Chapter 1

A new polarimeter

*It is remarkable that it is more difficult to think of methods of detecting polarization, which seems apt for realization, than of methods of producing polarization.*  

H.A. Tolhoek [1]

The above quotation is taken from the classic and often cited review on “Electron Polarization, Theory and Experiment” by Tolhoek [1] published 40 years ago. The field has changed since then. However, the number of realized methods to detect the polarization of electrons and photons is still limited and remains mostly restricted to lower energies (below 10 MeV) or to the very high energies (GeV regime).

This thesis describes a search for possibilities to arrive at novel polarimetry for electrons, positrons and photons in the less accessible energy regime from 10 to 100 MeV. The main idea is to develop a polarimeter whose sensitivity is increased by incorporating several polarization sensitive processes in one device and by placing multiple scattering layers behind each other in one and the same polarimeter.

In the literature only few polarimeters operating in the energy range between 10 and 100 MeV [2, 3] can be found. At lower energies Mott scattering is generally used. In the past Mott scattering played an important role at energies below 1 MeV. The ‘fall of parity’ in β decay was experimentally studied by using Mott scattering. See for example the work of van Klinken [4] and the overview in the book of Kessler [5]. Recently, Sromicki et al. [6] obtained results for energies up to 14 MeV. With the advent of polarized high-energy (>100 MeV) electron beams, other types of polarimeters suitable for this energy regime were developed. They are either based on Möller
scattering (see for example [7, 8]) or Compton scattering (see for example [9]). In chapter 2 a general introduction to and an overview of polarimetry methods will be given.

### 1.1 Motivation for a new polarimeter

The motivation to consider the feasibility of a novel polarimeter originated during the planning of proton-proton-bremsstrahlung experiments with polarized proton beams at the KVI-Groningen. Such studies are presently restricted to measurements of the analyzing power of the nucleons participating in the reaction. Here attention is directed to the possibility of performing polarimetry with the emitted photon. In the ‘ppγ experiment’ [10], at present ongoing with the first polarized proton beams of the new KVI accelerator AGOR, a beam of polarized protons of 200 MeV is interacting with a liquid hydrogen target. The scattered and recoiling protons are measured in coincidence with bremsstrahlung photons of around 50 MeV. The experiments are intended to provide valuable information on the off-shell nucleon-nucleon interaction by measuring the analyzing power. However, it was expected, and confirmed by calculations [11], that the polarization of the bremsstrahlung photon also contains information on the off-shell behaviour of the interaction. Photon polarimetry could thus provide a novel, and so far not yet pursued, approach to study the nucleon-nucleon interaction.

The use of the envisioned polarimeter is not restricted to photons but may also be extended to electrons and positrons. This possibility allows an extension of the concept to ‘electromagnetic polarimetry’. For example, it might be incorporated in muon decay experiments planned at PSI in Switzerland [12, 13].

### 1.2 The proposed polarimeter

Electromagnetic polarimetry at energies of several tens of MeV has thus far hardly been pursued because the polarization sensitive methods are characterized by a decreasing efficiency with increasing energy. One of the few experiments with photons found in the literature was done by Garwin and co-workers [2] as early as 1957. Their aim was to determine the circular polarization of 70 MeV photons emitted by neutral pions. The detector used in
their pioneering experiment was based on the spin dependence of Compton scattering of photons in magnetized iron. Because Compton scattering is not the most dominant process in photon interactions with matter at 70 MeV the resulting detector efficiency is low. Pair production, the dominating process at these energies, is in theory polarization sensitive but in practice difficult to use (see chapter 2 and 3). However, in pair production part of the circular polarization of the photon is transferred to the electrons and positrons. The secondaries are partly longitudinally polarized: this opens the way to polarimetry based on Möller and Bhabha scattering and the annihilation process.

![Diagram of the multilayer polarimeter](image)

**Figure 1.1:** The multilayer polarimeter using NdFe scattering foils. The BaF$_2$ detectors are included to reconstruct the full energy of the primary photons (or electrons) and to provide a trigger for the silicon strip detectors (SSDs; see 6.2). The arrows symbolize the magnetization direction of the NdFe target.

This leads to a polarimeter concept as sketched in figure 1.1. It consists of magnetic neodymium iron (Nd$_2$Fe$_{14}$B; in short notation NdFe) layers sandwiched between position sensitive silicon strip detectors (SSDs). Three aspects are novel in this polarimeter: First, the use of a permanent magnet as scattering target, second, the use of SSDs to detect the scattering processes, and third, the multilayer approach.
The soft magnetic iron foil of the Garwin experiment is replaced by layers of hard magnetic NdFe. This has two advantages: First, an NdFe layer can be magnetized perpendicularly to its plane (which is impossible when using soft magnetic materials in weak external magnetizing fields). And second, the NdFe does not need magnetizing coils. The NdFe layers can have thicknesses of about 1 mm. Usually, a thin permanent magnet has its magnetization direction in the plane of the material rather than perpendicular to it. Magnetization perpendicular to the surface became possible with the appearance of magnetic materials featuring large coercive forces. Such magnets can be made from materials containing rare earth elements, well known compounds being SmCo$_5$ and Nd$_2$Fe$_{14}$B.

The SSDs in between the layers of neodymium iron offer the possibility to localize and recognize the polarization sensitive interactions on an event-by-event basis. The silicon detectors give no signal when a photon passes through them, while a minimal ionizing electron loses a well-defined amount of energy. The different interactions in the NdFe layers like Compton scattering, Möller/Bhabha scattering, positron annihilation, pair production and bremsstrahlung can be discriminated on the basis of the number of particles observed with the SSDs before and after the magnetized layer. For example, the pair production occurring in the electromagnetic shower shown in figure 1.1 is identified by the absence of signals in the SSDs before the process occurs and the presence of signals of two particles afterwards. The Möller interaction is identified by detecting one particle before the scattering event and two particles after it.

The multilayer design increases the efficiency of the polarimeter in two ways. First, the chance that a particle interacts in the polarimeter is increased and second, by opening the possibility of detecting the polarization after the polarization is transferred from the primary particle to its secondaries in the electromagnetic shower.

Two aspects of the new polarimeter concept are investigated in this thesis:

1. The suitability of neodymium iron as polarimeter target material.

2. The above outlined scheme to discriminate the various relevant interactions.
1.3 Towards a new polarimeter

The feasibility of the polarimeter was investigated by designing and constructing one basic element of the detector. In the prototype one layer of NdFe is sandwiched between four SSDs, two on either side providing two-dimensional position detection. Tests were performed with fully longitudinally polarized electrons and positrons from $\beta$-decay sources with energies up to 16 MeV in an effort to demonstrate the polarimeter capability of the layer in its low-energy regime. Experiments with a $^{106}$Ru/Rh-source (endpoint energy 3.5 MeV) and online produced $^{12}$N- (16.4 MeV) and $^{12}$B-sources (13.4 MeV) are discussed in chapter 6. Properties of NdFe and other rare earth based magnetic materials are the subject of chapter 5.

Until recently technological constraints prevented the utilization of the various polarization sensitive processes in the way outlined above (NdFe was not available, there were no SSDs). The QED-theory for most of these processes was, however, available. It was developed before 1965 and will be presented in chapter 3 in a uniform way using the Stokes parameters [14, 15, 16].

Simulations play an important role in both the design and analysis of experiments. The Monte Carlo method is widely used and is applied in chapter 6. The GEANT [17] package contains all the relevant electromagnetic processes playing a role in the polarimeter. However, no polarization transport is included in this code. The implementation of the polarization phenomena discussed in chapter 3 in GEANT 3.21 is discussed in chapter 4. Both polarization transfer and scattering asymmetries can be simulated with the extended version of the package. The work was partly inspired by and in continuation of ideas and developments in the work of den Bok [18] and Flöttermann [16].

With the extended version of GEANT the experiments with the $^{106}$Ru/Rh source are simulated and the behaviour of the basic detector layer at particle energies of up to 90 MeV is investigated. The simulations provide information on the event recognition capabilities and offer a way to estimate the polarization sensitivity of the polarimeter. The results are presented and compared with the explorative measurements in chapter 6.

Chapter 7 summarizes the main conclusions and gives an outlook on future research.
1.4 Results

The efforts to show the polarization capability of the prototype polarimeter did not yet result in a clear demonstration of the polarization sensitivity. The measurements with the $^{106}$Ru/Rh-source did not reveal a statistically significant polarization asymmetry. Monte Carlo simulations explain that this lack of asymmetry is caused by a large non-polarization sensitive background which reduces the expected effect to below the detection limit of the polarimeter. The background is caused by non-NdFe-target related scattering events. The low energy (<3.5 MeV) of the electrons from the $^{106}$Ru/Rh-source made the use of a thin NdFe-target (0.5 mm) necessary. This resulted in a relatively large contribution from events originating in the SSDs. The time available for the experiments with the $^{12}$B- and $^{12}$N-sources was insufficient (two weeks) to be conclusive and to overcome the unexpected problems with the beam and target conditions and the SSD electronics in an accelerator environment. Background radiation related to the source production made a measurement of the scattering asymmetry impossible. The conclusions from these data are discussed in chapter 6. Simulations with mono-energetic electrons and photons with energies of 10 MeV and more indicate that further work on the polarimeter for these energies is promising. The simulations are presented at the end of chapter 6.