the neutron form factors is more difficult than the measurement of the proton form factors for several reasons: first of all there are no targets composed only by neutrons and so corrections due to the nucleon-nucleon interaction must be taken into account and second the electric form factor is small due to the overall zero charge of the neutron.

The early attempts to determine the neutron form factors were based on measurements of the elastic $ed$ cross section.

### 3.4 Discussion on Rosenbluth results

The most spectacular result coming from the Rosenbluth separation method is the simple law connecting the proton electric form factor with the magnetic form factor and the dipole form factor (see formula 3.2), which is then related to the neutron form factors (see formula 3.4 and 3.5).

However, the formula was brought into question with the advent of the double-polarization method.

The results coming from double-polarization experiments were incompatible with the ones coming from the Rosenbluth separation method at high $Q^2$. The values obtained in the last years from double-polarization experiments show beyond any doubt that for $Q^2$ higher than 2 GeV$^2$, $G_{E_p}$ decreases faster than $G_{M_p}/\mu_p$. 
Figure 3.1: Comparison of $\mu_p G_{Ep}/G_{Mp}$ from JLab polarization data and Rosenbluth separation. JLab polarization data from [16][17] shown as filled circle and square, JLab Rosenbluth results from [18][19] shown as open, filled triangles, respectively. The open circles are other data obtained by the Rosenbluth method. Dashed curve is a refit of Rosenbluth data; solid curve is the fit of $\mu_p G_{Ep}/G_{Mp} = 1.0587 - 0.14265Q^2$.

The discrepancy between the two method results is not understood in simple terms. As we have already seen, as $Q^2$ increases the contribution of $G_{Ep}$ to the cross section rapidly decreases. To achieve good results with the Rosenbluth separation method radiative corrections must be taken into account. The effect of the radiative corrections on the cross section is typically in the range of 10%-30%, but what is important is that the radiative corrections are $\epsilon$ dependent: they affect the slope of the Rosenbluth plot, and thus the measure of the proton electric form factor.[10]

The only way to get good results with the Rosenbluth separation method is to take into account in the computation all the required radiative correction in the right way. Up to now, radiative corrections are not complete. Maybe corrections associated with the exchange of two photons could solve the discrepancy between Rosenbluth and recoil polarization results, but until the origin of the difference is not fully understood it is safe to take the polarization results as the closest to real.

But why should we trust on recoil polarization results more than Rosenbluth ones?

As I will explain in the next section, polarization observables are obtained from ratios with the numerator and the denominator being affected in the same way by radiative corrections. Polarization observables are therefore affected only at the level of a few percent by radiative correctons.

The use of the polarization technique has also resulted in a constant progress in the measure-
3 THE EXPERIMENT

ment of \(G_E\) and \(G_M\), and this is the reason I am going to describe this almost new experimental method in the next section.

3.5 Nucleon form factors from double-polarization observables

In the 1960s, Akhiezer and Rekalo\[20\], and separately Dombey\[21\], proposed that polarization observables could be used instead of scattering probabilities to better determine form factors.

However, over twenty years passed before the technical elements were in place for the first polarization measurements, performed at the beginning of the 1990s at the MIT-Bates and Mainz laboratories.

Both measures of the proton recoil polarization in \(\vec{e}p \rightarrow e\vec{p}\) and the asymmetry in \(\vec{e}\vec{p} \rightarrow ep\) have been used to obtain nucleon form factors. I will present both methods, but I will especially discuss the second one as it was used in "my" experiment.

3.5.1 Polarization transfer

In a review paper in 1974 Akhiezer and Rekalo discussed specifically the interest in doing \(\vec{e}p \rightarrow e\vec{p}\) reactions to obtain \(G_E\).

In polarized electron-proton scattering, the longitudinal and transverse components of the recoil polarization are sensitive to different combinations of the electric and magnetic form factors. The ratio of the form factors can be obtained directly from the ratio of the components of the recoil polarization as follows:

\[
\frac{G_E}{G_M} = -\frac{P_x}{P_z} \frac{(E_e + E'_e)}{2M} \tan \left( \frac{\theta_e}{2} \right)
\]  

(3.6)

where \(E_e\) and \(E'_e\) are the energy of the incident and scattered electrons respectively, \(\theta_e\) is the angle between the initial and final direction of the lepton and \(P_x\) and \(P_z\) are the transverse and longitudinal components of the final proton polarization.

The polarization transfer technique involves, for a given \(Q^2\), a single measurement if the polarimeter can measure both the longitudinal and the transverse components at the same time. This greatly reduces the systematic errors associated with angle and beam energy change. Moreover, the knowledge of the beam polarization and of the analyzing power of the polarimeter is not requested to measure the ratio \(G_E/G_M\).

3.5.2 Asymmetry with polarized target

Another method for measuring nucleon form factors based on double polarization consists in calculating the asymmetry related to the scattering of longitudinally polarized electrons off a polarized nucleon target. It was Dombey who first discussed this method.\[21\]
3 THE EXPERIMENT

The elastic $eN$ cross section can be written as the sum of an unpolarized part and a polarized part as follows:

$$\sigma^{pol} = \Sigma + h\Delta,$$

(3.7)

where $h$ is the electron beam elecity, $\Sigma$ is the elastic un-polarized cross section and $\Delta$ is the polarized part of the cross section.

I avoid to write the whole formula which connects $\Sigma$ and $\Delta$ with $G_E$, $G_M$ and the other variables, as is not fundamental in my writing. However, I point out that, unlike $\Sigma$, $\Delta$ contains two terms related to the direction of the target polarization.

The second part of formula 3.7 is non-zero only if the electron beam is longitudinally polarized.

The physical asymmetry is then defined as:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma},$$

(3.8)

where $\sigma_+$ and $\sigma_-$ are the cross section for the two beam helicities.

The measured asymmetry is related to the physical asymmetry $A$ by:

$$A_{meas} = P_e P_n A,$$

(3.9)

where $P_e$ and $P_n$ are the electron and neutron polarization respectively.

The resulting asymmetry is related to $G_E$, $G_M$ and the direction of the target polarization by:

$$A_{meas} = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2 + \frac{\tau}{c}\tau G_M^2} \sin \theta^* \cos \phi^* G_E G_M$$

$$+\sqrt{\tau [1+(1+\tau)\tan^2(\theta_e/2)]} \cos \theta^* G^2_M] P_e P_n$$

(3.10)

where $\theta^*$ and $\phi^*$ describe the direction of the target polarization vector relative to the momentum transfer and to the scattering plane, respectively.

The formula is correct for the ideal case of a free nucleon target, corrections due to reaction mechanisms such as final state interactions and meson exchange currents are required in general.

It is evident that if the target spin is within the reaction plane ($\phi^* = 0^\circ$ or $\phi^* = 180^\circ$) and oriented perpendicular to the momentum transfer ($\theta^* = 90^\circ$) the asymmetry $A_\perp$ simplifies in

$$A_\perp = P_e P_n \frac{a G_E G_M}{c G_E^2 + d G_M^2},$$

(3.11)

where $a$, $c$, $d$ are determined by the electron kinematics.

On the other hand, with $\phi^* = 0^\circ$ or $\phi^* = 180^\circ$, the asymmetry $A_{\parallel} (\theta^* = 0^\circ)$ is

$$A_{\parallel} = P_e P_n \frac{b G_M^2}{c G_E^2 + d G_M^2},$$

(3.12)
so it can serve as normalization.

The ratio $A_\perp/A_\parallel$ results:

$$\frac{A_\perp}{A_\parallel} = \frac{a}{b} \frac{G_E}{G_M}$$

From the last formula it is possible, for example, to calculate the electric form factor of a nucleon measuring $A_\parallel$ and $A_\perp$ and knowing the magnetic form factor from other experiments.

This is exactly how the A1 experiment performed in July of the current year will be analyzed.

3.6 The experiment

The central point of this chapter is to highlight the importance of measurements of nucleon form factors, since form factors provide important informations for our understanding of the many-body structure of the nucleon.

Nowadays the least known form factor is the neutron electric form factor, and the reasons are more than one.

Firstly, measures on the neutron are complicate by the fact that there are not free neutron targets. Secondly, the electric form factor of the neutron is difficult to measure since it is small due to the zero total charge. However, in order to get information on the intrinsic charge structure of the neutron, precise measurements of the neutron electric form factor are requested over a large range of momentum transfer.

The experiment I was involved in began July 1 and ended July 21. The aim of the experiment was the measure of the charge form factor of the neutron at a momentum transfer $Q^2$ of 1.58 (GeV/c)$^2$ from the quasi-elastic $^3\text{He}(e,e'n)$ reaction. The beam current was up to 10 $\mu$A.

3.6.1 The Target and the beam

The target consisted of high pressure polarized $^3\text{He}$ gas. $^3\text{He}$ is quite a good neutron target as the spin of $^3\text{He}$ is carried to $\sim$90% by the neutron, since for the major part of the ground state wave function the spin of the two protons are coupled antiparallel, and thus to zero.

$^3\text{He}$ gas was polarized outside the experimental area and transported to the target place in specially prepared spherical glass containers with two cylindrical extensions.

Figure 3.2: The $^3\text{He}$ target.
3 THE EXPERIMENT

When in the experimental area, the target was enclosed in a rectangular box which served as an effective shield for the magnetic spectrometers and provided a homogeneous magnetic guiding field of about 4 G. The magnetic field was produced by independent coils, thus allowing for the rotation of the target spin in any desired direction by remote control to measure $A_{||}$ and $A_{⊥}$.

![Figure 3.3: The target box.](image)

The target cell was changed twice a day in order to reduce errors coming from the reduced polarization.

Moreover, to reduce the dependence on the target polarization, data were taken alternatively for $A_{||}$ and $A_{⊥}$ at regular intervals by corresponding rotation of the target spin.

The polarized cw\(^1\) electron beam was accelerated to an energy of 1.5 GeV at beam currents up to 10 $\mu$A and guided to the three spectrometer hall. The electron beam polarization was monitored by a Moeller Polarimeter.

The electron spin was flipped statistically with 1 Hz to avoid systematic errors.

3.6.2 The experimental Setup

The quasi-elastically scattered electrons were detected in spectrometer A, which was placed at a scattering angle $\theta_e$ of 78°. Neutrons (and also protons) were detected in coincidence in a dedicated neutron detector.

The hadron detector consisted of an array of six 10-cm thick layers of five plastic scintillator bars, placed at an angle of $\theta_n -24.9^\circ$ (see figure 3.4).

\(^1\)continuous wave
Each of the plastic scintillator bars was equipped with photomultipliers on both ends to reconstruct the vertical coordinate of the hit by TOF\(^2\) difference.

Two additional 1-cm thick layers, known as "Veto" detectors, enabled distinction between protons and neutrons. The basic idea with the Veto detectors is that protons passing through the scintillator leave a signal, while neutrons not.

As protons interact electromagnetically the detection efficiency for protons in plastic scintillator is \(\sim 100\%\). Neutrons on the other hand only interact hadronically with the scintillator so their detection efficiency is \(\sim 1\%/\text{cm of plastic scintillator}\).

Thus with 1-cm thick bars at the front of the neutron detector only 1\% of neutron events are misunderstood.

\(^2\)Time Of Flight
3 THE EXPERIMENT

Figure 3.6: The photomultiplier tubes associated with the external bar of each layer. The first photomultiplier is associated with the two additionally layers which enable distinction between protons and neutrons.

The entire neutron detector was shielded with lead in order to suppress electromagnetic background.

Figure 3.7: The neutron detector shielding.

3.6.3 First estimate of $G_{E_n}$

$G_{E_n}$ is calculated from the ratio $A_\perp/A_\parallel$ as in eq. 3.13.

The asymmetry values are found using the formula:

$$A_{meas} = P_e P_n \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{N^+ - N^-}{N^+ + N^-} \quad (3.14)$$

where $N^+$ and $N^-$ are the normalized $^3\vec{He}(e',e'n)$ events for positive and negative electron helicity respectively.
3 THE EXPERIMENT

In the table below I list the values measured during the experiment at the four different target spin angles:

<table>
<thead>
<tr>
<th>target spin angle</th>
<th>n° neutrons</th>
<th>$A_{meas}$</th>
<th>$\Delta A_{meas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.9 $\parallel$</td>
<td>2402</td>
<td>0.60</td>
<td>0.06</td>
</tr>
<tr>
<td>114.9 $\perp$</td>
<td>9849</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>204.9 $\parallel$</td>
<td>2507</td>
<td>-0.55</td>
<td>0.06</td>
</tr>
<tr>
<td>294.9 $\perp$</td>
<td>9425</td>
<td>-0.09</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 3.1: "Online analysis"

The asymmetry values are corrected from an average polarization of the electrons $P_e = 75\%$ and of the target $P_n = 50\%$.

The number of neutrons is just the sum of neutrons observed with positive and negative electron helicity for the different target spin angles.

Since the time the data were taken with the target spin perpendicular was almost four times the time the data were taken with the target spin parallel, the number of neutrons detected when the target spin was oriented perpendicular to the momentum transfer is almost four times the number of neutrons detected when the target spin was oriented parallel to the momentum transfer; and this was because measured $A_{\parallel}$ and $A_{\perp}$ differ by factor six and thus we wanted to reduce the error on the smaller value.

With the values in the table it is possible to give a first estimate of the neutron electric form factor that A1 collaboration members will measure.

For this purpose I have to find out the neutron magnetic form factor and the kinematic variables $a$ and $b$, together with the average of the two values of $A_{\parallel}$ and of the two values of $A_{\perp}$.

To calculate $G_{M_n}$ I use the dipole form, that is

$$G_{M_n}(Q^2) = \mu_n G_D(Q^2),$$

with $\mu_n = -1.91$.

Inserting $Q^2 = 1.59$ (GeV/c)$^2$ in the dipole formula 3.3 I find for $G_D$ the value 0.095, and thus for $G_{M_n}$ the value 0.18.

The ratio $b/a$ is equal to $\sqrt{\tau [1 + (1 + \tau) \tan^2(\theta_e/2)]}$, with $\tau$ being $\frac{Q^2}{4M^2c^2}$. Inserting the values for $Q^2$, $\theta_e$ and the neutron mass, I find for $\frac{b}{a}$ the value 0.95.

Adding the asymmetries from opposite angles will improve the uncertainty.

I use a weighted sum

$$A_C = \frac{\sum A_i w_i}{\sum w_i},$$

(3.15)

with the weights $w_i = \frac{1-A_i^2}{(\delta A_i)^2}$.

Errors propagation yields for the uncertainty.
3 THE EXPERIMENT

\[ \delta A_c = \sqrt{1 - A_C^2 \sum w_i} \] (3.16)

In this way I find \( A_{C||} = 0.574 \pm 0.042 \) and \( A_{C\perp} = 0.095 \pm 0.021 \).

With the values I have just calculated for \( G_{Mn}, \frac{b}{a}, A_{C||} \) and \( A_{C\perp} \), I finally obtain a preliminary value for the electric form factor of the neutron:

\[ G_{E_n} = 0.0283 \pm 0.0067 \] (3.17)

This result is consistent with the data obtained in other previous experiments at MIT-Bates, MAMI and JLab (see figure 3.8).

Figure 3.8: Overview on \( G_{E_n} \) data from polarization experiments.

Data for \( G_{E_n} \) from beam asymmetry with polarized D₂ [Pas99, Zhu01, War04], and \(^3\)He [Mey94, Bec99, Roh99, Ber03], and recoil polarization with D₂ [Ede94, Her99, Ost99, Gla05, Pla05], and \(^3\)He [Abo99]. Included values obtained from T₂₀ [Abo99] in elastic \( ed \), in \[^{12}\)C. The new value of \( G_{E_n} \) obtained at MAMI at \( Q^2 = 1.58 \text{(GeV/c)}^2 \) is in green.

This value is a first guess and not the final value as there are many other corrections to this value. There are the shifts in gain or discriminator thresholds in the spectrometer and neutron detector. There are energy losses due to Bremsstrahlung, that is electromagnetic radiation produced by a sudden slowing down of charged particles (in our case electrons) when deflected...
by other charged particles (in our case protons).

The evaluation of the neutron electric form factor finally needs corrections for effects due to nuclear structure and due to reaction mechanism. This factor comes from the comparison of DWIA and PWIA calculation with sophisticated realistic models.

I have not considered the interaction of the photon with the other particles in the nucleus (see figure 3.9 c) and d): the virtual mesons, which are responsible for the force among the nucleons, and the $\Delta$, which represents an excited (isobar) status of the nucleons. These interactions are equivalent to consider a two body current owing to the exchange of mesons (MEC$^3$) or the isobar status (IC$^4$). Moreover, I have not considered the FSI$^5$ and thus the interaction in the final state between the hit particle and the residual nucleus.

Figure 3.9: a) PWIA, b) FSI, c) MEC, d) IC.

The full analysis will be done in Mainz.

---

3 Meson Exchange Currents
4 Isobar Configuration
5 Final State Interaction
4  MY WORK

4.1  Introduction

Till now I have described the accelerator and the A1 collaboration hall, I have described the experiment itself with its implications, but I have not told about what Andrea and I exactly did during our stage yet.

We first entered the nuclear physics institute on 4 July. The experiment had already been running for three days.

We had studied nuclear physics just for one semester.

People could wonder how could we help, what could we do among people who probably had been working on nuclear physics for much more time. Well, this is a right question and I am going to answer it, but I hope people will not question only about what we were already able to do, but above all what we learnt, what we saw and how atomic scientists work.

In this final chapter I am going to answer all these questions.

4.2  Necessary work

The A1 Collaboration hall facilities are equipped with electronics that are read out by VME front end computers running Linux. The readout values are sent to the central process in the control room via fast ethernet. This main process of the control system collects the raw values from all front-end computers and converts them into physical values. The main task of the central process is to compare the nominal and actual values of each channel every time the value changes and to report mismatches. The central process also manages logical names (alias) of each channel, so that the user always deals with meaningful names, and checks the communication to the front-end computers periodically. The values are then sent and analyzed in other rooms reserved for A1 collaboration members.

Andrea and I used to stay in one of the rooms. The room was equipped with computers running Linux as well.

4.2.1  Changing the magnetic field direction

The first thing we could do was changing the magnetic field direction, and thus the direction of the target spin.
As I have already said in section 3.6, the target spin was rotated thanks to a remote control. Well, we did it using one of the computers in our room.

We arranged the new angle direction and waited until the spin was oriented correctly. So the data taking, called run, could start. Each run lasted half an hour and then it stopped. After that time we had to change the field direction and to give the start to the run again, or we had just to give the start to the run: it depended on the last field direction, as four measurement cycles were made in sequence with the neutron spin direction perpendicular to the momentum transfer, while only one cycle with the spin parallel was made before changing the target spin direction.

Every time we started a run we controlled the electron beam current and we wrote down in a notebook the time and the actual field direction, together with the value of the beam current.

![Figure 4.1: User interface to change the magnetic field direction.](image)

### 4.2.2 Checking the spectra

After every measurement cycle we had to check on another pc some spectra. It was quite an approximate control, but if something had gone wrong it was simple to see. They were about the coincident detection of electrons and protons or the energy deposited in the detectors by particles. After every check, we had to write the response down on the notebook as well.
4.2.3 Changing the target

As I have already said in section 3.6, the target cell was changed twice a day. Changing the target cell took about half an hour and it needed two or three people: one had to bring the Helium target to the target box, the other had to move the hook to lift the box cover and to carry the battery connected with the transport box until the Helium was put in the box. The battery was to keep the target in a magnetic field so that the Helium nuclei stayed polarised.

4.2.4 Warning if the alarm sounded

Another thing we had to do was staying there. I mean, the beam run all the day and every day till 21 July. It required every second at least two people in the room, so if the alarm sounded they
could phone the control room for warn, help, and answer their questions if necessary. The alarm could sound for different reasons: the most frequent was the crash of the front end computers in the experimental hall due to high radiation levels, then there could be problems with the beam. Every people working there had to be in the room for eight hours a day, with the exception of a few days off.

4.3 ROOT

During our eight hours a day we learnt how to use ROOT, while we were waiting from one run start to the next.

ROOT is an object-oriented framework for large scale data analysis developed by CERN. ROOT command line interpreter and script processor is CINT. An interpreter takes a program, in the ROOT case a C++ program, and carries it out by examining each instruction and in turn executing the equivalent sequence of machine language.

![Figure 4.4: Me in the room, while programming.](image)

There are many ROOT versions available for download at the website: [http://root.cern.ch/root/Availability.html](http://root.cern.ch/root/Availability.html)

ROOT provides packages for many applications.

We learnt how to create, fill and fit graphs and histograms. Then we learnt how to divide a canvas, which is the basic whiteboard on which an object is drawn, in more parts, the so-called pads, so that more graphs or histograms can be visualized on the same canvas. We learnt how to apply the derivative and the integral to the object we drew, how to make copies of the objects and how to save them to files or read them from files. We also learnt how to draw error bars and how to create files in PostScript format.

After becoming confident with ROOT, we created some PostScript files similar in structure to the ones we were used to check after each run.

We worked on files that Duncan Middleton, one of the scientists working there, gave us.
4 MY WORK

Our purpose was to check the stability of gain of the photomultiplier tubes used in the experiment.

As I have already said, the neutron detector consisted of six layers, each composed of five bars. We wanted to plot each ADC channel against time, to see if the gain was constant in time. Each ADC channel is connected with one bar of one layer. To be more precise, we had two ADC channels for each bar, as each bar was equipped with photomultipliers on both ends and thus one ADC channel referred to the upper photomultiplier, while the other one referred to the lowest photomultiplier. Therefore, sixty ADC channels were in the aggregate, and as a consequence the PostScript graphs to realize were sixty.

Obviously, the reference calibration had been done with cosmic rays before the experiment began.

The obtained values had been saved to ROOT files, and those were the files which Duncan gave us. There were twenty files, and each file contained sixty histograms. Each histogram displayed two gaussians (see figure 4.5). The first gaussian, the one obtained at the lowest energy, was connected with the electrical noise: it was centered at a value, known as pedestal value, that had to be subtracted from the mean value, the so-called flasher value, of the second gaussian to obtain the ADC channel.

So we read the histograms from the ROOT files, we fit them with gaussians to obtain the mean and sigma values from the fitting and we saved these values in another file, that I named "results.dat", together with the difference between the mean values.

Plotting the ADC channels against time was equivalent to plotting the ADC channels against the files the ADC channels were calculated from, as each file contained the same kind of datas, but taken at a different time.

So at the end we should have had sixty graphs, with twenty points each as there were twenty files.

We used the file "results.dat" to generate the sixty graphs and the respective error bars. On the x-axis, which represented time, we put no error, we just put an error bar on the y axis, which represented the ADC channel. As the y value had been obtained by subtracting the mean pedestal value from the mean flasher value, the y error bar depended on the sigma connected with both values. Anyway, as the sigma connected with the flasher value was usually almost ten times bigger than the sigma connected with the pedestal value, we just neglected the error on the pedestal value.

Finally, we generated a PostScript file with the graphs we had drawn. We divided the canvas in ten pads, and thus we generated a PostScript file with six pages as each pad contained a single graph.

Images 4.6 and 4.7 show a few of the final graphs we obtained. They represent the ADC output for a light pulse that was fed into the bars.
Figure 4.5: Pedestal and flasher peak.
Figure 4.6: Two of the final graphs.
The upper one refers to Layer4/Bar2/ADC up, the lower one refers to Layer4/Bar3/ADC up.

Figure 4.7: One of the final graphs.
It refers to Layer1/Bar1/ADC up.

One expects that a stability of gain implies a continuous straight line in the graph of the ADC channel against time. Well, this is correct and a trend like this is found in many of the graphs drawn. Figure 4.6 shows just two of these graphs.

Anyway, other graphs, like the one in figure 4.7, do not show a continuous straight line, but two different straight lines. This was due to change in high voltage to the photomultiplier. The ADC signal was becoming saturated because of high count rates for the bar so the high voltage was reduced to lower the count rate.
4 MY WORK

These two ADCs look quite good because the signal position seems to have stayed reasonably constant apart from the step.

For other bars where a slope is seen (see figure 4.8) a correction factor will be applied to correct for decrease of pulse height.

![Figure 4.8: One of the final graphs. It refers to Layer2/Bar1/ADC down.](image)

In the appendix I include the programs I wrote to create the histograms, the graphs, the files I needed and the PostScript files.

4.4 Helping dismounting

The last thing we did was helping A1 Collaboration members to rid A1 hall of the features it did not need anymore, or at least it did not need for the next experiment. In particular, we helped disassembly the neutron detector: we moved the hooks to elevate its pieces (which were quite heavy: each was some tons heavy), and drove the fork lift to move the pieces.

We also helped removing cables connected with the electronics.

![Figure 4.9: Fork lift with a piece of the neutron detector.](image)
4 MY WORK

![Image](4.10.png)

Figure 4.10: Piece of the neutron detector which is being elevated.

![Image](4.11.png)

Figure 4.11: Disassembling the cables.

4.5 Conclusions

In conclusion, my stage in Mainz has been a really good experience: I saw how physicists work and collaborate with each other during experiments, I learnt to use ROOT and how to move in an experimental hall. The experiment led to a result consistent with the expectations and finally, but not for this reason less important, I worked among nice people.
A Appendix

A.1 Creating histograms as the one in figure 4.5 and the file "results.dat"

```c
int bar, layer, run; char file_name[50] = "results.dat";
char histo_up[10]; char histonew_up[10];
char histo_down[10]; char histonew_down[10];
char title[20]; Int_t MAX_RUNS = 20;
char datafile[MAX_RUNS][256]; char textfile[MAX_RUNS][256];
TCanvas *cand = new TCanvas("canvas","canvas",500,500,1600,1600);
cand.Draw(); canvas.Print("mypictures.ps");
fprintf(fp_out, " file histo ped peak diff sigma peak\n\n");
for(Int_t run=0;run<MAX_RUNS;run++) {
  cout<"datafile[run]<"<endl; sprintf(textfile[run], "%s", datafile[run]);
  TFile *f=new TFile(datafile[run], "READ");
  layer=0; for(layer=0;layer<6;layer++) {
    bar=0; for(bar=0;bar<=4;bar++) {
      cout<"Layer \%d Bar \%d UP\n\n",layer+1,bar+1; sprintf(histo_up,"h%d",2*bar+1+(10*layer));
      printf(histo_up); up_ped = (TH1F*)f.Get(histo_up); up_ped.Draw();
      gaus.SetLineColor(4); up_ped.Fit("gaus", "W", "L", 0, 90);
      mean_ped = gaus.GetParameter(1); printf("mean ped = %.4f\n\n", mean_ped);
      TString hname = histo_up->GetName();
      TString histo_up = (TString)hname+(TString)"new histo: \"; histo_up=";
      _<TFile*>f->Open("\"new histo: \"; histo_up+"hs\"");
      hname.SetName(histonew_up);
      TH1F *hnew_ped = (TH1F*)f->Get(histonew_up); hnew_ped.Draw();
      gaus.SetLineColor(2); hnew_ped.Fit("gaus", "W", "L", 0, 90);
      mean_ped = gaus.GetParameter(1); mean_peak = gaus.GetParameter(2);
      printf("mean peak = %.4f\n\n", mean_peak);
      bar=1; for(bar=1;bar<=4;bar++) {
        printf("Layer \%d Bar \%d DOWN\n\n",layer+1,bar+1);
        sprintf(histo_down,"h%d",2*bar+(10*layer));
        printf(histo_down); down_ped = (TH1F*)f->Get(histo_down); down_ped.Draw();
        gaus.SetLineColor(4); down_ped.Fit("gaus", "W", "L", 0, 90);
        mean_ped = gaus.GetParameter(1); mean_peak = gaus.GetParameter(2);
        printf("mean peak = %.4f\n\n", mean_peak);
        bar=0; for(bar=0;bar<=4;bar++) {
          printf("Layer \%d Bar \%d UP\n\n",layer+1,bar+1);
          sprintf(histo_up,"h%d",2*bar+1+(10*layer));
          printf(histo_up); up_ped = (TH1F*)f->Get(histo_up); up_ped.Draw();
          gaus.SetLineColor(4); up_ped.Fit("gaus", "W", "L", 0, 90);
          mean_ped = gaus.GetParameter(1); mean_peak = gaus.GetParameter(2);
          printf("mean peak = %.4f\n\n", mean_peak);
        }
      }
    }
  }
}
```

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TH1F(\*down\_peak = (TH1F\*)f.Get(histonew\_down); down\_peak.Draw();
gaus.SetLineColor(2); down\_peak.Fit("\char"{}gaus\char"{}",\char"{}W\char"{},\char"{}L\char"{},100,960);
mean\_peak = gaus.GetParameter(1); sigma\_peak = gaus.GetParameter(2);
printf("\char"{}mean peak = \%10.4f\textbackslash{}n\textbackslash{}n\textbackslash{}n\char"{},mean\_peak);
printf("\char"{}sigma peak = \%10.4f\textbackslash{}n\textbackslash{}n\textbackslash{}n\char"{},sigma\_peak);
diff=mean\_peak-mean\_ped;
fprintf(fp\_out,"\%10.0d \%10.0d \%10.2f \%10.2f \%10.2f \%10.2f\textbackslash{}n", run+1,2*bar+(10*layer),mean\_ped,mean\_peak,diff,sigma\_peak);
} canvas.Print("mypicutures.ps"); }
}
canvas.Print("mypicutures.ps");
fclose(fp\_out);
}

A.2 Creating the final graphs

Examples of the final graphs are the ones in figure 4.6 and 4.7.

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```cpp
TGraphErrors file = gtimes();

TGraphErrors *my_histo = new TGraphErrors(file, xval, yval, xerr, yerr);
my_histo->SetTitle(htitle);
my_histo->GetXaxis()->SetTitle("time");
my_histo->GetYaxis()->SetTitle("ADC channel");
my_histo->GetXaxis()->SetRangeUser(0, 21);
if (bar==5) {
    layer++; bar=0;
} bar++;
}

Int_t layer=1; Int_t bar=1;
for(Int_t my_histo=2; my_histo <= 60; my_histo+=2) {
    sprintf(htitle, "ndet/layer %d/Bar %d/ADC down");
    for(Int_t i=0; i<no_files; i++) {
        xval[i] = x_value[my_histo][i+1]; yval[i] = y_value[my_histo][i+1];
        xerr[i] = x_err[my_histo][i+1]; yerr[i] = y_err[my_histo][i+1];
    }
    my_histo = new TGraphErrors(file, xval, yval, xerr, yerr);
    my_histo->SetTitle(htitle);
    my_histo->GetXaxis()->SetTitle("time");
    my_histo->GetYaxis()->SetTitle("ADC channel");
    my_histo->GetXaxis()->SetRangeUser(0, 21);
    if (bar==5) {
        layer++; bar=0;
    } bar++;
}

TCanvas *cantime = new TCanvas("cantime", "cantime", 100, 100, 800, 600);
cantime->Divide(2, 5, 0.01, 0.01); cantime->cd(); TPostScript *ps = new TPostScript("ndet_grafici.ps", 112);
temp=1;
for(Int_t my_histo=1; my_histo <= 60; my_histo++) {
    cantime->cd(temp); my_histo->SetMaximum(1000); my_histo->SetMinimum(0);
    my_histo->SetMarkerStyle(21); my_histo->SetMarkerColor(kRed);
    my_histo->SetMarkerSize(0.2); my_histo->Draw("AP");
    printf(" next histo: %d \n");
    cantime->Update(); if (my_histo==10) {
    cantime->Update(); ps->NewPage();
    if(temp==10 && my_histo==60) {
        cantime->Update(); ps->NewPage(); temp=0; cantime->cd();
    }
    temp++;}
    ps->Close();
}
```

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Bibliography


[36] Several other publications available at the website: http://www1.kph.uni-mainz.de/AI/publications/
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