Doctoral Thesis

Development of a polarized atomic beam source and measurement of spin correlation parameters

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Development of a Polarized Atomic Beam Source and Measurement of Spin Correlation Parameters.

A dissertation submitted to the

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## Contents

1 Introduction .................................................. 2

2 Atomic Beam Source ........................................ 4
   2.1 Description of the Apparatus ............................ 5
       2.1.1 ABS Overview ...................................... 5
       2.1.2 Vacuum system ...................................... 5
       2.1.3 Dissociator ......................................... 7
       2.1.4 Sextupole Magnets ................................... 8
       2.1.5 High-Frequency Transition Units .................... 14
       2.1.6 Intensity and Degree-of-Dissociation Diagnostics .. 17
   2.2 Intensity Measurements .................................. 19
   2.3 Performance of High-Frequency Transition Units ....... 21
       2.3.1 Hydrogen Transitions ................................ 22
       2.3.2 Deuterium Transitions ............................... 24
   2.4 Summary ................................................ 25

3 Experiment .................................................... 28
   3.1 Overview of the experimental setup .................... 29
   3.2 Target layout and operation ............................. 32
       3.2.1 Atomic beam source ................................. 34
       3.2.2 Target ............................................. 38
Abstract

The polarized data from pion electro-production in the $\Delta$ region give new constraints to treatments of the underlying nucleon structure. In this work an experiment measuring spin correlation parameters in the $^1H(e,e')$ reaction is presented. The experiment was performed in the internal target facility of the MEA-AmPS accelerator at NIKHEF, Amsterdam. Electrons with energy of 720 MeV and longitudinal polarization of $\sim 60\%$ were scattered off the nuclear-polarized hydrogen gas provided by an upgraded Atomic Beam Source (ABS). The tracking and energetic information of scattered electrons was recorded in a large acceptance magnetic spectrometer, Bigbite. A maximal target thickness of $1.2 (1.1) \pm 0.1 \times 10^{14}$ nuclei/cm$^2$ was achieved with deuterium (hydrogen). With typical beam currents of 110 mA, this corresponds to a luminosity of about $8.4 (7.8) \pm 0.8 \times 10^{31}$ cm$^{-2}$ s$^{-1}$.

The upgrade of an ABS and its run-time performance as an internal target in the polarized electron facility are discussed in details. The upgrade resulted in an enhancement of the atomic beam intensity by a factor of $\sim 2.5$ and all required radio-frequency transitions working with efficiencies in the range 92-100$.\%$. The maximal output flux amounted to $(7.6 \pm 0.2) \times 10^{16}$ $^1$H/s and the target polarization amounted to $P_t = 0.78 \pm 0.07$ for deuterium and $0.65 \pm 0.08$ for hydrogen.

The analysis of experimental data was based on a Monte Carlo simulation technique. A theoretical model employed in the simulations allowed for an extraction of the electric and charge quadrupole form factors $E_2$ and $C_2$ at a four-momentum transfer $Q^2 = 0.11$ GeV$^2$/c$^2$. A non-zero value of these multipoles can be related to a D-state admixture in the nucleon wave function.
Kurzfassung

Die Daten zur Pion Elektro-Erzeugung in der $\Delta$ Region mit polarisierten Elektronen und Protonen ergeben Einschränkungen für die theoretische Behandlung der zugrundeliegenden Kernstruktur. In dieser Arbeit wird ein Experiment zur Messung der Spin-Korrelations-Parameter in der $^1H(e,e')$ Reaktion vorgestellt. Das Experiment wurde an der "Internal Target Facility" des MEA-AmPS Beschleunigers am NIKHEF, Amsterdam durchgeführt. Elektronen mit einer Energie von 720 MeV und einer longitudinalen Polarisation von 60% wurden an kernpolarisiertem Wasserstoffgas gestreut. Das Wasserstoffgas stammt von einer verbesserten Atomstrahlquelle (ABS). Die Bahnen von und die Energieinformationen der gestreuten Elektronen wurden in einem Magnetspektrometer mit grosser Akzeptanz (Bigbite) aufgezeichnet. Eine maximale Targetdicke von $1.2 (1.1) \pm 0.1 \times 10^{14}$ Kernen/cm$^2$ wurde mit Deuterium (Wasserstoff) erreicht. Bei einem typischen Strahlstrom von 110 mA entspricht dies einer Luminosität von etwa $8.4 (7.8) \pm 0.8 \times 10^{31}$ cm$^{-2}$s$^{-1}$.

Der Umbau der ABS und ihr Laufzeitverhalten als internes Target in der "Polarized Electron Facility" werden detailliert besprochen. Der Umbau resultierte in einer Vergrösserung der Atomstrahlintensität um einen Faktor von etwa 2,5; des weiteren arbeiten alle benötigten elektromagnetischen Übergänge mit einer Ausbeute im Bereich von 92-100%. Der maximale Fluss am Ausgang beträgt $(7.6 \pm 0.2) \times 10^{16}$ $^1H$/s und die Polarisation des Targets liegt bei $P_t = 0.78 \pm 0.07$ für Deuterium bzw. $0.65 \pm 0.08$ für Wasserstoff.

Die Analyse der experimentellen Daten beruht auf einer Monte Carlo Simulation. Das in der Simulation verwendete theoretische Modell erlaubt die Bestimmung des elektrischen ($E_2$) und des Ladungs-Quadrupol-Formfaktors ($C_2$) bei einem Viererimpulsübertrag von $Q^2 = 0.11$ GeV$^2$/c$^2$. Ein von Null verschiedener Wert dieser Multipole könnte mit einer Beimischung eines D-Zustandes zu der Kern-Wellenfunktion in Beziehung gebracht werden.
Chapter 1

Introduction

There is a global effort in nuclear and high-energy physics to describe nuclei and nucleons in terms of their constituents in one fundamental theory. A topic of interest is a possible admixture of D state in the nucleon and Δ wavefunctions. The spherically symmetric quark model successfully derives the masses and magnetic moments of baryons, but it fails to predict the value of the axial-vector coupling constant $g_A$, the SU(3) decay ratio $(D+F)/(D-F)$ and the $\pi N\Delta$ coupling constant. The description of these observables can be improved if a D-wave admixture is introduced [1, 2]. Besides, several bag models predict a deformation of some baryons due to quark interactions [3, 4, 5]. These issues can be experimentally addressed using spin-dependent electron scattering from hydrogen and have prompted worldwide efforts to develop polarized atomic beam sources to be used with polarized electron beam facilities.

An experiment measuring D-state sensitive quadrupole transition form factors for the reaction $^1\bar{\text{H}}(e',e)\bar{\text{H}}$ was recently performed. This measurement of longitudinal and perpendicular spin correlation parameters for the $N-\Delta$ transition is the first such measurement in the world. This work describes the preparation of the polarized hydrogen/deuterium target (ABS), its performance during the entire experiment and analysis of the experimental data. The electron scattering experiment described in this work was based on the internal target technique which offers important advantages. The target polarization can be rapidly switched between selected values, and the polarization axis can be oriented in any direction. Furthermore, since pure hydrogen or deuterium gas is used and the electron beam encounters no window materials when passing through the target, the chemical and isotopical purities of the target itself are high, typically above 99 %. Therefore, uncertainties related to scattering from contaminants are small in most cases. This allows performing measurements of spin observables with low systematic errors, dominated by the uncertainty of the polarization measurement. However, when compared to
external target experiments, the internal target technique suffers from a relatively low luminosity (typically $10^{31-33} \text{s}^{-1} \text{cm}^{-2}$). Therefore, much effort in this field is devoted to the development of denser targets, and in particular of brighter polarized gas sources. For that purpose one of the ETH atomic beam sources (ABS) was upgraded. After a few modifications (new sextupole magnet focusing system, new hydrogen RF cavity, new pumps and hardware optimizations) it was employed at the AmPS electron storage ring at NIKHEF in Amsterdam. By means of high-frequency transition units polarized hydrogen targets were produced. An atomic beam intensity of about $7.6 \cdot 10^{16}$ atoms/sec and a target thickness of about $1.1 \cdot 10^{14}$ nuclei/cm$^2$ has been achieved, which corresponds to a luminosity of about $7.5 \cdot 10^{31}$ nuclei/cm$^2$-s at beam currents of $\sim 110$ mA. The nuclear polarization of the target was $\sim 70\%$. The sign of the target polarization was rapidly switched by changing the high frequency transitions in the ABS. Polarized atoms produced in the ABS were injected into an open-ended cylindrical storage cell located in the ring. Scattered electrons were detected in the large acceptance Bigbite detector, which consisted of a dipole magnet, two sets of wire chambers, a scintillator hodoscope and an aerogel Cerenkov detector.

This work is organized as follows: Chapter 2 describes the principles of a typical ABS, introduces the previously available hardware and focuses on its improvement process. Chapter 3 is devoted to the experimental setup and the ABS performance during the data-taking period. Chapter 4 provides the theoretical background and presents the analysis and interpretation of the experimental data. Chapter 5 summarizes the whole work with some remarks and final conclusions.
Chapter 2

Atomic Beam Source

In the last decade, the application of atomic beam sources (ABS) as sources for nuclear-polarized hydrogen and deuterium gas targets internal to storage rings has proved a fruitful technique for particle physics experiments [6, 7, 10, 11, 12, 13]. Pioneering work was carried out at BINP (Novosibirsk) [14], and later at DESY (Hamburg) [15], IUCF (Bloomington, IN) [16] and NIKHEF (Amsterdam) [8].

The ABS presented in this work was based on an existing apparatus previously used at the NIKHEF electron storage ring (AmPS) for measuring tensor analyzing powers of the elastic $^2\text{H}(e, e'd)$ and quasi-elastic $^2\text{H}(e, e'p)n$ reactions [6, 7, 10, 11]. A new set of experiments with polarized hydrogen and deuterium was planned [18] to investigate the electromagnetic response of the nucleon and deuteron, both in quasi-elastic kinematics and in the $\Delta(1232)$ region. These experiments required vector polarization of order unity and a target thickness in excess of $1 \times 10^{14}$ nuclei/cm$^2$. The major improvements applied to the ABS to achieve sufficient luminosity were (a) the design, implementation and optimization of a new Stern-Gerlach focusing system using rare-earth permanent sextupole magnets, and (b) the reduction of the H/D pressure in the beam-formation chamber by doubling the pumping speed. Furthermore, as the ABS needed to be configured as a source for internal target experiments to measure polarization observables, with either polarized hydrogen or vector/tensor polarized deuterium, high-frequency transition units were constructed (or modified) and tested. The ABS upgrade resulted in an enhancement of the atomic beam intensity by a factor of $\sim 2.5$ and all required transitions working with efficiencies in the range 92-100%. The maximal output flux amounted to $(7.6 \pm 0.2) \times 10^{16}$ $^1\text{H}$/s.

This chapter is organized as follows. In section 3.1 an overview of the apparatus and basic working principles are given. Selected results of intensity measurements are presented in section 3.3.1. Section 2.3 is devoted to the performance of the high-frequency
transition units.

2.1 Description of the Apparatus

2.1.1 ABS Overview

Conventional polarized atomic beam sources (ABS) are based on the well-known principle of Stern-Gerlach separation [19]. The ABS described in this work uses a three-stage differential vacuum system. As can be seen in fig. 2.1, molecular hydrogen (or deuterium) gas is injected into a pyrex tube where an RF-driven discharge dissociates the molecules. The produced atoms diffuse into the first high-vacuum chamber through a cryogenically cooled nozzle (typically 65 – 80 K). An atomic beam is formed by a wedge-shaped collimator (‘skimmer’) situated between the first and the second chamber. The atomic beam passes from the second to the third chamber via a second collimator. In the third chamber the beam is nuclear-polarized by two Stern-Gerlach sextupole magnets, employed to focus (defocus) the electron spin up (down) hyperfine states, and high-frequency units used for inducing transitions between selected hyperfine states (hfs). The second collimator dimensions are chosen to maximally reject atoms that fall outside the acceptance of the focusing system. During the testing and upgrading period a calibrated compression tube was mounted at the exit flange of the ABS for absolute beam intensity measurements. A fraction of the beam could be sampled out of the compression tube by opening a valve which connected the compression tube to a chamber containing a quadrupole mass spectrometer (QMS). This was used to analyze the molecular fraction of the beam. At a later time, and also during the whole experiment, the compression tube and QMS chamber were replaced by a simple Breit-Rabi polarimeter (BRP), consisting of a sextupole magnet and a QMS. This was used for studying the high-frequency transitions. The two beam diagnostics configurations are depicted in fig. 2.1. The picture of the ABS in the test setup with no beam monitoring part is presented in fig. 2.2.

2.1.2 Vacuum system

As mentioned above, the ABS vacuum system consisted of three chambers evacuated by powerful pumps. Chamber 1 was evacuated with two turbomolecular drag pumps (Pfeiffer 1600MC) with each 1150 ℓ/s pumping speed*, backed with a single two-stage rotary pump (Pfeiffer DUO-035D). Chamber 2 was evacuated with a 2200 ℓ/s turbomolecular

*Pumping speeds are for molecular hydrogen gas.
Figure 2.1: Schematic view of the atomic beam source test configuration. Ch1, ch2 and ch3: first, second and third vacuum chamber, respectively; 1: coldhead; 2: dissociator; 3a,3b,3c: sextupole magnets; 4: medium field transition unit; 5: strong field transition unit; e: ABS’s exit; 6: compression tube; 7: ionization gauge; 8: capillary with valve; 9: precision pressure transducer; 10: buffer vessel; 11: shutter; 12: quadrupole mass spectrometer; 13: target test chamber (schematic); 14: conductance limiter.
pump (Pfeiffer TPH 2200), backed with a turbomolecular drag pump (Pfeiffer TPD020) in series with a diaphragm pump (Balzers/Vacuumbrand MD8). A 5600 ℓ/s cryogenic pump (Leybold RPK3000) was used to evacuate chamber 3. With no gas throughput (no atomic beam), this vacuum system resulted in pressures of about $10^{-4}$, $10^{-6}$ and $10^{-7}$ mbar in the first, second and third chamber, respectively and about a factor five higher with the atomic beam. As previous studies already demonstrated [15, 16, 20], these pressures are sufficient to keep attenuation losses in each chamber below a few percent. The most critical pressure remained that of chamber 1: when halving the pumping speed by shutting off one of the two pumps, a loss of $\sim 16\%$ in intensity resulted (at H throughputs in the range of 1.0-1.4 mbar ℓ/s), which is in fair agreement with the results reported in Ref. [16].

### 2.1.3 Dissociator

The dissociator was described in details in Ref. [8], here only a brief description is given. The only substantial modification consisted of moving the coldhead from a side flange to the front flange, next to the dissociator can, as shown in fig. 2.1. This simplified all maintenance operations on the dissociator and nozzle.

Molecular gas was supplied to the ABS dissociator through a thermovalve controlled by a precision pressure transducer. Flow rates could be chosen in the range of 0-5 mbar ℓ/s and were measured by a flowmeter. The dissociation of molecules took place in a pyrex glass tube by means of an RF-driven discharge. This tube was placed inside another one
through which water was flown as a coolant. Cooling of the nozzle was provided by a 10 W closed-cycle He-refrigerator. A small water vapor admixture (0.5 – 1.0% of the absolute pressure at the entrance of the glass tube) was added. In addition to enhancing the degree of dissociation, this provision extended the lifetime of the glass tube and reduced the deposition rate of sputter products on the nozzle surface.

2.1.4 Sextupole Magnets

The principles of Stern-Gerlach separation magnets are fully described in ref. [19]. Here only a brief summary concerning sextupole magnets is presented while the focus is on implementing new permanent sextupole magnets to the existing setup. Fig. 2.3 shows the energy-level diagram of a hydrogen atom in a magnetic field. It can be seen from the plot that in the inhomogenous magnetic field of a sextupole magnet the energy $E$ of the atom becomes a function of its position. The force the atom experiences is given by:

$$F = -\nabla E,$$  \hspace{1cm} (2.1)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{energy_level_diagram.png}
\caption{Energy-level diagram of a hydrogen atom in a magnetic field. The magnetic field is measured in units of a critical field (507 G) and the energy is measured in units of the resonant frequency 1420.4 MHz (5.8 \times 10^{-6} eV).}
\end{figure}

This force can be used to spatially separate atoms in different magnetic substates. In a sextupole magnet $B$ has a radial symmetry, thus the force on the atom is also radial and points toward (away from) the magnet’s symmetry axis for states with $m_j = +1/2$ ($m_j = -1/2$). Thus almost entirely atoms with $m_j = +1/2$ remain focused near the axis.
while \( m_j = -1/2 \) atoms are driven off the axis and eventually evacuated by the pumping system.

Stern-Gerlach magnets for atomic beam sources come in various forms: as conventional electromagnets (e.g. Ref. [21, 22]), superconducting magnets (e.g. Ref. [23]), or permanent magnets (e.g. Ref. [15, 16, 24]). To this date, best performance results for internal target applications were obtained with permanent magnets. Based on the results reported by the groups of UW-Madison [16] and MPI-Heidelberg [15], and the properties of commercially available rare-earth permanent sextupole magnets, raytrace calculations were performed to design a new focusing system [8], compatible with the existing setup. Seven sextupole elements, with the parameters given in table 2.1, were fabricated and mounted instead of old electromagnets available in the setup. Each element consists of 24 sectors with either a tapered or straight bore, as shown in fig. 2.4.

The orientation of the magnetization is rotated by 45° from sector to sector. This configuration results in a sextupolar magnetic field in the bore. The material (Vacodym 362HR) used for the sectors with radial and 45°-tilted magnetization was chosen for its high remanence field (1.33 T). For sectors with transverse magnetization, a material (Vacodym 396HR) with somewhat larger coercivity (2070 kA/m instead of 1360 kA/m) and lower remanent field (1.22 T) was chosen. All magnets, after assembly, were encapsulated in a vacuum-tight stainless steel can of a cylindrical shape (fig. 2.5). Inside the bore the can walls are 0.3 mm thick. The (front and back) flat walls are 0.5 mm thick, whereas

<table>
<thead>
<tr>
<th>Magnet element</th>
<th>( d_{in} ) [mm]</th>
<th>( d_{out} ) [mm]</th>
<th>( D ) [mm]</th>
<th>( L ) [mm]</th>
<th>( B_{tip}^{in} ) [T]</th>
<th>( B_{tip}^{out} ) [T]</th>
<th>( B_{exp}^{tip} ) [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>11.2</td>
<td>13.0</td>
<td>40.0</td>
<td>35.0</td>
<td>1.71</td>
<td>1.66</td>
<td>1.48 ± 0.19</td>
</tr>
<tr>
<td>#2</td>
<td>13.6</td>
<td>17.2</td>
<td>60.0</td>
<td>35.0</td>
<td>1.76</td>
<td>1.70</td>
<td>1.63 ± 0.16</td>
</tr>
<tr>
<td>#3</td>
<td>18.0</td>
<td>24.0</td>
<td>60.0</td>
<td>40.0</td>
<td>1.68</td>
<td>1.56</td>
<td>1.50 ± 0.12</td>
</tr>
<tr>
<td>#4</td>
<td>25.0</td>
<td>25.0</td>
<td>80.0</td>
<td>25.0</td>
<td>1.67</td>
<td>1.67</td>
<td>1.44 ± 0.10</td>
</tr>
<tr>
<td>#5</td>
<td>25.0</td>
<td>25.0</td>
<td>80.0</td>
<td>35.0</td>
<td>1.67</td>
<td>1.67</td>
<td>1.44 ± 0.10</td>
</tr>
<tr>
<td>#6</td>
<td>25.0</td>
<td>25.0</td>
<td>80.0</td>
<td>45.0</td>
<td>1.67</td>
<td>1.67</td>
<td>1.44 ± 0.10</td>
</tr>
<tr>
<td>#7</td>
<td>25.0</td>
<td>25.0</td>
<td>80.0</td>
<td>65.0</td>
<td>1.67</td>
<td>1.67</td>
<td>1.44 ± 0.10</td>
</tr>
</tbody>
</table>

Table 2.1: Dimensions and pole-tip fields of the new sextupole magnets. \( d_{in, out} \), \( D \) and \( L \) are defined in fig. 2.4. \( B_{tip}^{in} \) \( (B_{tip}^{out}) \) is the pole-tip value of the magnetic field at the entrance (exit) of the magnet bore calculated from expression 1. \( B_{exp}^{tip} \) is the determined pole-tip field halfway between the entrance and exit, as explained in the text.

\( ^{\dagger} \)By Vacuumschmelze GmbH, Gruener Weg 37, D-6450 Hanau 1.
the outer cylindrical can walls are 5 mm thick. The cans were evacuated and sealed. This canning is necessary to prevent degradation of the magnet materials by exposure to hydrogen. Note that the magnets were glued to the can walls in order to avoid undesired rotations of the magnets inside the cans.

The magnet elements were grouped in two sets. Sufficient space between the two sets was provided to accommodate the installation of a high-frequency transition unit (section 2.1.5). The elements were mounted in frames, as shown in fig. 2.5, which allowed for independent manual displacements of each element by a few mm along the atomic beam axis. In this way the optical properties of the system and the vacuum conductance between the elements could be fine-tuned. The frames were retractable via pneumatically activated linear feedthroughs. This feature was needed during optimization of the focusing system: it allowed monitoring the degree of dissociation independently of the magnet configuration, thus ensuring a meaningful comparison between the various measurements. Also, the retractability of the second magnet set allowed for collecting additional information when measuring hyperfine state populations with various combinations of high-frequency transitions. Fig. 2.6 shows pictures of sextupole magnet elements in the retractable frames.

The radial magnetic field of a sextupole magnet is expected to have the form $B(r, \phi) = B_{\text{tip}}(2r/d)^2 \cos(3\phi)$, where $r$ is the radial distance from the axis, $\phi$ is the azimuthal angle, $B_{\text{tip}}$ is the field strength at the pole tip, and $d$ is the bore diameter. The expected pole-tip field $B_{\text{tip}}$ for a given multipolarity, number of sectors $N$, magnet bore diameter $d$, outer diameter $D$ and remanence field $B_{\text{rem}}$, was derived by Halbach for infinitely long magnets.
Figure 2.5: View of the sextupole magnets in their retractable frames. Part of the vacuum chamber is visible.

To a good approximation it is given by:

$$B_{\text{tip}} = 1.5 \cdot B_{\text{rem}} \cdot (1 - d^2/D^2) \cdot K_N,$$

(2.2)

where $K_N$ is a factor that takes the value of 0.95 for $N = 24$ sectors. Based on this formula (thus neglecting tapering, finite size effects and gaps between sectors), and using an average of 1.3 T for $B_{\text{rem}}$, the pole tip field values given in table 2.1 under $B_{\text{in}}^{\text{tip}}$ and $B_{\text{out}}^{\text{tip}}$ were calculated. The quality of the magnets was judged by (a) measuring the $\phi$ dependence of the radial magnetic field at a close and constant distance from the pole tips and (b) by scanning the radial $B$ field between two opposite poles. This was repeated at three positions on the magnet’s axis (near the entrance, middle and exit of each element). Fig. 2.7 and 2.8 show the fieldmap measurements for all the sextupole elements. The pole tip values were determined by extrapolation and are listed in table 2.1, under $B_{\text{exp}}^{\text{tip}}$. The measurements were corrected for the finite size of the sensitive area of the Hall probe. The results of the measurements were found slightly lower than the values calculated from expression 2.2. However, the calculated values do not take into account the finite length of the magnets and the gap between the various sectors due to the use of glue.
Figure 2.6: (a): One of the sextupole magnet’s elements placed in a retractable frame. (b): Sextupole magnet in a retractable frame mounted inside the ABS. The coil of the RF transition unit is visible to the right.
Figure 2.7: Radial field as a function of the azimuthal angle for sextupole magnet elements #1-#7.
2.1.5 High-Frequency Transition Units

The following deuterium transitions required for tensor-polarization experiments were previously available (Ref. [26]): strong field transitions (SFT) 2-6, 3-5, and medium field transition (MFT) 1-4 (in fact, a sequence of 3-4, 2-3 and 1-2). In order to support both vector and tensor polarization and both hydrogen and deuterium beams, the following additional transitions were implemented:

1. The MFT was modified to facilitate the hydrogen 1-3 and 2-3 transitions and the deuterium 2-4 and 3-4 transitions, in addition to the previously available 1-4 transition. This was achieved by shortening the RF coil (4 loops, Ø28 mm, 20 mm long) setting the magnet pole surfaces parallel instead of tapered and adding a gradient coil on the poles capable of producing a slope of up to ±0.3 mT/cm. The RF coil was placed between two grounded copper cylinders (Ø28 mm, 30 mm long and 20 mm away from the coil), to reduce the RF field outside the coil. The RF power was given by a 20 W broadband RF amplifier (Kalmus 250FC) fed by a variable frequency (1-100 MHz) sine-wave generator (frequencies in the range 8-65 MHz were used). The MFT was mounted between the first and second sextupole sets and was used in combination with the second sextupole magnet to reject, when needed, a given hyperfine state.

2. An additional cavity was constructed for the SFT to produce the 2-4 hydrogen sigma
transition. The cavity is identical in design to the deuterium sigma cavity except for the tunable ceramic capacitors in the resonant structure [26], which were simply removed. The proper capacitance to achieve a resonance frequency of 1.46 GHz was obtained by adding short bends at the open ends of the current-carrying copper legs as sketched in fig. 2.9. Fig. 2.10 shows pictures of SFT cavity. The copper legs are grounded on one end only, forming thus a quarter-wave cavity. Such stray capacitances are well-suited to adjust the resonance frequency in the range of interest.

3. A weak field transition (WFT) was added, to reverse the populations of Zeeman substates with opposite total spin projection \( m_F \) (H: 1-3, D: 1-4, 2-3, and 5-6). A shielded electromagnet available from the former polarized ion-source of the ETH tandem accelerator (Zürich) was used [27]. The RF field was produced in a 14-turn, Ø22 mm, 4 cm long coil wound around the teflon pipe (Ø20 mm, 10 cm long, 1 mm wall thickness) that provided the connection between the ABS chamber 3 and the internal target vacuum chamber. The coil was at the same time used as the inductance of a home-made electron-tube oscillator circuit. The WFT was operated at a frequency in the range of 6-12 MHz.

Some of the relevant transition schemes enabled by these high-frequency units are listed in table 2.2. As can be seen, only the 2-hfs scheme for hydrogen in a strong target field required vacuum access for swapping the deuterium and hydrogen cavities.
Figure 2.10: (a): SFT cavity. (b): SFT cavity mounted inside the transition unit. The whole unit is mounted on the ABS’s exit flange. The arrow shows where the SFT cavity is mounted.
Table 2.2: Some of the transition schemes facilitated by the present apparatus. $B_t \gg B_c$ indicates that a B-field large compared with the H or D critical field $B_c$ is applied in the target region. $P_z$ and $P_{zz}$ give the theoretically achievable vector and tensor polarizations for the specified schemes. Note that the MFT is located between two sextupole magnets.

### 2.1.6 Intensity and Degree-of-Dissociation Diagnostics

The atomic beam intensity measurements were performed by using a calibrated compression tube. The atomic beam was directed into a stainless steel chamber via a stainless steel tube of 122 mm length and diameter $D_{ct} = 10, 12$ or $16$ mm. The pressure in this chamber was monitored with a Bayard-Alpert ionization gauge. The pressure obtained while injecting the H atomic beam was compared to the values measured when injecting known amounts of molecular H$_2$ gas directly into the compression tube. This was done by filling a known buffer volume $V$ with H$_2$ to a few mbar and letting the gas bleed out to the compression tube chamber through a capillary. The flux $f$ is related to the time derivative of the buffer pressure $p$ by $f = 2 \cdot V \cdot dp/dt \cdot (k_BT)^{-1}$ (in atoms/s), where $k_B$ is the Boltzmann constant and $T$ the buffer vessel temperature. During the calibration, atomic beam was flown into chamber 3 (and blocked by a partly retracted sextupole such that the gas could not enter the compression tube directly) in order to set a chamber 3 background pressure identical to the one obtained when injecting atomic beam into the compression tube. Without this provision, beam intensity results would be increased by 5 to 10%.

In order to be able to compare the performance of different configurations of the beam-formation elements or of the sextupole magnets, a monitor for the relative degree of dissociation was needed. This was done by retracting the sextupole magnets, opening a valve at the exit of the compression tube chamber, and measuring the atomic and molecular responses, $S_1$ and $S_2$, in a quadrupole mass spectrometer (fig. 2.1). The degree
of dissociation was defined as follows: $\delta = S_1/(S_1 + 2cS_2)$, where $c$ is a coefficient of order unity that takes into account mass-dependent effects, such as those due to differences between atoms and molecules in the velocity distribution, the ionization cross section or the transport efficiency. Note that $c$ is only needed if one wishes to determine an ‘absolute degree of dissociation’ (at the location of the QMS).

The $c$ was experimentally determined by calibrating the QMS, as described next. Note, however, that due to the higher attenuation for molecules throughout the ABS, $\delta$ is still expected to give values larger than the actual degree-of-dissociation at the nozzle. The QMS-dependent coefficient $c$ was extracted from measurements in which the relative amount of atoms and molecules was varied by changing the RF power in the discharge, while recording both the atomic and molecular QMS signals. The gas throughput in the dissociator was kept constant. A low throughput was chosen (0.3 mbar $\ell$/s) to keep scattering effects\(^1\) at a negligible level. This assertion is based on the observed linear behavior of the beam intensity as a function of gas throughput $Q$, for low values of $Q$ (up to $\sim 0.5$ mbar $\ell$/s) [16, 20]. Under this assumption, one expects also a linear relation

\[ S_2 \quad S_1^\theta \]

\[ 1.5 \quad 1 \quad 0.5 \quad 0 \]

\[ 0 \quad 0.5 \quad 1 \quad S_1^\theta \]

Figure 2.11: Quadrupole mass spectrometer calibration: the mass-2 ($H_2$) response is shown as a function of the mass-1 ($H$) response while changing the degree of dissociation at the nozzle.

\(^1\)Non-linear rest gas attenuation or $\delta$-dependent velocity distribution in the nozzle-skimmer region.
between the signals $S_1$ and $S_2$, which was indeed observed, as outlined by the oblique line in fig. 2.11. A value for $c$ can be extracted from this linear fit: $c = \frac{S_1^0}{S_2^0}$, with $S_{1,2}^0$ the intersections of the line with the x- and y-axes. Using the extracted value $c = 0.34 \pm 0.01$, values of $\delta$ in the range 75 – 85 % were routinely obtained at throughputs $Q$ up to $\sim 1.3$ mbar/\(\ell/s\) and nozzle temperatures of 65 – 80 K.

2.2 Intensity Measurements

Many parameters affect the atomic beam intensity, e.g. the nozzle temperature, gas throughput, geometry of the beam formation elements, configuration of the sextupole magnets, etc. In view of the large number of parameters, an investigation of the complete parameter phase-space was not possible. Instead, the optimum magnet configuration given by the raytrace studies (which, however, do not take into account scattering processes) and a beam-formation scheme close to what Wise et al. [16] and Stock et al. [15] quote as their optimum was taken as a starting point. Subsequently, the attention was paid to: (a) fine-tune the distances between the elements, (b) to optimize the trade-off between optical properties and evacuation of unfocused gas, and (c) optimize the nozzle-to-skimmer distance. In most cases, for a new configuration, a scan of the gas throughput and nozzle temperature was performed to find the maximum intensity. Note that only hydrogen gas was used during these optimization studies. Unless otherwise indicated, the measurements were done with a $\Theta 12$ mm x $122$ mm compression tube, at a distance of 27 cm from the last focusing element. This configuration realistically simulates the feed tube of the storage cell to be used in the 97-01 internal target experiments [18].

In order to facilitate magnet configuration studies, a valve separating the third chamber from the others as well as a valve on the cryopump were foreseen. This allowed to change the sextupole setup within a few hours while keeping the same conditions in the beam formation chamber. The sextupole elements were aligned on the atomic beam axis to a precision of 0.3 mm. The spacing between the magnet elements was found critical only in the initial part of the first set. From the originally chosen value of 5 mm for all gaps, an increase in intensity of 10 % was obtained by using 14 mm space between element #1 and #2, 9 mm between #2 and #3, and 7 mm between #3 and #4. For the subsequent elements, varying the spacing did not add any performance increase, suggesting that the rest gas scattering in these magnets was sufficiently small. Fig. 2.12 shows an example of beam intensity measurements where the distance between the nozzle and the skimmer was varied. A maximum for this setup was found for a distance of 9 mm and a throughput of about 1.1 mbar/\(\ell/s\). For internal target applications, where the atomic
beam needs to be injected into a long and narrow feed tube of a storage cell, the diameter and divergence of the atomic beam are important. Measurements of the intensity were performed with compression tubes of different diameters, both at a distance of 697 mm and 823 mm from the nozzle exit (i.e. 145 mm and 270 mm from the exit of the last sextupole element). Fig. 2.13 shows a comparison of these measurements with raytrace calculations that were performed using velocity distribution parameters from Ref. [28]. The solid (dashed) curve is the result of these calculations for the compression tube at 697 mm (823 mm) from the nozzle. Table 2.3 summarizes the configuration of the setup that gave best results with respect to absolute atomic beam intensity. The distances are given relative to the (Ø2.5 mm) nozzle exit. Both the position and diameters are given of the beam-formation elements, magnet elements (including canning), and high-frequency transition units. For the transition units, the restrictions are determined by the RF-cutoff cylinders (MFT), the cavity (SFT) and the teflon tube (WFT), see section 2.1.5. With this configuration the ABS was capable of delivering fluxes of $5.9 \pm 0.2 \times 10^{16}$ H/s into a Ø12 mm x 122 mm compression tube, at a distance of 823 mm from the nozzle exit (270 mm from last focusing element). Also, a few measurements with deuterium were carried out and generally resulted in an atomic beam intensity lower by a factor of ~ 1.4, with the optimum throughput shifted to lower values (typically 0.9-1.0 mbar l/s). These
findings are in agreement with earlier measurements [8] and those of Ref. [16].

2.3 Performance of High-Frequency Transition Units

The mechanism of RF induced transitions between atomic hyperfine states is well known and has been discussed in several publications (e.g. [29]). By means of an oscillating magnetic field, transitions between selected energy substates can be induced, provided that the frequency of the RF field matches the energy splitting of the substates in the static field. In the case of an atomic beam, a small gradient is superimposed to the static field in order to ensure that the resonance conditions are met once for each atom passing through the RF field. In order to generate nuclear polarization, the required spin substates are populated using high-frequency transitions inbetween and after the two sextupole magnets (table 2.2). By switching on and off selected transitions the polarization can be rapidly
Table 2.3: Configuration of the setup that gave best results with respect to absolute atomic beam intensity. The position of the item’s entrance is relative to the nozzle exit.

<table>
<thead>
<tr>
<th>item</th>
<th>position</th>
<th>length</th>
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<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>skimmer</td>
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<td>12.5</td>
<td>5.5-30.5</td>
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<tr>
<td>collimator</td>
<td>50</td>
<td>4.0</td>
<td>7.9-15.9</td>
</tr>
<tr>
<td>element #1</td>
<td>62</td>
<td>36</td>
<td>10.6-12.4</td>
</tr>
<tr>
<td>element #2</td>
<td>110</td>
<td>36</td>
<td>13.0-16.6</td>
</tr>
<tr>
<td>element #3</td>
<td>155</td>
<td>41</td>
<td>17.4-23.4</td>
</tr>
<tr>
<td>element #4</td>
<td>200</td>
<td>26</td>
<td>24.0</td>
</tr>
<tr>
<td>MFT</td>
<td>235</td>
<td>140</td>
<td>28.0</td>
</tr>
<tr>
<td>element #5</td>
<td>390</td>
<td>36</td>
<td>24.4</td>
</tr>
<tr>
<td>element #6</td>
<td>433</td>
<td>46</td>
<td>24.4</td>
</tr>
<tr>
<td>element #7</td>
<td>486</td>
<td>66</td>
<td>24.4</td>
</tr>
<tr>
<td>SFT</td>
<td>564</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>WFT</td>
<td>677</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>

changed. To test high-frequency transition units, the compression tube and QMS chamber were replaced by a simple Breit-Rabi polarimeter, consisting of a sextupole magnet and a QMS (fig. 2.1). This third sextupole magnet defocused atoms in the electron spin-down hyperfine states (H: hfs 3 and 4, D: hfs 4, 5 and 6). The QMS was set to record the atomic response (1 amu for hydrogen, 2 amu for deuterium). Next, several measurements are presented that show the performance of the required transitions. Note that the BRP response was normalized to the value obtained with all high-frequency transitions turned off.

### 2.3.1 Hydrogen Transitions

In the case of hydrogen, the first sextupole magnet, defocuses the ‘spin-down’ states 3 and 4, leaving two hfs in the atomic beam. Fig. 2.14 shows the QMS response while scanning over the magnetic field of the SFT. In this case, a gradient of $\sim 0.3$ mT/cm and an RF power of 5.5 W were used. The central static field at the center of the transition plateau was $12.7 \pm 0.1$ mT, which matches the resonance field of the 2-4 transition (12.6 mT) for a frequency of 1.46 GHz. Averaged over multiple scans, the efficiency of the SFT was $95 \pm 3\%$.

As shown in table 2.2, the MFT was used to induce a 2-3 transition before the second
sextupole, in order to eliminate hfs 2. Fig. 2.15 shows the QMS response scanned over the MFT central magnetic field with the SFT 2-4 transition turned off (solid curve) and on (dashed curve). In the first case, one can see a 1/2 signal drop when the ‘spin-down’ state 3 is maximally populated by the MFT. That the emptied state is indeed hfs 2 (and not 1) can be inferred from the fact that, when the SFT 2-4 is turned on, no further signal drop is observed. Here, the frequency was 45.8 MHz, and the field slope was set to \( \sim 0.05 \text{ mT/cm} \). The average efficiency of the MFT 2-3 transition was 97 \( \pm 1 \) %.

The WFT is used to switch the population numbers \( n(m_F = 1) \) and \( n(m_F = -1) \) of hfs 1 and 3 respectively. Fig. 2.16 shows a scan over the WFT magnet coil current with the MFT 2-3 turned on and off and SFT 2-4 transition turned off, and with the second sextupole magnet taken out. When operated alone (solid curve) one can see a drop of almost 1/2 of the BRP signal, which means that hfs 3 has been almost maximally populated. With the MFT 2-3 transition turned on (dashed line), hfs 1 and 3 enter the WFT with essentially equal population numbers, \( n(m_F = 1) \approx n(m_F = -1) \approx 0.5 \), while hfs 2 is empty, \( n(m_F = 0) \approx 0 \). Therefore the WFT is expected to leave the BRP signal unchanged if a pure \( n(m_F) \leftrightarrow n(-m_F) \) is taking place. This is indeed (approximately) observed at zero coil current (comparing the difference between the solid and dashed curves). On average an efficiency of 92 \( \pm 1 \) % for the WFT was obtained, when assuming that the transitions induced by the WFT unit are purely exchanging populations with opposite \( m_F \).

Figure 2.14: QMS response as a function of the SFT central magnetic field around the 2-4 transition.
2.3.2 Deuterium Transitions

The deuterium strong field transitions 3-5/2-6 and the ‘cascade’ medium field transition 1-4 were already demonstrated to have efficiencies close to unity [26]. The 3-4 medium field transition is demonstrated in fig. 2.17, which shows the QMS response scanned over the MFT central magnetic field with the SFT either off (solid curve) or tuned to either the 2-6 or 3-5 sigma transitions (dashed and dotted curve, respectively). These scans were taken with a MFT frequency of 35 MHz and a field gradient of $\sim 0.075$ mT/cm. From the observed scans one can conclude that the 3-4 medium field transition occurs with an efficiency of $97 \pm 1.5\%$. Similar results were obtained for the 2-4 transition at lower RF frequencies.

The WFT unit was tested similarly in combination with the SFT unit. As can be seen from fig. 2.18, the weak field transition unit is, as in the case of hydrogen, less efficient than the transitions induced by the MFT and SFT units. Again, the scan with the SFT unit turned off (solid curve) shows a close to $1/3$ drop of the QMS signal. With either SFT turned on an additional drop of about $1/3$ is observed, as expected. However, although a complete decomposition of the population numbers was not possible, the visible difference between the scan with the 3-5 turned on (dotted curve) and the scan with the 2-6 turned on (dashed curve) indicate that the WFT unit is not purely exchanging population numbers with opposite $m_F$. Neglecting this effect, a WFT efficiency of about $92 \pm 1.5\%$ was gained.
Figure 2.16: QMS response as a function of the WFT magnet coil current with the second sextupole magnet taken out and with the MFT 2-3 transition turned on/off.

The somewhat low performance achieved with the WFT unit, typically with efficiencies around 92%, might be attributed to improper shielding from the fringe fields of neighboring magnets (second sextupole and SFT), in view of the fact that the WFT operates at relatively small B-fields, in the range 0.5 – 1.0 mT. All other transitions, induced with the medium and strong field transition units, were measured to have efficiencies in excess of 95%, for both hydrogen and deuterium beams.

2.4 Summary

In this chapter the upgrade of an ABS to be operated as a source of nuclear-polarized hydrogen and deuterium for internal target experiments was presented. The vacuum conditions in the beam-formation chamber were improved which resulted in an increase of the beam intensity by a factor of 1.2. High tip-field (~ 1.5 T) rare-earth permanent magnets were used for a newly designed sextupole system. The overall intensity improvement factor was about 2.5. The ABS is now capable of injecting fluxes of \((5.9 \pm 0.2) \cdot 10^{16} \, \text{1H/s}\) into a \(\bar{D}12 \text{ mm}, 122 \text{ mm} \) long tube, while the total output flux amounted to \((7.6\pm0.2) \times 10^{16} \, \text{1H/s}\).

A versatile high-frequency transition scheme permits to deliver nuclear-polarized hydrogen beams as well as vector or tensor polarized deuterium beams. The required high-frequency transitions were developed and tested. All medium and strong field transition efficiencies exceeded 95%. The deuterium and hydrogen weak field transitions were some-
what less efficient (~ 92 %).

This apparatus has been recently used in a series of spin-dependent hydrogen/deuterium scattering experiments [18, 30] with a 720 MeV polarized electron beam stored in the AmPS ring in Amsterdam (NIKHEF). Target polarizations of 0.65 ± 0.08 for hydrogen and 0.78 ± 0.07 for deuterium could be achieved. Detailed description of the target performance as well as the target polarization will be discussed in the next chapter.
Figure 2.18: QMS response as a function of the WFT magnet coil current with the SFT either off or tuned to either the 2-6 or 3-5 sigma transitions.
Chapter 3

Experiment

In this chapter performance of a high-density polarized hydrogen/deuterium gas target internal to a medium-energy electron storage ring is presented. Compared to the previous electron scattering experiments with tensor-polarized deuterium at NIKHEF [8, 6, 7, 11, 10] the target figure-of-merit, \((\text{polarization})^2 \times \text{luminosity}\), was improved by more than an order of magnitude. The target density was increased by upgrading the flux of nuclear-polarized atoms injected into the storage cell and by using a longer (60 cm) and colder (\(\sim 70 \text{ K}\)) storage cell. A maximal target thickness of \(1.2 (1.1) \pm 0.1 \times 10^{14} \text{ nuclei/cm}^2\) was achieved with deuterium (hydrogen). With typical beam currents of 110 mA, this corresponds to a luminosity of about \(8.4 (7.8) \pm 0.8 \times 10^{31} \text{ e}^- \text{nuclei cm}^{-2} \text{s}^{-1}\). By reducing the molecular background and using a stronger target guide field, a higher polarization was achieved. The target was used in combination with a 720 MeV polarized electron beam stored in the AmPS ring (NIKHEF) to measure spin observables in electron-proton and electron-deuteron scattering. Scattered electrons were detected in a large acceptance magnetic spectrometer. Ejected hadrons were detected in a single time-of-flight scintillator array. The product of beam and target vector polarization, \(P_e P_t\), was determined from the known spin-correlation parameters of \(e'p\) (quasi) elastic scattering. With the deuterium (hydrogen) target, values up to \(P_e P_t = 0.49 \pm 0.03 (0.36 \pm 0.04)\) were obtained with an electron beam polarization of \(P_e = 0.62 \pm 0.04 (0.56 \pm 0.03)\) as measured with a Compton backscattering polarimeter [32]. From this, a cell-averaged target polarization of \(P_t = 0.78 \pm 0.07 (0.65 \pm 0.08)\) can be deduced, (including the dilution by unpolarized molecules).

This chapter is organized as follows. In section 3.1, an overview of the experimental setup is given. Section 3.2 describes in detail the target layout, i.e. ABS, storage cell and Breit-Rabi polarimeter (BRP). In section 3.3 issues related to the target performance, such as the target thickness, polarization and the background rates are addressed. Section 3.4
summarizes the contents of this chapter.

3.1 Overview of the experimental setup

The electron scattering experiments were performed at NIKHEF, Amsterdam, using the storage ring facility shown in fig. 3.1. Polarized electrons were produced by photo-emission from a strained layer semiconductor cathode (InGaAsP) [35]. The polarization at the polarized electron source (PES) was measured using a Mott polarimeter. The electrons were subsequently accelerated to 720 MeV in the Medium Energy Accelerator (MEA) and injected (~ 2 mA/injection on average) into AmPS [36]. By stacking pulses, stored currents in excess of 250 mA were obtained. However, due to the strong rise of the beam halo and the degradation of the beam polarization at such high currents, start currents of about 110 mA were typically employed during the measurements. The electron polarization was maintained by means of a Siberian snake [37, 38, 39] located in the ring section opposite to the internal target facility. The longitudinal polarization of the electrons in the ring was measured after the first dipole following the internal target with a Compton backscattering polarimeter (CBP) [32]. Two sets of movable slits, located in the ‘south’ and ‘east’ sections of the ring, were used to reduce background events originating from beam halo scattering from the storage cell.

In the internal target region the electron beam was guided through the 60 cm long storage cell. A doublet of steering dipole magnets around the target chamber allowed for

Figure 3.1: The medium energy accelerator (MEA) facility and the Amsterdam Pulse Stretcher storage ring (AmPS) at NIKHEF.
correcting for the deflection of the beam trajectory by the transverse component of the target magnetic field. The polarized atomic beam was produced by an ABS and injected into the storage cell feed-tube mounted inside the target chamber (see fig. 3.7). The target polarization was alternated every 8 s between two values by switching on/off the RF-fields of two high-frequency transition units in the ABS. The ABS was positioned vertically above the beam line (see picture 3.2) to facilitate usage of a large acceptance

Figure 3.2: Picture of the ABS configuration in the internal target hall. 0: supporting frames, 1,2: turbomolecular pumps, 3: cryogenic pump, 4: cryogenic coldhead, 5: target chamber with protective covers (100 μm thick stainless steel windows underneath), 6: cryogenic coldhead, 7: cryogenic pump, 8: Breit-Rabi polarimeter.

magnetic spectrometer, Bigbite [40, 41] used for detecting scattered electrons (see fig. 3.4) and translating tracking and energetic information of the scattered electrons into physical
quantities: angles and energies. Fig. 3.3 shows the ABS direct control station that was located on the BigBite side of the beam.

Figure 3.3: ABS direct control station located on the BigBite side of the beam.

The Bigbite spectrometer features a solid angle of 96 msr and a momentum acceptance of $200 - 900$ MeV/c. The spectrometer detector package consisted of two drift chambers, a scintillator and a diffusely reflecting aerogel Čerenkov detector [42]. On the other side of the beam line the scattered hadrons were detected in a time-of-flight 250 msr detector consisting of two scintillator walls. Each wall contained four vertically stacked 3-layer telescopes of 160 cm length and 20 cm height. The thicknesses of the three layers $\delta E$, $\Delta E$ and $E$ were 3, 10 and 200 mm, respectively [43].

For the measurement of spin asymmetries in the $\Delta$ region using polarized hydrogen the environment consisted essentially of the vertically mounted ABS providing nuclear-polarized hydrogen gas target and an electron spectrometer Bigbite, mounted at 40° with respect to the beam line. No hadron detector was used for this measurement. To reduce the background in inclusive measurements an additional scintillator was mounted in front of the Bigbite detector and added to the trigger. Both the Bigbite detector and its front scintillator were simulated in subsequent Monte Carlo simulations described in the next chapter. Two separate measurements of $A_T^\prime$ and $A_{TL}^\prime$ spin correlation parameters (see next chapter for definitions), about 2 weeks each, were taken for two settings of the proton polarization angle - parallel and perpendicular to the elastic 3-momentum transfer. The proton polarization axis was changed by adjusting the magnetic field in the target electromagnets.
Fig. 3.5 shows a typical cycle of a data-taking run during one fill of the ring. Before starting injecting electron pulses into the ring, the high voltages of the detectors were ramped down (see fig. 3.6) to prevent damage from excessive rates. Once the desired stored current was reached, injection was stopped, the high voltages were ramped up and data acquisition was initiated. Due to depolarization of the beam (with a depolarization decay time of $\tau = 1931^{+3850}_{-960}$ s [44]) the maximum measuring time was set to approximately 5 minutes. After this time, the data acquisition system was stopped, the detector high voltages ramped down, and the electron beam was dumped before starting a new cycle with the opposite sign of the electron beam helicity. Data acquisition was occasionally interrupted for re-tuning of the electron beam optics and optimization of the slit positions, or maintenance of the involved devices (e.g. exchange of the PES cathode, LH filling of the siberian snake, regeneration of the ABS nozzle, cleansing of the CBP optics elements etc.). Including these interruptions, data was routinely collected with an integrated charge of about 6 kC per day, over a period of three months.

### 3.2 Target layout and operation

The polarized target presented in this work was based on an existing apparatus previously used at AmPS for measuring tensor analysing powers of the elastic $^2\text{H}(e, e'd)$ and quasielastic $^2\text{H}(e, e'p)n$ reactions [10, 11, 6]. However, for the spin-correlation experiments...
mentioned here (see for example [18]) vector polarized hydrogen and deuterium targets with polarization close to unity and target thicknesses in excess of $1 \times 10^{14}$ nuclei/cm$^2$ were required. Therefore, the following major improvements were applied to the target setup:

1. a longer storage cell was employed and the cooling power was increased which allowed reaching lower cell temperatures. This resulted in an increase of the target thickness by about a factor of $\sim 2.7$.

2. the background H$_2$/D$_2$ pressure was reduced by adding pumping speed to the target vacuum chamber. In this way, the amount of unpolarized molecules (relative to atoms) in the target was approximately reduced by more than a factor of 2.

3. a stronger target guide field was used, which, for deuterium, resulted in a higher polarization.

Improvements on the ABS itself were presented in chapter 2 and will not be discussed here. Next, only a brief description of the relevant subsystems is given, namely the ABS, internal target, and BRP. For more details see ref. [8, 26].
3.2.1 Atomic beam source

General principles of an Atomic Beam Source are given in chapter 2. Here only aspects concerning the experiment are discussed. The ABS run configuration is schematically depicted in fig. 3.7. Molecular hydrogen or deuterium gas is flown (typically 1.3 mbar l/s for H$_2$ and 1.0 mbar l/s for D$_2$) through a straight, 9 mm inner diameter pyrex tube. A 27.1 MHz RF-discharge dissociates the molecules into atoms. About 0.5 – 1.0% absolute pressure of H$_2$O or D$_2$O is added to enhance the degree of dissociation and to extend the life time of the glass tube. The nozzle is connected via a copper braid and a copper arm to a 10 W closed-cycle He refrigerator. At nozzle temperatures $T_{\text{nozzle}} < 100$ K the hydrogen recombination coefficient increases drastically with decreasing temperature [45]. The optimal working temperature is experimentally found to be in the range of 65-80 K. $T_{\text{nozzle}}$ was determined by a temperature sensor and could be adjusted by varying the power in a heater element (50 W maximum power), which was mounted near the nozzle. A beam of atoms is formed by the cooled nozzle, a skimmer and a collimator, and enters the third chamber. Two sets of sextupole magnets, S1 and S2, focus atoms with electron spin parallel to the magnetic field (‘spin up’) into the storage cell feed tube. Atoms with electron spin antiparallel to the magnetic field (‘spin down’) are defocused and pumped away.

Nuclear polarization was obtained by using high-frequency transitions between selected hyperfine states. A medium field transition unit (MFT) inbetween the two sets of
Figure 3.7: Schematic view of the ABS on top of the target region and the BRP. Pumping speeds are given for H₂. CH1, CH2, CH3: coldheads; S1, S2, S3: permanent sextupole magnets; MFT, SFT, WFT: medium, strong and weak field transition units; V1, V2: pneumatic valves; HM: target holding field magnet; CM1, CM2: compensation magnets; QMS: quadrupole mass spectrometer.
sextupole magnets was applied to remove atoms in a given hyperfine state by making a transition from one of the occupied electron spin-up states to an empty electron spin-down state before the second sextupole. After the second sextupole the beam entered a strong field transition unit (SFT), in which a transition between states from the two Zeeman multiplets could be made. Subsequently, a weak field transition unit (WFT) was used to induce transitions within a Zeeman multiplet. This unit was added for producing vector polarization and is located outside the vacuum, around a Teflon tube which connects the third chamber of the ABS to the target chamber. With this setup, vector polarized hydrogen or deuterium as well as tensor polarized deuterium can be produced. These schemes have been described in chapter 2. When required, the polarization scheme could be changed within a few minutes without access into the experimental area (e.g. between vector and tensor polarized deuterium, or between polarized deuterium and polarized hydrogen with a single hyperfine state injected). This was achieved by selecting the proper gas in the remote-controlled gas feed system and adjusting the static magnetic field (and, in some cases, the high frequency) of the transition units. Only for the hydrogen scheme with two injected hyperfine states, a vacuum access was needed to exchange the cavity of the SFT. This was done by lifting the ABS up, while leaving the ABS exit flange (on which the SFT was mounted) attached to the target chamber. In this way, the alignment of the ABS to the storage cell and electron beam line was preserved. One of the subsequent improvements could be mounting the two cavities on the atomic beam line within the same vacuum chamber, in order to avoid inconvenient vacuum access.

Fig. 3.8 shows a typical ‘cool-down’ curve during the preparation of the atomic beam. To monitor the (relative value of the) intensity, the valve separating the WFT Teflon pipe from the target chamber was closed and the pressure just in front of the valve was measured with a Penning gauge. The intensity obtained at the working-point nozzle temperature (typically 65-80 K) varied substantially from a cool-down curve to another, indicating a degradation of the purity of aluminum nozzles. However, after reaching the working-point nozzle temperature, the discharge was turned off to accelerate ice coating of the nozzle surface. This reduced surface recombination and required about one hour to significantly affect the beam intensity. After completion of this procedure, the same maximum intensity could be reproduced within approximately 10 %.

The performance of the ABS decreased slowly in time (see fig. 3.9). This is attributed to a degradation of the nozzle surface due to a deposition of a white substance, possibly sputter products from the discharge in the pyrex tube. Therefore the nozzle was exchanged

*A Penning gauge was used instead of a Bayard-Alpert-type because of the reduced sensitivity to the strong fringe fields of the nearby magnets.

†Deposition of sputter products due to the discharge or the low temperature.
regularly after \( \sim 2 \) weeks of continuous operation with deuterium gas. A longer nozzle lifetime was obtained with hydrogen gas: the nozzle was changed after \( \sim 3 \) weeks of operation. This difference between operation with deuterium and hydrogen gas might be either due to the higher purity of the hydrogen gas (the nominal purity in the bottle was 99.999 % for \( \text{H}_2 \) and 99.7 % for \( \text{D}_2 \)) or to mass-dependent sputter effects in the dissociator. The replacement of the nozzle costed approximately 16 hours of polarized data taking time. The operation was carried out by (a) warming up the nozzle (4 hours), (b) venting the first/second ABS chambers and replacing the nozzle (1-2 hours), (c) pumping down the ABS (1-2 hours), and finally (d) preparing the atomic beam with the above cool-down procedure (9 hours). Note that phases (a), (c) and (d) did not require access to the experimental area. This time was also used to collect data with unpolarized gas for calibration purposes, electron beam polarization studies and/or regeneration of the cryogenic pumps. Therefore, the actual down-time was about 2 hours for each nozzle change.
3.2.2 Target

Only the modifications applied to the parts of the apparatus directly related to the internal target itself (i.e. storage cell, target chamber vacuum, and magnetic holding field) are described here. For a detailed description of these devices, see Ref. [8].

As shown on fig. 3.7, the atomic beam produced by the ABS was injected into the feed tube of a Ø15 mm, 60 cm long storage cell. The cell body consisted of a Teflon-coated 30 μm thick ultrapure aluminum foil and was supported by a 3 mm thick aluminum frame. The Ø12 mm, 12.2 cm long feed tube consisted of two parts. The first 2.2 cm were integral part of the cell body and were thus made of 30 μm thick aluminum foil. The feed tube extension towards the ABS consisted of 1 mm thick aluminum pipe with a conical end pressed against the entrance of the 2.2 cm section using a spring. Like the cell, the feed tube was coated with Teflon over its full 12.2 cm. To reduce the vacuum conductance of the cell and the depolarization of the gas on the cell walls, the storage cell was cooled with two coldheads connected via copper braids to the cell frame.

The cell frame temperature was monitored on both ends with carbon-glass resistors. A copper braid provided thermal contact between the feed tube extension and cell frame. The feed tube temperature was monitored with a platinum-resistor thermometer (PT100). The cell frame was wrapped in ~ 15 layers of super-insulating foil (with a total thickness ~ 10 μm) to reduce radiative heat load. The cell temperature was regulated with heaters mounted on each coldhead. The cell temperature was slightly affected by the presence of
the electron beam (especially during injection). The temperature just after a beam dump was \( \sim 4 \) K higher than just before beam filling. This might be due to the fact that no wakefield-surpressing connections between the cell ends and the electron beam pipe were implemented, thus enhancing resistive losses in the cell walls.

The target chamber could be isolated from the ABS by shutting a remotely controlled valve positioned between the feed tube housing and the WFT Teflon pipe. The target chamber sides facing the detectors were provided with exit foils made of 100 \( \mu \)m thick stainless steel, in order to minimize energy losses of scattered particles. The chamber was interfaced to the beam pipe via bellows. In each bellow a vacuum conductance limiter was placed which consisted of a pair of kapton foils separated by 5.7 cm and provided with a circular aperture of 2 cm diameter. Fig. 3.10 shows a picture of the vented target chamber without steel foil walls.

Figure 3.10: Picture of the vented target chamber without steel foil vacuum windows. WFT cavity, BRP, coldfinger and cryogenic pump are visible.

In the previous experiments, the molecular background from rest gas in the target chamber substantially contributed to a dilution of the target polarization [9]. About 12% of the electron scattering events originated from these molecules. In the present setup, the target vacuum chamber was evacuated by two cryogenic pumps, each with a pumping speed of 2000 \( \ell/\text{s} \). This resulted in a background pressure of about \( 5 \times 10^{-7} \) \((1 \times 10^{-8})\) mbar with (without) injecting the atomic beam. With this increased pumping speed the molecular rest gas contribution was reduced by more than a factor of 2.

The target polarization axis was defined by providing a magnetic holding field over the storage cell. This magnetic field was produced by a pair of electromagnets and could
be oriented in any direction in the electron scattering plane. The water cooling capacity limited the coil currents to about 600 A which resulted in a maximum field strength in the center of the cell of \( \sim 34 \, (59) \, \text{mT} \) for the component transverse (parallel) to the electron beam. Steering dipoles, each with a maximum field integral of 3.08 T cm, were added at the entrance and exit of the target vacuum chamber to compensate for the deflection of the electron beam by the transverse component of the target holding field. During the experiments the target field strength was set to about 46, 44 and 38 mT for the quasielastic sideways, "N-Δ" longitudinal, and "N-Δ" sideways asymmetry measurements, respectively, with a polar angle with respect to the electron beam axis of 33°, 155°, and 64° at the center of the cell. A vectorial field map was taken with a Hall probe for each of these settings. Note also that the strength and orientation of the target holding field rapidly changes along the electron beam axis for \( |z| > 20 \, \text{cm} \) (where \( z = 0 \, \text{cm} \) represents the storage cell center). However, for these outer sections of the cell the detector acceptance is considerably reduced and the resulting ‘loss’ in useful target thickness is only about 8 % of the total target thickness.

3.2.3 Breit-Rabi polarimeter

A 0.4 mm sample tube of 2.2 cm length was provided on the storage cell, opposite to the feed tube, to allow for sampling of the injected atomic beam into a Breit-Rabi–type polarimeter. Note that, because of this sample tube, a fraction of the injected atomic beam passed the storage cell unobstructed. From the raytrace calculations, and taking into account beam attenuation in the feed tube and cell (see section 3.3.2), this fraction is estimated to amount to 14 ± 4 %. This value is relevant for the determination of the actual atomic beam intensity injected into the storage cell feed tube (see section 3.3.1).

The BRP was used to both tune the high-frequency transition units and monitor their performance. The sampled beam passed through a 0.6 mm, 10 cm long conductance limiter (see fig. 3.7) which connected the target vacuum chamber to the BRP vacuum chamber. In this way, diffused flow from the heavily loaded target chamber into the BRP was minimized. A 44 cm long, tapered sextupole magnet, S3, with entrance (exit) diameter of 6 mm (3 mm) and a maximum pole-tip field of 0.4 T, was positioned in the atomic beam path, thereby defocusing atoms with electron spin up. Subsequently, the transported atoms were detected in a crossed-beam quadrupole mass spectrometer (QMS). The beam was chopped with a fork-shaped rotating shutter at a frequency of about 240 Hz. The chopped QMS signal (atomic mass) and a reference voltage from an emitter-receiver LED couple were fed into a lock-in amplifier from which the atomic beam signal could be read out. This lock-in method was especially needed for the deuterium
beam, because of the high background signal originating from residual hydrogen molecules. To study a given high-frequency transition unit, the locked BRP signal was recorded while scanning the magnet coil current, gradient coil current, or high-frequency power of the unit. Changes in the BRP signal indicate that a transition is taking place. Selected results obtained with the BRP are shown in section 3.3.2.

3.3 Performance of the target

Presented here are the results of a number of measurements performed to determine the target thickness and polarization, and the amount of background events from the cell wall materials and residual gas. The absolute target thickness was measured by comparing the electron scattering rates of a selected reaction (e.g. $e'p$ elastic or quasielastic) obtained when injecting the atomic beam and when injecting a known flux of unpolarized molecular gas from a buffer vessel. The absolute target polarization was determined indirectly by (a) extracting the product of electron and target polarization from the asymmetry of a calibrated electronuclear reaction and (b) by measuring the electron beam polarization with the CBP.

3.3.1 Target thickness and ABS intensity

An absolute value of the (polarized gas) target thickness was determined by comparing the $e'p$ (quasi) elastic coincidence rates, $R$, for electron-proton (deuteron) scattering obtained when injecting atomic beam to those recorded when injecting unpolarized molecular gas from a buffer vessel at a known flux. The target thickness for unpolarized molecular gas was determined in the following way. Molecular gas stored in a buffer vessel of known volume and temperature was injected into the target cell near its center. The flux was obtained by measuring the pressure decay in the buffer vessel with an absolute pressure transducer gauge. From the calculated conductance of the storage cell, the target thickness was obtained. As shown in fig. 3.11, different unpolarized fluxes were used to determine the event rate per unit of flux.

A small offset due to background events from the cell walls was measured and corrected for (see section 3.3.3 below). In this way, a target thickness of $(1.1 \pm 0.1) \times 10^{14}$ atoms/cm$^2$ for polarized hydrogen (2 states) and $(1.2 \pm 0.1) \times 10^{14}$ atoms/cm$^2$ for polarized deuterium (3 states), at $T_{cell} \approx 70$ K was found. The quoted accuracies are dominated by the uncertainty in the cell conductance $(8.3 \pm 0.8 \ell/s$ for H$_2$ at $T_{cell} = 70$ K). At an
average electron beam current of 110 mA, these target thicknesses correspond to a luminosity of about $(7.8 \pm 0.8) \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ for hydrogen and $(8.4 \pm 0.8) \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ for deuterium.

In order to estimate the injected atomic beam flux, a number of effects needed to be taken into account:

1. A fraction of the atomic beam entered the BRP sample tube without stopping in the storage cell. This fraction was estimated using the raytrace Monte-Carlo method \cite{8} and amounted to $0.14 \pm 0.04$. The velocity distribution of the gas atoms in the beam formation region was generated based on the parametrization given in Ref. \cite{28}.

2. The polarized gas target contained a small amount of molecules due to recombination on the cell walls, molecular beam from the nozzle and finite pumping speed in the target vacuum chamber. Since molecules spend on average more time in the storage cell than atoms, this correction reduces the extracted atomic beam intensity by about 6 % and introduces the largest uncertainty in the extracted value. The molecular content was estimated from previous measurements \cite{9} while taking into account the increased intensity of the atomic beam and pumping speed on the target chamber.
All rates were normalized to the temperature of the calibration measurements ($\sim 60$ K for hydrogen and $\sim 83$ K for deuterium) by properly correcting for temperature differences using the proportionality law $R \propto 1/\sqrt{T_{cell}}$ (see also fig. 3.17). The resulting fluxes for the full atomic beams amounted to $(6.4 \pm 0.3) \times 10^{16}$ atoms/s for hydrogen and $(4.5 \pm 0.3) \times 10^{16}$ atoms/s for deuterium.

### 3.3.2 Performance of the MFT unit

The performance of the high-frequency transition units was already presented in the previous chapter. However, two issues specific to the configuration of the internal target and the use of a transition unit inbetween two focusing magnets to reject a given hyperfine state from the injected atomic beam are addressed. Firstly, the question of the rejection efficiency arises. A deficiency could be caused e.g. by a less-than-unity high-frequency transition efficiency, or by an imperfect matching of the sextupole optics combined with the acceptance of the feed tube. The latter depends on both the sextupole magnet configuration and on the position and geometry of the storage cell feed tube. Secondly, an effect due to the high density of the target gas in the injection region is discussed which affected the interpretation of the values measured with the BRP when studying the MFT.

#### Second sextupole rejection efficiency

Using the $e'p$ coincidence rates it is possible to determine the overall rejection efficiency of the combined MFT and second sextupole. The rejection efficiency can be defined as

$$
\varepsilon_{rej} = \frac{N_{hfs}}{R(MFT \, off)} \frac{R(MFT \, on)}{R(MFT \, off)}
$$

where $N_{hfs} = 2$ (3) for hydrogen (deuterium). $R(MFT \, on)$ and $R(MFT \, off)$ are the event rates measured with the MFT unit turned on and off, respectively. From these rates, the defined rejection efficiency amounted to $0.78 \pm 0.04$ for hydrogen and $0.76 \pm 0.05$ for deuterium. However, a correction needs to be applied to take into account the contribution to the rates originating from molecular beam, since ballistic molecules are affected by neither the MFT nor the sextupole system. Correcting for the estimated amount of molecular beam using the results of the previous measurements [9], the rejection efficiencies quoted above are increased by about $0.05-0.10$. Using the raytracing Monte-Carlo, the expected rejection efficiency $\varepsilon_{rej}^{MC} = 0.91 \pm 0.02$ for hydrogen and $\varepsilon_{rej}^{MC} = 0.90 \pm 0.01$ for deuterium was calculated (the uncertainties are statistical only). Note that the code assumes a transition efficiency of 100 % and only atoms are taken into
account which reach the cell without hitting the feed tube. Reasonable agreement is found with the measured values when taking into account the effect of the non-vanishing molecular beam and the measured efficiency of the MFT transition (0.97 ± 0.02, see the previous chapter and ref. [26]).

**Hyperfine state removal and attenuation effects**

Another effect observed while studying the MFT with the BRP is described here. The performance of the MFT can be analyzed in terms of population numbers before and after the transition unit by using information with the SFT unit turned on/off (as explained in e.g. ref. [26]). The SFT occurs after the second sextupole and is assumed to be a pure two-state transition with a given (measured) efficiency. Only an example for deuterium is shown here, but the same technique can be used for hydrogen (using e.g. a 2-4 SFT). Three scans over the MFT magnet are performed, as shown in fig. 3.12: first with the SFT turned off (solid line), then with the SFT 3-5 turned on (dashed line), and finally with the SFT 2-6 turned on (dotted line).

Figure 3.12: Response of the BRP as a function of magnet coil current with strong field unit transitions on and off and with the second sextupole retracted.

In this case, the second sextupole was taken out of the atomic beam line. The three scans can be used to extract the population numbers after the MFT (assuming states 1, 2 and 3 were equally populated before the MFT), thereby obtaining the effect of the MFT unit. In fig. 3.12, a 93 % efficient 3-4 transition is clearly identified at MFT magnet currents in the range 5.6-6.2 A.
When performing the same scans with the second sextupole inserted in the atomic beam line, the following is observed (see fig. 3.13). The signal drop in the first scan (SFT off) is reduced and is accompanied by a signal rise when turning on the SFT 3-5. The drop with the SFT 2-6 turned on is also smaller, and of the same size as the drop with the SFT off. Any fringe field effects due to the second sextupole were excluded by adding shielding between the MFT and the sextupole magnet: no difference was observed. These effects can be explained by beam gas scattering which occurs after the SFT, on the way to the BRP, in the sections where the gas density can be sufficiently large to cause a substantial attenuation. When turning on the 3-4 MFT with the second sextupole inserted, the atomic beam intensity injected in the feed tube area is reduced by almost one third, which results in a reduced attenuation. In consequence, the BRP signal is increased when compared to the case where one removes a hfs in the BRP magnet only (e.g. when the SFT 2-6 or 3-5 is turned on). This explains both qualitatively and quantitatively the structures observed in fig. 3.13. This has been verified by injecting molecular D₂ gas into the target cell (with all transitions off), thereby increasing the gas thickness traversed by the atomic beam sampled by the BRP. At an injected molecular flux corresponding approximately to a one-third increase of the total gas thickness the BRP signal was reduced by about 10 %.

Figure 3.13: Response of the BRP as a function of magnet coil current with strong field unit transitions on and off and with the second sextupole in the beam.
3.3.3 Background rates

One of the main advantages of polarized internal gas targets is the low (background) contribution from undesired nuclei. The high purity of such targets offers the possibility to interpret the collected data in a clean and reliable manner. During the experiments measurements with an empty storage cell were performed to determine background contributions from the cell walls and from residual gas. In fig. 3.14 the coincidence rate is plotted versus the vertex position for $e'p$ events in quasielastic kinematics, with a polarized deuterium target. The deuterium beam enters the cell at $z = 0$ cm and the atoms diffuse out of the target cell from the open ends of the cell. This results in an approximately triangular density distribution in the cell. Deviations from this shape, seen in the figure, are explained by the relatively large acceptance of the detectors, and the ensuing correlations between $z$ and the cross section. The rates obtained with an empty cell are also shown in the figure (shaded area). These events originating from scattering off the cell walls or residual gas, contribute about 2 % to the total rate when injecting atomic beam into the cell. Clearly, the signal-to-background ratio critically depends on the reaction channel under study and on the analysis cuts applied. For example, this ratio was about 10:3 for inclusive $^1\text{H}(e,e')$ scattering events in the delta region while the same ratio amounts to circa 50:1 for the example shown in the figure.

![Graph](image)

Figure 3.14: Reconstructed vertex position with (blank) and without (shaded) $^2\text{H}$-gas in the cell, for $e'p$ (quasielastic) coincidence events with cuts on missing momentum and missing energy. The length of the cell is 60 cm. Deviation from the triangular shape is caused by BigBite acceptance.
The two sets of slits (in the east and south sections of the ring) were crucial in reducing these background event rates. Typically, after a new tune of the ring parameters, the slit positions were re-optimized. This was done by minimizing the singles rates in the scintillators of the Bigbite spectrometer. Each of the four slits were optimized sequentially by moving them in steps of about 0.5 mm until a degradation of the electron beam injection efficiency was observed. Usually this observation also coincided with a reduction of the beam lifetime. At this point, all slits were retracted by one step (0.5 mm) to allow for small drifts in the beam parameters over time. The reduction in cell-wall event rates obtained after optimization of the slits was about a factor 1.6 (see fig. 3.15).

![Graph](image)

Figure 3.15: Background contributions before (white) and after (shaded) optimizing beam optics and slit positions. These measurements were done without gas in the target cell. The same selection cuts were used as in fig. 3.14. With the slits taken out the background rates were about a factor of five times larger.

### 3.3.4 Polarization

To be able to produce vector/tensor polarized deuterium and polarized hydrogen, three high-frequency transition units were used. The high-frequency transition schemes available with the setup were presented in the previous chapter. Only the relevant schemes are briefly reminded here. For polarized hydrogen, the hyperfine state composition of the injected atomic beam was alternated between states (1,4) and (2,3) by inducing either the 2-4 SFT or 1-3 WFT, respectively. In this case, a target magnetic field as strong as...
permitted by the target magnet configuration was applied (38–44 mT, see section 3.2.2). In these conditions, the maximum polarization of the mixed states (2 and 4) was limited to 80-83 % of the pure states (1 and 3). A scheme with only one injected hyperfine state was also tested by inducing the 2-3 MFT and turning on/off the 1-3 WFT to alternate between the pure states 1 and 3. However, even at equal target field strength the gain in polarization (squared) offered by this scheme was not sufficient to compensate the factor 2 loss in injected flux. For vector polarized deuterium, state 3 was removed by inducing a 3-4 MFT before the second sextupole magnet, and subsequently either a 2-6 SFT or a 1-4 WFT was turned on, which resulted in a composition of states (1,6) and (3,4) respectively. Tensor polarized deuterium was obtained as described in ref. [26], but no further electron scattering experiments were performed using this scheme. The efficiencies of the RF-transition units were determined with the BRP (see the previous chapter). All were found larger than 95 %, except for the WFT unit which operated with 92 % efficiency, probably because of insufficient shielding from the large fringe fields of the nearby magnets (target magnet and SFT magnet). From these efficiencies and the rejection efficiency, the injected hyperfine state populations can be inferred. Using in addition the known target holding field map, and by estimating the amount of molecules from previous measurements, an upper limit for the expectable target polarization was estimated. In this configuration, this value was 0.68 ± 0.02 for hydrogen and 0.71 ± 0.03 for (vector polarized) deuterium. However, the polarization in the target cell can differ from the polarization of the atomic beam, because of effects from e.g. recombination, dilution by residual gas or molecular beam, spin-exchange collisions, depolarization due to cell-wall interactions, or depolarization induced by the RF field of the electron beam. For these reasons, a measurement of the polarization in the storage cell, as seen by the electron beam, is needed. More precisely, only the product of electron beam and target polarization needs to be known in order to extract a spin-correlation parameter from an experimental asymmetry - knowledge of the individual polarization degrees are not required. This product was determined by monitoring the asymmetry of (quasi) elastic scattering from $^1\text{H}$ (resp. $^2\text{H}$) in kinematics for which the spin-correlation parameters are known [33, 34, 46]. Fig. 3.16 shows the asymmetry for $^2\text{H}(e,e'p)n$ quasielastic scattering versus the reconstructed vertex position ($z$-axis), for the data collected over a 2-month period (duration of the $G_{\text{e}}^n$ experiment). The curve shows the expected asymmetry as obtained from a Monte Carlo simulation, assuming 100 % beam and target polarizations. The $z$-dependence of the asymmetry is due to a change in target field orientation, which is accounted for in the Monte-Carlo simulation. The asymmetry data points were normalized by the factor $P_e P_t = 0.32$ [44]. From the fact that the experimental asymmetry closely follows the expected asymmetry, it was concluded that the target polarization had
no substantial $z$-dependence. Furthermore, regular measurements of the electron polarization in the AmPS ring by using a Compton backscattering polarimeter were performed. From the (quasi) elastic asymmetry the target polarization can be extracted at the times that electron beam polarization measurements were performed. In the central 40 cm of the cell, values of $P_e P_t$ up to $0.49 \pm 0.03$ ($0.32 \pm 0.03$) with the deuterium (hydrogen) target, were obtained with an electron beam polarization of $P_e = 0.62 \pm 0.04$ ($0.56 \pm 0.03$) (measured with a Compton backscattering polarimeter [32] and including electron depolarization due to the depolarization decay time in the ring [44]). This corresponds to $P_t$ up to $0.78 \pm 0.07$ ($0.58 \pm 0.07$). This relatively low value obtained for hydrogen might be explained by beam-induced RF depolarization from a residual 1.415 MHz component in the beam, or by the relatively low value of the target magnetic field. It is known that, for instance, spin-exchange effects and cell-wall depolarization become stronger at low holding field values [47]. This could explain the gain in polarization, when including only events originating from the central 20 cm of the cell. In this case values of $P_e P_t$ up to $0.36 \pm 0.04$ with the hydrogen target, were obtained (again $P_e = 0.56 \pm 0.03$), resulting in $P_t$ up to $0.65 \pm 0.08$. In the experiments, the target holding field used for hydrogen was limited to less than 1 critical field ($B_c(H) = 50.7$ mT). In contrast, for deuterium, the

![Figure 3.16: Quasielastic asymmetry for $^2H(e, e'p)n$ versus reconstructed vertex position. The expected asymmetry is indicated by the solid line.](image)
average field was \( \sim 4.2 \) times the critical field \( (B_c(D) = 11.7 \text{ mT}) \).

### 3.3.5 Temperature of the cell

Because the conductance of the target cell lineary depends on \( \sqrt{T} \) for molecular flow [48], the target thickness (and thus the event rates) was increased by improving the cell cooling with the installation of an additional coldhead. Fig. 3.17 shows the \( e'p \) coincidence rate as a function of cell temperature. It is seen that the data follow the expected \( 1/\sqrt{T \text{cell}} \) behaviour. From a linear fit it can be observed that the temperature of the cell deduced from the rates was \( 8 \pm 4 \) K higher than the value measured by the temperature sensor. This indicates the presence of a small temperature gradient between the storage cell body and the storage cell frame (on which the temperature sensors were mounted). The measured temperatures shown in fig. 3.17, are corrected for the temperature offset.

Although the target density increases with decreasing temperature, below a given temperature \((\sim 100 \text{ K})\) the target nuclei are expected to depolarize more rapidly [49]. Therefore, an optimal temperature for the cell must be found which results from the tradeoff between target gas density increase and polarization losses. A set of measurements at different temperatures was performed to verify the optimal temperature. The results of the measurements are shown in fig. 3.17 (middle). The curves on the figure are the results of a fit using the parametrization of ref. [49]. This parametrization is based on a model for cell wall depolarization in weak magnetic fields \((B \ll B_c, \text{ where } B_c \text{ is the critical magnetic field for hydrogen } (50.7 \text{ mT})\)). This model predicts a temperature dependence of the polarization given by:

\[
P = \frac{P_{\text{max}}}{1 + (N_b \frac{\tau_0}{\tau}) \exp \left( \frac{E_b}{kT} \right)}.
\]

Here \( P_{\text{max}} \) represents a given maximum polarization (no cell-wall depolarization), \( N_b \simeq 500 \) is the average number of wall bounces, \( \frac{\tau_0}{\tau} \) is the quotient of high temperature sticking time on the cell-wall and the characteristic spin relaxation time and \( E_b \) is the binding energy for hydrogen atoms on a Teflon PTFE 3170 surface (30 meV according to Ref. [50]). \( k \) is the Boltzmann constant and \( T \) is the temperature of the cell. Fitting the asymmetry data using values for \( E_b \) varying from 20 to 60 meV yields values of \( A_{\text{max}} \) ranging from \( -0.095 \pm 0.01 \) to \( -0.086 \pm 0.007 \), and of \( (N_b \frac{\tau_0}{\tau}) \) of \( 8 \times 10^{-3} \) to \( 2 \times 10^{-6} \). Clearly, an accurate value of \( \frac{\tau_0}{\tau} \) cannot be extracted from this analysis.

A target figure of merit can be defined as \((\text{asymmetry})^2 \times (\text{rate})\) and is shown in the bottom plot of Fig. 3.17. From this plot the cell temperature \((\sim 70 \text{ K})\) giving maximum
Figure 3.17: *Top:* $(Rate)^{-2}$ versus the cell temperature $T_{cell}$ for $^{1}\bar{H}(\bar{e},e')p$. *Middle:* Elastic asymmetry versus $T_{cell}$ for $^{1}\bar{H}(\bar{e},e')p$. The solid line is a fit according to the parametrization of [49]. *Bottom:* Figure-of-merit, $Rate \times (Asymmetry)^2$ scaled, versus $T_{cell}$. Here, the solid curve is a product of the above parametrizations.
A figure of merit was deduced and used as a working point of the described nuclear physics experiment.

### 3.4 Summary

In this chapter the upgraded polarized hydrogen/deuterium internal target used at the NIKHEF polarized electron storage ring AmPS was presented. The target setup consisted of an atomic beam source, a cryogenic storage cell and a Breit-Rabi polarimeter. The major improvements with respect to the previous experiments with tensor polarized deuterium [8] involved the implementation of permanent sextupole magnets, more powerful pumping systems in the beam formation chamber and in the target region, and a longer and colder storage cell. Furthermore, new high-frequency transition units were constructed so as to be able to produce vector polarized hydrogen and deuterium, or tensor polarized deuterium.

During the experiments fluxes up to \((6.4 \pm 0.4) \times 10^{16}\) atoms/s for hydrogen and up to \((4.5 \pm 0.3) \times 10^{16}\) atoms/s for deuterium were injected into the \(0.12\) mm, \(12.2\) cm long feed tube of the storage cell. The target thickness was \((1.1 \pm 0.1) \times 10^{14}\) atoms/cm\(^2\) for polarized hydrogen and \((1.2 \pm 0.1) \times 10^{14}\) atoms/cm\(^2\) for polarized deuterium at a cell temperature of \(70\) K. The resulting luminosity was about \((7.8 \pm 0.8) \times 10^{31}\) e\(^-\) nuclei cm\(^{-2}\) s\(^{-1}\) and \((8.4 \pm 0.8) \times 10^{31}\) e\(^-\) nuclei cm\(^{-2}\) s\(^{-1}\) for an electron beam current of 110 mA. A maximum polarization in the cell of \(0.65 \pm 0.08\) for hydrogen and \(0.78 \pm 0.07\) for deuterium was reached, in agreement with the maximum expectable polarization estimated from the known high-frequency transition efficiencies, target field map, and molecular dilution. The product of the electron beam and target polarizations, needed to extract the electronuclear spin-correlation parameters from the measured asymmetries, was determined from the known asymmetry for (quasi) elastic electron scattering off \(^1\)H (\(^2\)H).

The target was recently used in conjunction with a 720 MeV polarized electron beam, with injected currents of about 110 mA, to measure spin-correlation parameters for (a) quasifree scattering from deuterium (\(e'n\) and \(e'p\)) and (b) pion electro-production in the \(\Delta\) region i.e. \(1^2\)H (\(\vec{c}, e'\)), \(1^2\)H (\(\vec{c}, e'p\)), \(1^2\)H (\(\vec{c}, e'n\)), \(1^2\)H (\(\vec{c}, e'\pi^\pm\)). The first data set provides precise information on the neutron charge form factor \(G_n^E\) [30] and on the S/D-wave structure of the deuteron. The second will give new constraints to treatments of the pion production mechanism and of the underlying nucleon structure and is the subject of the next chapter. Several advantages of the polarized internal target technique, crucial to the realization of these experiments, were presented, e.g. the purity of the target gas, the high polarization, and the ability to rapidly change the polarization.
Chapter 4

Analysis of inclusive electron scattering data

Spin-dependent electron scattering from polarized protons or deuterons provides new information on the electro-magnetic response of the nucleon and two-body system, with an enhanced sensitivity to small amplitudes which enter the cross-section via an interference with large amplitudes. For example, the charge form factor of the neutron $G_E^n$, which is closely related to the charge distribution inside the neutron, can be constrained by measuring the perpendicular spin-correlation asymmetry or recoil polarization of the ejected neutron in quasifree neutron knock-out [33]. Information on the quadrupole form factors, $E_2$ and $C_2$, of the $N$-$\Delta$(1232) transition, which are related to the orbital angular momentum content in this system (D-state admixture in the wave function), can be obtained by measuring the longitudinal and perpendicular spin correlation parameters of the $^1\bar{H}(e,e')$ reaction [34]. Such measurements were recently carried out at the Amsterdam electron storage ring (AmPS) using polarized deuterium and hydrogen gas targets located in the path of a stored polarized electron beam. The nuclear-polarized gas was produced in an atomic beam source (ABS) and injected into the feed tube of a storage cell, a cylindrical and open-ended aluminum tube traversed by the electron beam. Angles and energies of scattered electrons were recorded in the large acceptance magnetic spectrometer, Bigbite [40, 41]. The result of the $G_E^n$ measurement at a four-momentum transfer $Q^2 = 0.21$ (GeV/c)$^2$ is reported in ref. [30], while the analysis of inclusive electron-proton scattering data is described here.

This chapter is organized as follows. The formalism of inclusive electron-proton spin-dependent scattering is presented in section 4.1. The data analysis of the experimental data is discussed in section 4.2. The data analysis results are summarized and discussed in Section 4.3.
4.1 Formalism of electron-proton scattering

A derivation and detailed discussion of the formalism for inclusive spin-dependent electron scattering can be found in ref. [34]. Here only the aspects necessary to interpret the experimental data are given. The derivations are carried out in the one-photon exchange approximation, which is depicted in fig. 4.1. The incident electron with four-momentum

\[ k = (\varepsilon, \mathbf{k}) \]
scatters off a proton at rest. \( k' = (\varepsilon', \mathbf{k}') \) is the four-momentum of the scattered electron and \( \theta_e \) is the angle of the scattered electron. Thus the four-momentum transfer is given by \( q = k - k' = (\omega, \mathbf{q}) \) and satisfies the condition \( q^2 = -Q^2 = \omega^2 - q^2 \leq 0 \). The four-momenta of the initial and final hadronic systems are \( p = (M_p, 0) \) and \( p' = p + q \), respectively. The general expression for the cross section of an inclusive scattering longitudinally polarized electrons off a polarized nuclear target is given by:

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} f_{\text{rec}}^{-1} \left[ v_L R_L + v_T R_T + h P' \left( v_T' R_T' + v_{TL}' R_{TL}' \right) \right],
\]

where:

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{\alpha}{2\varepsilon} \sin^2(\theta_e/2),
\]

\[
f_{\text{rec}}^{-1} = 1 + \frac{2\varepsilon \sin^2(\theta_e/2)}{M_p},
\]

\[
v_L = \left( \frac{q^2}{Q^2} \right)^2,
\]

\[
v_T = -\frac{1}{2} \frac{q^2}{Q^2} + \tan^2(\theta_e/2),
\]

\[
v_{TR} = \sqrt{\frac{q^2}{Q^2} + \tan^2(\theta_e/2) \cdot \tan(\theta_e/2)},
\]

\[
v_{TL} = \frac{1}{\sqrt{2} q^2} \tan(\theta_e/2).
\]
with $\alpha \approx 1/137$, $M_p$ the proton mass, $\theta_e$ the scattering angle and $R_x$ the nuclear response functions. $h$ is the electron helicity and $P$ is the target polarization, which is explicitly factored out (as opposed to the original notation of ref. [34]). $\Sigma_0$ and $\Delta$ are the spin-averaged and spin-dependent parts, respectively.

The response functions $R_x$ contain all the information on nuclear structure and can be expressed in terms of multipoles (transverse electric, magnetic and charge, usually denoted $E_x$, $M_x$ and $C_x$ respectively, with $x$ the rank of the multipole). The total spin $J$ and parity $\pi$ of the initial and final states constrain the kind and rank of multipoles entering the cross section. In the case of elastic e-p scattering ($J^\pi : \frac{1}{2}^+ \rightarrow \frac{1}{2}^+$), $\Sigma_0$ and $\Delta$ are given by:

\[
\begin{align*}
\Sigma_0 & = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \left[ G_E^2 + \tau G_M^4 \right] + 2\tau G_M^2 \tan^2(\theta_e/2), \quad (4.5) \\
\Delta & = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \left[ 2\tan(\theta_e/2) \left[ \tau \sqrt{\frac{1}{1 + \tau}} + \tan^2(\theta_e/2) G_M^2 \cos \theta^* + \right. \right. \\
& \quad \left. \left. + \sqrt{\frac{\tau}{1 + \tau}} G_E G_M \sin \theta^* \cos \phi^* \right] \right]. \quad (4.6)
\end{align*}
\]

where $\tau = \frac{Q^2}{4M_p^2}$, $\theta^*$ and $\phi^*$ denote target polarization angles with respect to $q$ and the electron scattering plane (see fig. 4.2) and $G_E$ and $G_M$ are nucleon’s electric and magnetic form factors*, respectively.

Figure 4.2: The definition of kinematic variables and frames (see text for explanations).

Information on the nucleon wave function can be obtained by measuring its electromagnetic response. In the case of a pure $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ transition, as is the case of the $N$-$\Delta$

\*The historical name ‘electric form factor’ and notation $G_E$ is used here, although strictly speaking it is a charge monopole form factor $C_0$ (and $G_M$ is a magnetic dipole form factor $M_1$).

56
excitation, three form factors, $E_2$, $C_2$ and $M_1$ contribute. In the simplest quark model $N$-$\Delta$ excitation is described by a quark spin flip (pure $M_1$ transition). A D-state admixture in the wave function can induce non-zero electro-magnetic $E_2$ or $C_2$ amplitudes which interfere with a dominant $M_1$ amplitude. Hence, determining $E_2/M_1$ and $C_2/M_1$ ratios can provide information on the D-state admixture in the nucleon wave function and thus a possible deformation of the nucleon. For the pure $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ transition, one can write:

$$\Sigma_0 = 4\pi \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} f_{\text{rec}}^{-1} \left[ v_L F_{C2}^2 + v_T (F_{E2}^2 + F_{M1}^2) \right].$$

(4.7)

$$\Delta = -4\pi \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} f_{\text{rec}}^{-1} \left[ \frac{1}{2} v_T (F_{M1}^2 - F_{E2}^2 - 2\sqrt{3} F_{M1} F_{E2}) \cos \theta^* + v_T \left( F_{C2} (F_{M1} + \sqrt{3} F_{E2}) \right) \sin \theta^* \cos \phi^* \right].$$

(4.8)

with $F_i$ being the $Q^2$-dependent form factors.

In order to get the sensitivity to the $E_2$ and $C_2$ amplitudes it is suggested [34] to measure spin correlation parameters defined as:

$$A_T = \frac{\sigma_{h=1} - \sigma_{h=-1}}{\sigma_{h=1} + \sigma_{h=-1}} \frac{1}{\sqrt{1 - \epsilon^2}} \quad (\theta^* = 0)$$

$$A_{TL'} = \frac{\sigma_{h=1} - \sigma_{h=-1}}{\sigma_{h=1} + \sigma_{h=-1}} \frac{1}{\sqrt{2}\epsilon(1 - \epsilon)} \quad (\theta^* = \pi/2).$$

(4.9)

where $\epsilon = [1 - 2(\frac{Q^2}{\mu^2}) \tan^2(\theta_e/2)]^{-1}$ and $\sigma_{h=x}$ is the cross section for electron helicity $x$.

So defined spin correlation parameter $A_T$ is sensitive to the electric quadrupole form factor $F_{E2}$, and $A_{TL'}$ is sensitive to the charge quadrupole form factor $F_{C2}$ as they interfere with the dominant $F_{M1}$ magnetic dipole form factor. The beam-target physics asymmetry is defined as:

$$A_{\text{phys}} \overset{\text{def}}{=} \frac{A_{\text{exp}}}{hP} \overset{\text{def}}{=} \frac{\sigma_{h=1} - \sigma_{h=-1}}{\sigma_{h=1} + \sigma_{h=-1}}$$

(4.10)

$$= k_{T} A_T \cos \theta^* + k_{TL'} A_{TL'} \sin \theta^* \cos \phi^*. \quad (4.11)$$

which means that measuring spin correlation parameters is basically equal to measuring the experimental asymmetry $A_{\text{exp}}$, which in turn means simply measuring count rate differences for different polarization states.

For longitudinal ($\theta^* = 0$) and perpendicular ($\theta^* = \pi/2$) spin kinematics one can further define:

$$A_{\text{long}} \overset{\text{def}}{=} A_{\text{phys}}(\theta^* = 0, \phi^* = 0),$$

(4.12)

$$A_{\text{perp}} \overset{\text{def}}{=} A_{\text{phys}}(\theta^* = \pi/2, \phi^* = 0).$$

(4.13)
Recently, an inclusive electron scattering experiment at the Amsterdam electron storage ring (AmPS) measuring the spin correlation parameters $A_T$ and $A_{TL}$ was performed covering the pion production region from the range of the invariant mass from the elastic peak to 1400 MeV, with $Q^2$ ranging from 0.25 to 0.08 GeV (see fig. 4.3).

![Graph showing the kinematics covered during the experiment. Elastic region is well visible at \( W \) equal to the mass of the proton.]

Figure 4.3: Kinematics covered during the experiment. Elastic region is well visible at \( W \) equal to the mass of the proton.

### 4.2 Experimental data analysis

#### 4.2.1 Software

Software is needed to interpret the data coming from the detectors in order to convert them into physical values like coordinates, energy, angles etc. The data-acquisition system was based on SUN workstations and the computer code ADAM [54] was employed for the analysis. In this complex modular code every event coming from the Bigbite detector was processed and the detector information was converted into physical quantities. The final output of the process was an ntuple file ready to be opened with PAW [55]. With its internal script language and built-in FORTRAN interpreter PAW is a convenient tool for
data evaluation and was used to perform most of the calculations. In order to compare the data to the theory a Monte Carlo simulation was developed. Basically, it consists of the event generator, a user code and hardware packages for detectors. The algorithms were developed within the collaboration and were written in FORTRAN. The output of the simulation was again an ntuple file and could be conveniently analyzed in PAW. Analysis of the experimental files and comparison to the simulation results were performed on a standard PC running under linux operating system.

4.2.2 MAID model

In order to calculate the asymmetry and compare it to the experimental results a theoretical model had to be involved. In this work the MAID model is used ([56]), but analysis with other models is under way [51]. Pion production has been an important technique for investigating the structure of nucleons and nuclei. Several contributions to the process of pion production on the nucleon by absorption of a photon are shown in the fig. 4.4. The MAID model has been developed to describe the pion

![Figure 4.4: Some terms engaged in pion photoproduction: Born terms with nucleon and pion poles (1-3), contact term (4) and resonant terms (5-...).](image)

photo- and electro-production from the nucleon at photon equivalent energies of up to 1 GeV ([57, 58]). The model contains Born terms, vector mesons and nucleon resonances ($P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535), F_{15}(1680)$ and $D_{33}(1700)$) and provides good agreement with the experimental data for pion production. In the notation of Drechsel and Tiator ([57]), the spin dependent inclusive cross-section for $e$-$p$ scattering is written as:

$$
\frac{d\sigma_{hp}}{dE_f\Omega_f} = \Gamma \left( \sigma_T + \epsilon \sigma_L + \hbar P(\sqrt{1-\epsilon^2} \sigma_T \cos \theta^* + \sqrt{2\epsilon(1-\epsilon)} \sigma_{TL} \sin \theta^* \cos \theta^*) \right). \quad (4.14)
$$

where

$$
\Gamma = \frac{\alpha(\omega + q^2/2m_e)}{2\pi^2q^2} \frac{E_f}{E_i} \frac{1}{\epsilon - 1}
$$
\[ \sigma_x \ (x=T,L,T',TL') \] are the four parts of the inclusive cross section (related to the response functions \( R_x \) and photon density factors \( v_x \) in expression 4.1), and \( E_i \ (E_f) \) are the beam (scattered) electron energy.

The beam-target physics asymmetry (4.10) becomes:

\[
A_{phys} = \sqrt{1 - \epsilon^2} \sigma_T' \cos \theta^* + \sqrt{2\epsilon(1 - \epsilon)} \sigma_{TL'} \sin \theta^* \cos \theta^* \sigma_T + \epsilon \sigma_L.
\] (4.15)

and

\[
A_{long.} = \sqrt{1 - \epsilon^2} \frac{\sigma_T'}{\sigma_T + \epsilon \sigma_L},
\] (4.16)

\[
A_{perp.} = \sqrt{2\epsilon(1 - \epsilon)} \frac{\sigma_{TL'}}{\sigma_T + \epsilon \sigma_L}.
\] (4.17)

A web interface is available for the MAID model to calculate \( \sigma_i \) components of the cross-section for a single kinematical point. In order to simplify the calculations a shell script was used, which allowed for automated multiple calculations needed to cover the whole kinematical region (see fig 4.3). Fig. 4.5 shows sensitivities of so defined asymmetries to the E2 and C2 amplitudes in the MAID model for \( q^2 = -0.11 GeV \).

Figure 4.5: Sensitivity of the longitudinal and perpendicular spin asymmetries to the E2 (left) and C2 (right) amplitudes in the MAID model. Dashed lines correspond to both the E2/M1 (for C2=0) and C2/M1 (for E2=0) ratios of -2.4\%, solid line to the value of 0 and the dashed line to the value of +2.4\%.

The model allows to turn on/off also resonances lying beyond \( \Delta(1232) \). Fig. 4.6 shows that their contributions to the asymmetry are not negligible. In further calculations all the resonances were taken into account.
Figure 4.6: Influence of further lying resonances for asymmetries in the MAID model. Solid line is p33 resonance only, dashed line is asymmetry including all resonances (see description in text.

4.2.3 Bigbite calibration

A basic description of the detector was given in chapter 3. Here only its calibration is discussed. The energy of an electron elastically scattered off a proton can be calculated by:

$$E_{\text{calc}}^{f} = \frac{E_i}{1 + 2E_i/M_p \sin^2(\theta_e/2)}.$$  \hspace{1cm} (4.18)

where $E_i$ is the known energy of the electron beam, $\theta_e$ is the scattering angle and $M_p$ is the mass of the proton. This formula can be used for fine-tuning energy calibration of the Bigbite detector. Fig. 4.7 shows the plots of the difference of reconstructed Bigbite energy ($E_{\text{data}}$) and calculated energy ($E_{\text{calc}}$) for all the events in both kinematics. These offsets were accounted for during the calculations, and the energy resolution of 5 MeV was used in Monte Carlo simulations. It is not possible to precisely calibrate the scattering angles and the vertex position without a second accurate detector capable of detecting recoiling protons with sufficient angular resolution. Therefore the scattering angle resolutions were taken from existing calibration and were assumed to be 0.005 for angles and 4 mm for the vertex position.

61
Figure 4.7: Energy resolution of Bigbite detector for longitudinal (left) and perpendicular (right) spin kinematics. The invariant mass range 920-1400 MeV was used.

4.2.4 Background estimation

To reduce background (cosmic events and random coincidences), a large scintillator was mounted in front of Bigbite and added to the trigger (compare to fig. 3.4 in the previous chapter). This, however, does not filter out all background events. Note also that background conditions varied during the experiment, because of several re-tunings of the accelerator optics. To account for such background contributions empty cell measurements had to be taken on a regular basis. For approximately one hour per day, or alternatively, during the ABS down time (changing the nozzle, regeneration of the cryogenic pumps, see previous chapter) measurements were taken with no gas supply to the target. Fig. 4.8 presents the picture of the charge-normalized event rates\(^1\) during the whole experiment while fig. 4.9 shows the rates for the whole invariant mass region covered in the experiment. Note, that the \(\Delta\) resonance region is much more contaminated with background events than the elastic channel. As the aim is to extract the information exactly in that channel, background corrections are essential in the analysis.

The target gas itself can influence the behavior of the electron beam. Due to scattering from gas particles the emittance of the beam can be increased. This effect is known as a beam blow-up and has to be taken into account while determining the contribution of background events. The increase of background event rates due to the beam blow-up can be determined by analyzing the events not coming from e-p scattering. Because

---

\(^1\)All rates discussed in this work are corrected for Bigbite deadtime and normalized to the integrated charge and not the time. Thus the rates are measured in proton per Coulomb.
radiative processes are not accounted for in this work, the region between the elastic peak and the \( \Delta \) region was not chosen for that purpose, as it is highly contaminated by the radiative contribution coming from events where a photon was emitted during the elastic scattering process. A simple alternative is to select the data which falls in the range of the invariant mass below the elastic peak. This region is kinematically forbidden for \( e-p \) scattering and is believed to consist predominantly of events in which an electron scatters off a 'complex' nucleus (e.g. Al from the cell wall, or C and F from the surface coating). If the presence of the hydrogen gas in the cell does not affect the background event rates (which arise from the scattering of the electrons from the cell walls), the rates with and without gas in the cell should be equal if one applies selection cuts that remove events from e-p scattering. The beam blow-up factor is defined then as a scaling ratio between the two rates. For a proper background subtraction, all empty-cell rates need to be multiplied by this factor. This ratio was found to be different for the two spin kinematics and amounted to \( 1.55 \pm 0.06 \) for the longitudinal spin kinematics and \( 1.89 \pm 0.07 \) for the perpendicular one (statistical errors only). This might be explained by the fact that the two spin orientations require different amplitudes of the target magnetic field transverse to the beam axis and a different setting of the correction magnets, which results in a slight modification of the beam trajectory. All the empty rates were multiplied with this number for further calculations (see fig. 4.10). More detailed investigation on this ratio (vertex dependence etc.) as well as on the radiative contributions to the background is under way [51].
4.2.5 Comparison of Monte Carlo spectra to data

The $N - \Delta$ measurement was performed in December 1998. About 60kC (6kC) were accumulated for longitudinal and 40kC (5kC) for perpendicular spin kinematics for the gas in the cell (no gas in the cell). On average 240,000 events for each kinematics in elastic channel and about 310,000 events for delta channel were gathered (numbers include background events). The kinematic region covered is shown in fig. 4.3.

In order to compare the MAID model prediction on asymmetry with the real experimental asymmetry, it is necessary to set up a Monte Carlo simulation taking into account the experimental setup and covered kinematics. For simplicity two independent simulations, one for the elastic channel and the other for the delta region, were used. For that purpose an existing code simulating elastic scattering ([52]) and the Bigbite detector ([53]) was modified. Scattering angles and electron energy were generated independently using a random algorithm, and an electron-proton scattering point (vertex) was generated to reproduce the triangular distribution of the gas in the target cell. All variables were generated in a phase-space bigger than the acceptance of Bigbite and the geometry of the cell. The scattered electron was then tracked through the Bigbite detector to check if it could be detected in reality. An existing detector package GEANT ([59]) was used for that purpose. The presence of the scintillator in front of Bigbite was simulated by adding cuts when analyzing ntuple files in PAW ([55]). Fig. 4.11 shows reconstructed scintillator hits as projections onto both scintillator axes. The small disagreement in the elastic region is attributed to radiative events, that were not accounted for in the elastic simulation.
Figure 4.10: Event rates for gas (filled squares) and no gas (empty squares) in the cell for longitudinal (top) and perpendicular (bottom) spin kinematics. Empty rates are multiplied with the beam blow-up factor explained in the text. Only events before the elastic peak were chosen for the procedure.

This is much more visible in the delta region, especially for the perpendicular direction, suggesting that radiative corrections should be taken into account when analyzing the pion production region (no corrections used for the figure).

To account for polarization in the simulation, a three dimensional fieldmap of the target cell was taken and implemented in Monte Carlo. Fig. 4.12 shows the distribution of the polarization angles versus position in the cell. Visible distortions in the angles for $|\text{vertex}| > 20$ cm are due to rapid changes of the magnetic field in this region. Fig. 4.13 and 4.14 show the comparison of the measured and simulated distributions of vertex
Figure 4.11: Front scintillator hits in $x$ and $y$ directions from data (solid line) and Monte Carlo (dashed line). The plots are presented for elastic and delta regions and the distinction is based on the invariant mass values: 920-960 MeV for the elastic peak and 1080-1400 MeV for the delta region.

position, angles and energies. As can be seen from the fig.4.13, discrepancies in scintillator hits in vertical position can be attributed to problems of reproducing the azimuthal angle (vertical component of the electron scattering angle).

To calculate the asymmetries a simulation covering the kinematics of the delta region, containing the MAID model predictions and using radiative corrections had to be set up. An existing code ([60]) was used to estimate the contribution from radiating electrons for the invariant mass region after the elastic peak. The code does not calculate the asymmetry at the elastic peak, but it was checked that the asymmetry calculated for $W \rightarrow W_{\text{elastic}}$ agrees with the asymmetry expected for elastic scattering. A grid was prepared, covering the $Q^2$ region of 0.0 – 0.5 GeV$^2$ every 0.01 GeV$^2$ and the invariant
Figure 4.12: Scatter-plot of proton spin angle for longitudinal and perpendicular spin kinematics as a function of the vertex position. The elastic and delta regions are defined as in Fig. 4.8
Figure 4.13: Distributions of the vertex position and the scattering angles for the elastic channel. The squares are the data points, the dots are Monte Carlo results.
Figure 4.14: Distributions of the transferred (virtual photon) energy $\omega$, invariant mass and $Q^2$ and the scattering angles for the elastic channel. The squares are the data points, the dots are Monte Carlo results.
mass $W$ region from $1080 \text{ MeV} - 1400 \text{ MeV}$ every $10 \text{ MeV}$. Fig. 4.15 shows the simulated asymmetries calculated with the above grid and a grid that was twice as dense. No significant differences were found, thus the smaller grid was chosen for calculation speed reasons.

Figure 4.15: Comparison of the Monte Carlo grid density influence on $A_{T'}$ (top) and $A_{TL'}$ (bottom) asymmetry (see equation 4.9). Triangles are the points calculated with a grid half as dense as a grid used to calculate square points.
4.2.6 E2 and C2 extraction

The information on the nucleon wave function and its resonances can be obtained by measuring electromagnetic response functions. Specifically, a D-state admixture in the nucleon’s wave function can induce a non-zero electromagnetic E2 or C2 amplitude. As demonstrated in fig. 4.5 the experimental asymmetries are expected to be sensitive to the E2 or C2 multipoles. Fig. 4.17 shows the comparison of the calculated asymmetries to the experimental ones (see eq. 4.10). Normalization of the calculated asymmetries was done based on the known elastic asymmetry. One way of extracting E2 and C2 is a repeated calculation of many asymmetries corresponding to different values of these multipoles and checking which calculation describes the experimental asymmetry best. However, due to the comparatively long time of producing one Monte Carlo file with high enough statistics another method was used. The following dependences of the multipole sensitivities were assumed:

\[
A_{E2=-x} = A_{E2=0} + x(A_{E2=-1} - A_{E2=0}), \quad \text{(corresponds to } A_T) \quad (4.19)
\]
\[
A_{C2=-x} = A_{C2=0} + x(A_{C2=-1} - A_{C2=0}). \quad \text{(corresponds to } A_{TL'}) \quad (4.20)
\]

The plot of longitudinal asymmetry around the delta peak as obtained with Monte Carlo with different values of \(x\) (see fig. 4.16) shows that the above assumption is sufficient for a good approximation.

Next, the parameter \(x\) was scanned with an accuracy of 0.01 and \(\chi^2\) was calculated for each value of \(x\). The error was estimated by finding the asymmetry values corresponding to \(\chi^2\) values increased by one. The following values were found:

<table>
<thead>
<tr>
<th>Multipole</th>
<th>value</th>
<th>ratio</th>
<th>(\chi^2)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2</td>
<td>(-1.1 \pm 0.6 \pm 0.02)</td>
<td>(-2.67% \pm 1.5% \pm 0.06%)</td>
<td>5.59</td>
<td>11</td>
</tr>
<tr>
<td>C2</td>
<td>(0.1 \pm 1.0 \pm 0.06)</td>
<td>(0.24% \pm 2.4% \pm 0.15%)</td>
<td>10.13</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 4.1: Results on the multipole extraction.

The first error given in the table is statistical and the second one is a systematic error. The latter was estimated from performing \(\chi^2\) minimisation routines with different invariant mass windows. This impact was found to be much smaller than the statistical error. However, the ratios tend to be considerably affected by the beam blow-up factor extraction technique. In this work the factor was determined by scaling the empty rates to the gas rates using the data before the elastic peak (see fig. 4.10). This, however, due to presence of the elastic peak, is an overestimation of the factor and also is not the only way of its extraction. Another method can be based on analyzing the region
between elastic peak and delta region while taking into account radiative events or using coincidence data ([51]). The beam blow-up factor was found to be technique-dependent, contributing considerably to the systematic error. Taking into account this effect at this stage of the analysis the systematic errors are of the order of the statistical errors.

Figure 4.16: Monte Carlo $A_{T\nu}$ asymmetry as a function of $x$ for a few invariant masses $\pm \sim 50$ MeV around the delta peak.

The fig. 4.17 shows the comparison of the asymmetries obtained with $\chi^2$ minimalization of the experimental asymmetry. Both calculations are in fair agreement with the experimental data in terms of $\chi^2$. However, from the asymmetry shapes one could have an impression that the MAID model seems to follow the experimental points a bit worse in perpendicular spin kinematics. Also, due to unexpected hardware failure at the end of December 1998 less statistics could be accumulated for this kinematics. In general it is possible to conclude that the MAID model can be used at least as a starting point for extraction of the multipole ratios. The experimental asymmetry, especially in the longitudinal spin kinematics is well reproduced by the calculations but the spectra are reproduced significantly worse when compared to the quality of elastic results. Thus, to draw reasonable conclusions on the quality of the MAID model it is necessary to precisely separate the radiative events with an additional simulation code as well as use other available theories for a comparison. Such an effort is under way and will soon be presented ([51]).
Figure 4.17: The spin asymmetries for the longitudinal (top) and perpendicular (bottom) data (points) and Monte Carlo (line) versus the invariant mass. The solid line is the asymmetry calculated for the multipole values that gave the least \( \chi^2 \). The dashed line in the upper plot demarcate the calculated asymmetry for \( \text{REM}=0 \), while the dashed lines in the lower plot demarcate the calculated asymmetries for \( \text{RCM} \) values \( \pm \) the error. They are plotted to give an impression of the sensitivity of the asymmetry to the multipoles.
Fig. 4.18 plots the calculated values against available world data points. Compared to other recent data points the E2/M1 ratio can be treated as small, negative and constant with $Q^2$ up to 2 GeV$^2$. C2/M1 was calculated to be practically zero, so is not in agreement with other latest results, but due to high errors no convincing conclusions can be drawn.

4.3 Summary

In this chapter an analysis of the $^1\text{H}(e, e')$ reaction data was presented. A two-stage Monte Carlo simulation was set up for the elastic and the delta region in order to generate events in the experimental phase space. For the theoretical description of the pion production the MAID model was used. In order to judge the quality of the simulation, comparison to experimental spectra was performed. Reasonable agreement has been found for the elastic channel, allowing the conclusion that the elastic process is well understood and can be accurately simulated. Nevertheless, discrepancies in reproducing the spectra in the $\Delta$ region point out that radiative corrections should be taken into account for inclusive analysis in that region. No radiative corrections were taken into account in this work. Such an analysis with optimization of different radiative codes is underway [51] and will soon be presented. However, up to now no significant influence of radiative effects on simulated asymmetries was observed making it reasonable to trust the first order extraction of the multipoles presented in this work. The E2/M1 ratio is found to be in a reasonable agreement with the available recent world data, although due to relatively big errors at this stage of the analysis no clear conclusions should be made. Further studies, especially on radiative corrections in inclusive scattering, should be performed to verify the results and reduce the systematic error coming from technique-dependent extraction of beam blow-up factor. Additional measurements, especially with brighter target sources, should also be considered to constrain the statistical errors.
Figure 4.18: World data available on E2/M1 (REM) and C2/M1 (RCM) ratios. The filled symbols are recent data while the open ones were obtained before 1975.
Chapter 5

Summary

Spin-dependent electron scattering experiments have become a fruitful technique in investigations on nucleon structure. Interesting issues, like the charge distribution of the neutron or the deformation of the nucleon can be experimentally addressed. Application of atomic beam sources (ABS) has lately become a fruitful approach for producing nuclear-polarized hydrogen and deuterium gas for internal target experiments. However, this requires dense atomic polarized targets with polarization of order unity and a target thickness in excess of \(1 \times 10^{14}\) nuclei/cm\(^2\). A previously available atomic beam source (ABS) was upgraded to comply with these requirements. The main improvements applied were the design, implementation and optimization of a new Stern-Gerlach permanent sextupole magnet focusing system, and the reduction of the H/D pressure in the beam-formation chamber by doubling the pumping speed. An intensity increase of \(\sim 2.5\) was obtained. The ABS is capable of injecting maximal fluxes of \((7.6 \pm 0.2) \times 10^{16}\) \(^1\)H/s, has all the RF units working with efficiencies in the range 92-100\% and can serve as a polarized gas target for a variety of experiments.

The updated ABS was then configured as a source for the internal target experiment proposed to be performed at NIKHEF, Amsterdam ([18]) to investigate the electromagnetic response of the deuteron and nucleon, both in quasi-elastic kinematics and in the \(\Delta(1232)\) region. Further improvements to achieve higher luminocity were applied, mainly longer storage cell, increased cooling and pumping power and a stronger target guide field. A maximal target thickness of \(1.2 (1.1) \pm 0.1 \times 10^{14}\) nuclei/cm\(^2\) was achieved with deuterium (hydrogen), which corresponds to a luminosity of about \(8.4 (7.8) \pm 0.8 \times 10^{31}\) e\(^-\) nuclei cm\(^{-2}\) s\(^{-1}\). The ABS was used in combination with a 720 MeV polarized electron beam stored in the AmPS ring (NIKHEF) to measure spin observables in electron-proton and electron-deuteron scattering. Scattered electrons were detected in a large acceptance Bigbite magnetic spectrometer, and ejected hadrons were detected in
a single time-of-flight scintillator array. With the deuterium (hydrogen) target an electron beam polarization of $P_e = 0.62 \pm 0.04$ (0.56 ± 0.03) and a target polarization up to $P_t = 0.78 \pm 0.07$ (0.65 ± 0.08) was obtained.

Using the above setup, the world-wide measurement of spin correlation parameters in the $^1\text{H}(e,e')$ reaction was performed. The MAID model was integrated with a Monte Carlo simulation and used in the data analysis for the first order extraction of the multipole ratios $E2/M1$ and $C2/M1$ in the $N-\Delta$ transition. The inclusive elastic spectra can be well reproduced, however radiative effects must be precisely accounted for before comparing the spectra in the $\Delta$ region. Radiative events were neglected during the analysis thus no unambiguous conclusions on the quality of the pion production model can be drawn right now. However, the quality of reproducing the experimental spin correlation parameters in this model allows for preliminary extraction of the multipole ratios. The non-zero $E2/M1$ ratio is in fair agreement with the other recent measurements, while due to the big statistical and systematic errors no clear conclusion on the $C2/M1$ ratio can be made yet. Nevertheless, the preliminary analysis presented in this work indicates that a D-state admixture in the nucleon wave function is well possible and should be further investigated in the future. The ABS described in this work can be employed for that purpose and will form the basis for subsequent internal target experiments at the MIT-Bates linear accelerator BLAST facility [31].
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79


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