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A new frozen-spin target for 4π particle detection

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Abstract

A new frozen-spin target has been developed, that allows the detection of emitted particles in an angular acceptance of almost 4π in the laboratory frame. The central part of this new target represents a ^{3}He/^{4}He dilution refrigerator that is installed horizontally along the beam axis. The refrigerator includes an internal superconducting holding coil to maintain the nucleon polarization in the frozen-spin mode longitudinally to the beam. The design of the dilution refrigerator and the use of an internal holding coil enabled for the first time the measurement of a spin-dependent total cross section in combination with a polarized solid state target. This new frozen-spin target was used successfully to measure the helicity asymmetry of the total photoabsorption cross-section at the Mainz accelerator facility MAMI. This experiment has been performed in order to verify for the first time the GDH sum rule. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

For scattering experiments investigating the spin structure of the nucleon the preparation of the target polarization is of major importance. The experiments involving low intense particle beams – e.g. a tagged photon beam – need the high density of a solid state target to achieve sizable luminosity. In order to enable detection of emitted particles over a wide angular range the frozen-spin technique with an internal holding coil is used. At this technique the polarization of the target nucleons is maintained during data-taking by a holding coil with a magnetic field of about 0.4 T. Its thickness of less than 1 mm enables outgoing particles to pass through. In former target systems the technique of an internal holding coil was applied in a vertical dilution refrigerator leading to a reduction in angular acceptance and an asymmetric mass distribution in azimuth [1,2]. In the new target system the

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horizontal alignment of the refrigerator allowed to place its cryogenic components in the backward region and extended thus the angular acceptance to almost 4π in the laboratory frame. The holding coil was built as a solenoid and provided by this a magnetic field homogeneous enough to allow a NMR-measurement. So for the first time at a scattering experiment the nucleon polarization could be measured directly during the frozen-spin period, i.e. during the data-taking period.

The development of this new target system was an important step for the first experimental verification of the GDH sum rule, since this test required the measurement of a total cross-section with a nucleon target polarized longitudinally to the beam momentum direction. Here we present the components of the new target system and discuss its operation and performance at the GDH experiment.

2. The GDH-experiment

The Gerasimov–Drell–Hearn (GDH) sum rule [3,4] relates static properties of the nucleon – its anomalous magnetic moment κ was its mass m – by the fine structure constant α to an integral that runs over all energies ν and contains the energy-weighted helicity asymmetry of the total photoabsorption cross-section $\sigma_{3/2}$ and $\sigma_{1/2}$:

$$\int_{\nu_0}^{\infty} \frac{d\nu}{\nu}(\sigma_{1/2} - \sigma_{3/2}) = -\frac{2\pi\alpha}{m^2}\kappa^2. \quad (1)$$

In the more general case of non-zero photon virtuality $-Q^2$ the helicity asymmetry can be expressed in terms of the polarized structure functions $G_1(\nu,Q^2)$ and $G_2(\nu,Q^2)$:

$$\sigma_{1/2}(\nu,Q^2) - \sigma_{3/2}(\nu,Q^2) = \frac{8\pi^2\alpha}{m^2}\frac{\nu}{\sqrt{\nu^2+Q^2}} \times \left(G_1(\nu,Q^2) - \frac{Q^2}{m\nu}G_2(\nu,Q^2)\right). \quad (2)$$

Integral I of the polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$, as probed in the deep inelastic lepton–nucleon scattering, is defined by

$$I(Q^2) = \frac{2m^2}{Q^2}\int_0^{x_0}\frac{dx}{\sqrt{1+4m^2x^2/Q^2}} \times \left(g_1(x,Q^2) - \frac{4m^2x^2}{Q^2}g_2(x,Q^2)\right) = \int_{\nu_0}^{\infty}\frac{d\nu}{\sqrt{\nu^2+Q^2}}\left(G_1(\nu,Q^2) - \frac{Q^2}{m\nu}G_2(\nu,Q^2)\right) \quad (3)$$

with $x = Q^2/2m\nu$ representing the Bjorken scaling, the GDH sum rule is connected with the quantity I by Eq. (2) and predicts for real photons $I(Q^2=0) = -\kappa^2/4$ [5].

The GDH sum rule is not model dependent, it is based only on fundamental physics principles such as casuality, unitarity, guage invariance and Lorentz invariance. A derivation of this sum rule was first published in 1965, but more than thirty years passed before the demands for a direct experimental check could be fulfilled. Now a first measurement of the GDH sum rule of the photon was performed at the Mainz microton (MAMI) for photons of energy up to 800 MeV [6]. The measurements will be completed using the Bonn electron accelerator facility ELSA with electrons of energy between 550 and 3400 MeV [7]. At MAMI furthermore, data were taken using a deuteron target in order to perform a first test of the GDH sum rules for the deuteron and for the neutron. This measurement will be continued after the end of the Bonn experiment using a more suitable detector set-up for the detection of uncharged particles [8].

3. Set-up at Mainz

For an experimental test of the GDH sum rule the total cross section of circularly polarized photons on longitudinally polarized nucleons has to be measured. Circularly polarized photons were obtained by the bremsstrahlung process of longitudinally polarized electrons and energy tagged in the Glasgow–Edinburgh–Mainz–tagger of the A2-collaboration with a resolution of 2 MeV. The beam

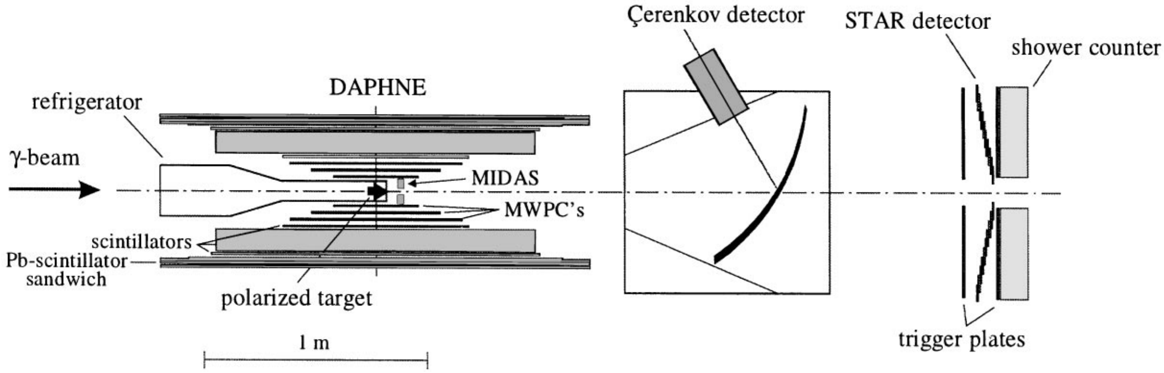

Fig. 1. Side-view of the experimental set-up at Mainz.

polarization was determined by a Møller polarimeter and the photon rate was about 500 kHz. Under these conditions it was necessary to use a solid state target with its high density of polarized nucleons ($\sim 10^{23}/\mathrm{cm}^3$). The DAPHNE detector represented the central part of the detector set-up and has an angular acceptance of 94% of 4π. DAPHNE is mainly a charged particle tracking detector with cylindrical symmetry. It consists of three layers of multi-wire proportional chambers (MWPCs) and six layers of plastic scintillators. In the forward region it was complemented by microstrip detectors (MIDAS) and a forward wall to increase its solid angle acceptance. This wall consists of the annular ring detector STAR to trigger on charged hadronic particles at small forward angles and a lead-scintillator shower counter. A Cherenkov detector was used for the suppression of the electromagnetic background. A side-view of the experimental set-up at Mainz is shown in Fig. 1.

4. Polarized Target

The polarization P of particles carrying spin J in thermal equilibrium (depending on the applied magnetic field B and the temperature T is given by the Brillouin function

$$P_J = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}\frac{g\mu BJ}{kT}\right) - \frac{1}{2J}\coth\left(\frac{g\mu BJ}{kT}\right) \qquad (4)$$

where k denotes the Boltzmann factor, μ the magnetic moment and g the corresponding g factor. The relation shows that electrons can easily be polarized, whereas the polarization of protons and deuterons requires a magnetic field of more than 10 T and a temperature below 20 mK. These difficult conditions, which moreover cause a long build-up time for the nucleon polarization, can be avoided by the principle of the dynamic nuclear polarization (DNP). To this purpose the target material was doped with a dilute assembly of paramagnetic radicals by chemical techniques. At a temperature of 300 mK and a magnetic field of 2.5 T the electron spin polarization of these paramagnetic impurities amounts to almost 100% and could be transferred to the nucleon spin system by irradiation with microwaves. In this way hyperfine transitions were stimulated and, depending on the selected transition (the microwave frequency), the nucleon spin could be aligned parallel or antiparallel to the applied magnetic field. A homogeneity of the magnetic field better than $\Delta B/B < 10^{-4}$ over the whole target sample is necessary to drive uniformly the transition. At a magnetic field of 2.5 T this condition can only be fulfilled by a large magnet that surrounds the target completely, resulting in a reduction of angular acceptance (compare Fig. 2, upper sketch) [9].

To increase the acceptance to a totally open geometry for the scattered particles the 'frozen spin' technique with an internal holding coil was used [1,10]. This technique is based on the long nucleon spin relaxation times at temperatures below

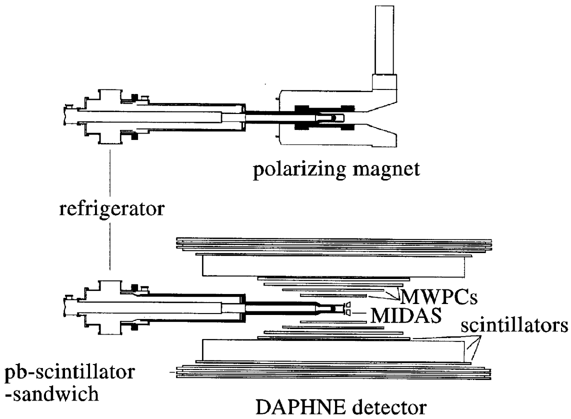

Fig. 2. Sketch of the refrigerator and the target area in the polarizing mode (upper sketch) and during the data taking in the frozen-spin mode (lower sketch).

70 mK. At these temperatures the nucleon polarization once optimally polarized was preserved at a lower magnetic field of about 0.4 T, which was provided by an internal holding coil. This superconducting coil was part of the refrigerator and its thickness of only 780 μm enabled scattered particles to pass through. In the lower sketch of Fig. 2 the experimental set-up in the frozen-spin mode is shown. The degree of nucleon polarization was measured by means of the NMR-technique.

5. Refrigerator

The refrigerator had to fulfill two different requirements due to the two modes of operation. In the polarizing mode at a temperature of about 300 mK a cooling power of more than 30 mW was needed for the DNP of 10 cm^3 target material, while in the frozen-spin mode a temperature below 70 mK was required to provide long relaxation times for the nucleon spins. Furthermore, it was necessary to choose a set-up that allows a measurement of the total cross-section. Additionally, the outer dimensions of the refrigerator were limited by the inner dimensions of the DAPHNE detector and by the warm bore of the polarizing magnet.

Thus a refrigerator of ^{3}He/^{4}He dilution type was built that was installed horizontally along the beam axis. It has a total length of 2215 mm and its diameter amounts to 95 mm in the target area and to 204 mm in the back part. The horizontal design allowed to place the cryogenic components at backward angles and to achieve a symmetric mass distribution in azimuth. The cryogenic components were placed symmetrically around the beam tube, which is the central part of the refrigerator and serves also as an internal isolation vacuum to reduce thermal heat load. For the same purpose the refrigerator also is enclosed by an isolation vacuum and surrounded by two heat shields. The outer heat shield is gold plated in order to lower the heat load by thermal radiation by more than a factor of nine from 75 to 8 W. In this arrangement, the operational temperature of the outer heat shield is below 90 K and that of the inner heat shield is below 15 K. In this way the thermal radiation of the inner shield loads the cryogenic components of the refrigerator by less than 1 μW.

The ^{3}He/^{4}He-gas mixture entering the refrigerator is liquified in a series of counter current heat exchangers cooled by two ^{4}He-evaporation stages: the seperator and the evaporator. It is pumped on the vapor phase of these percooling stages to reduce their temperature and the cold vapor is used for the cooling of the heat shields. Simultaneously it is pumped on the liquid phase of the separator to cool the incoming gas mixture down to about 2.2 K in a coaxial heat exchanger. The liquefaction of the gas mixture is accomplished in the following heat exchanger cooled by the evaporator. It serves as a thermal sink where a definite temperature of 1.5 K can be set. After passing a further heat exchanger the gas mixture enters the dilution unit consisting of the still, the final heat exchanger and the mixing chamber. This unit permits by the dilution process a continuous cooling of the target material, located in the mixing chamber, at temperatures in the millikelvin region. Especially, the design of the final heat echanger is of major importance as the cooling power depends directly on the energy exchange between the gas flowing into and out of the mixing chamber. Therefore, it is build as a helical copper tube with sintered copper walls to increase its surface area and thermal conductivity. The dilution unit is designed as a tube-in-tube system to minimize heat load.

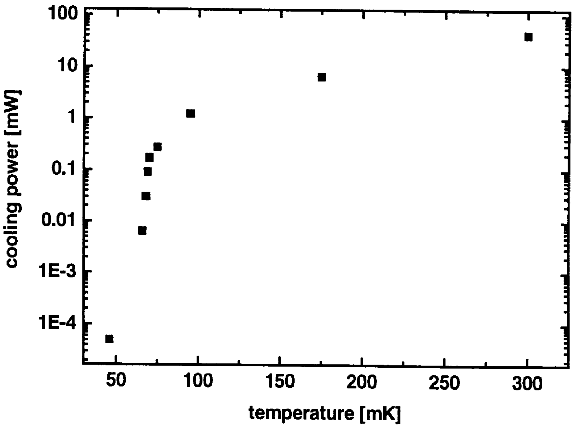

Fig. 3. Cooling power of the refrigerator.

The pumping system of the $^3He/^4He$-circuit consists of a combination of oil-free compressing Roots pumps (Balzers WKP4000, WKP1000, WGK500 and WGK250), which are equipped with canned motors. The pumping speed can be adjusted by frequency converters so as to adapt dynamically the pumping power to the actual performance of the refrigerator.

This design allowed a maximum ^3He circulation rate of 30 mmol/s. In the polarizing mode at a temperature of about 300 mK, a cooling power of up to 50 mW was available (Fig. 3). A base temperature of 40 mK was measured at a circulation rate of 1.4 mmol/s. In latter conditions the cooling power just covered the heat load by thermal radiation and conductivity. In the frozen-spin mode the refrigerator was usually operated at 50–60 mK with a cooling power of a few microwatts, whereby the beam heated the target by less than 1 μW. The performance, especially the temperature, is mainly regulated by the needle valve metering the inlet of the gas mixture. The still heating was also adapted to the actual operation mode in order to exceed 90% ^3He quota in the circulating gas. This quota was controlled by the mass spectrometer. Another needle valve enabled to bypass the final heat exchanger and thereby to cool down the refrigerator with ^4He from the separator to 1 K within approximately 20 h. The total ^4He consumption amounted to 7 l/h liquid helium during the cooling down and to 5 l/h in the frozen-spin mode.

The target material was located in a cylindrical container made of polytetrafluorethylen (PTFE). This container was mounted at the end of an insert, that also contained NMR – and microwave guides. By sliding the insert in the beam tube of the refrigerator from the upstream side the target material could be placed in the mixing chamber with only a slight warming of the refrigerator. The mixing chamber was insulated against the beam tube vacuum by a cold indium seal. After a change of target material the indium seal was heated by resistors to almost room temperature and then pressed with a force of 1.5 kN to tighten it again. Afterwards the heated parts were cooled by an additional ^4He-circuit, that was integrated in the insert. The heat load on the mixing chamber by thermal radiation along the beam tube was minimized by the shielding of four thin aluminium foils (10 μm) placed in

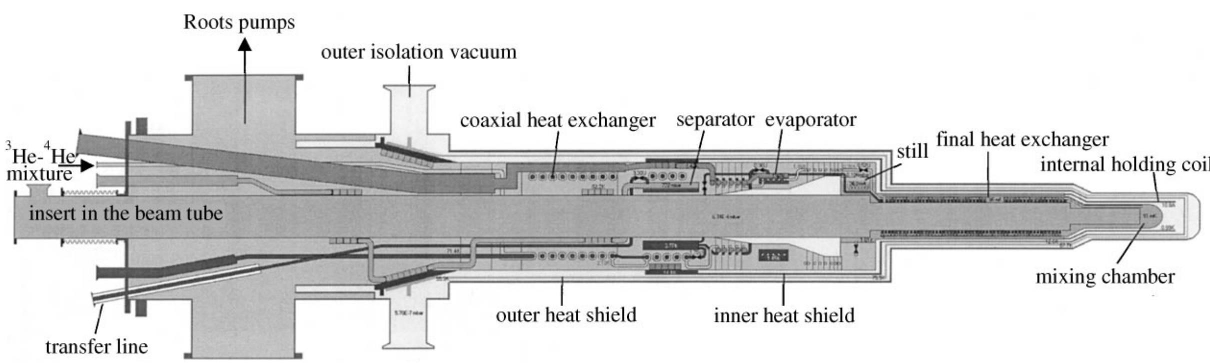

Fig. 4. Schematic diagram of the dilution refrigerator.

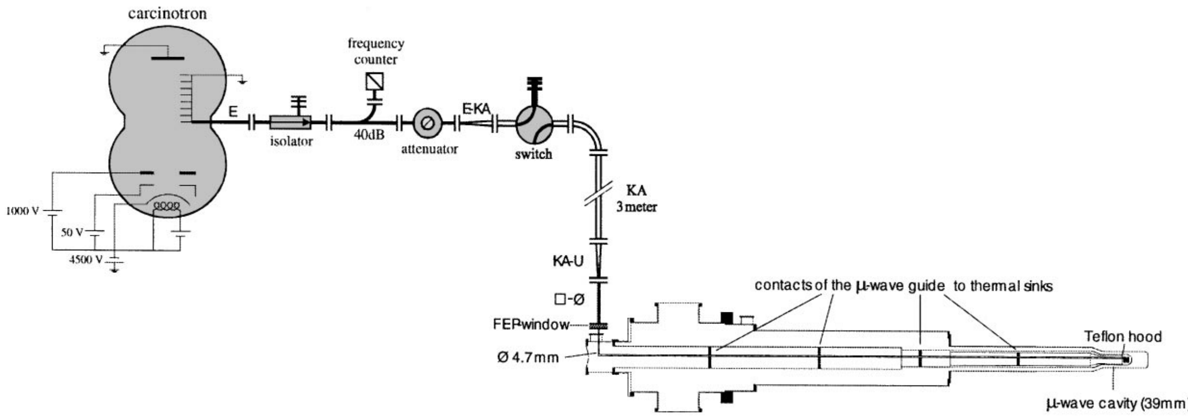

Fig. 5. The microwave system.

the insert. A schematic diagram of the dilution refrigerator is shown in Fig. 4.

6. Microwave system

For the dynamic nuclear polarization the target material was irradiated by microwaves near the electron Larmor frequency to induce transitions between the Zeeman levels. This process required a frequency stability of at least 10^{-4} to drive single transition. The ability to tune the frequency was needed as the frequencies related to the polarization process in positive and negative direction differ by several 100 MHz. In order to achieve a fast polarization build-up a microwave power of 2–3 mW/cm^3 was required, which added up to about 25 mW for a target of 10^3 cm volume.

In the GDH-experiment a carcinotron (Thompson CSF) was used as microwave source. It provides a power output of 3.5 W and its central frequency of 70 GHz corresponds to the electron Larmor frequency at a magnetic field of 2.5 T. The microwaves were conducted to the refrigerator by a rectangular waveguide, which was oversized to minimize the power loss. Inside the refrigerator they were guided by a stainless-steel tube into a cylindrical multimode cavity of 39 mm diameter represented by the mixing chamber. The stainless-steel tube was part of the target insert. It was connected to the rectangular waveguide by a vacuum feed-through containing a window made of fluoronated ethylene propylene (FEP) and it was tightened against the mixing chamber by a Teflon hood. In order to minimize the heat load by thermal conductivity along the stainless steel tube it was contacted at four different points to thermal sinks of the target insert. The set-up of the microwave system is shown in Fig. 5.

During the DNP the microwave frequency was modulated in a bandwidth of 20 MHz with a frequency of 1 kHz by varying the cathode voltage of the carcinotron. In this manner the maximum polarization for deuterons was increased by 3% and furthermore, the polarization build-up time was shortened. At a polarization value exceeding 70% the microwave power was strongly reduced by an attenuator to lower the temperature of the target material and thus to lower was strongly reduced by an attenuator to lower the temperature of the target material and thus to lower its influence on the polarization process.

7. Polarizing magnet

The magnetic field at the polarization build-up was provided by a superconducting solenoid, which was built by the Saclay group and formerly used in the experiment E704 at Fermilab [11]. Its maximum field amounted to 6.5 T. During the DNP process it was operated in nonpersistent mode at a current of 70 A corresponding to a magnetic field of 2.5 T. The magnet has a warm bore of 95 mm and enclosed in the polarization mode the target completely to fulfill the stringent requirements of field homogeneity of better than 10^{-4} over the target area. After switching into the frozen-spin mode, the magnet was removed from the refrigerator, in order to place the detector in the data-taking position, where it surrounded the refrigerator (lower sketch of Fig. 2). For the movements the polarizing magnet and the detectors were mounted on a railway system, which allowed for reproducible position.

8. The internal holding coil

In the frozen-spin mode a superconducting, internal holding coil maintained the nucleon polarization. This magnet is wound in four layers of 1050 turns each on a copper carrier, that is located in the outer isolation vacuum and surrounded by the inner cooling shield. It consists of a 100 μm multifilament NbTi-wire insulated by 10 μm varnish. Thus the total thickness of the coil including the 300 μm copper carrier amounts to only 780 μm. Due to this low mass content the majority of outgoing particles were unaffected; a significant loss of particles occurred only close to their production threshold. The small thickness allowed the detection of particles in a wide angular range. Fig. 6 presents the placement of the internal holding coil in the front part of the refrigerator.

As a result of its compact and small design the coil has a weak outer fringe field that does not exceed 200 G outside the refrigerator. Thus, the influence on the detectors located close to the target (especially the microstrip detectors and the inner tubes of the DAPHNE detector) was small in comparison to that of the big outer holding coils formerly used. This simplified also the tracking of the charged particles. The computed distribution of the fringe field was verified with a Hall probe.

The homogeneity of the magnetic field over the target area ($< 10^{-3}$) allowed for the first time a NMR measurement with a holding coil to determine the polarization on-line during the 'frozen-spin mode'. Thus, the determination of the target

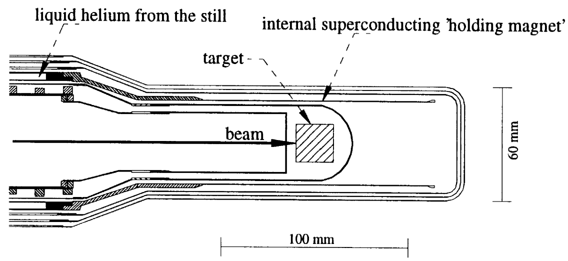

Fig. 6. View of the front part of the refrigerator containing the internal holding coil.

polarization during the data-taking period was substantially improved. The homogeneity of the magnetic field was measured by the NMR-technique.

The coil was cooled to an operational temperature below 1.2 K by a thermal contact to the liquid helium of the still. At this temperature a maximum field of 0.48 T at a current of 12 A was achieved. The superconducting current leads consist of 600 μm multifilament wires, that are glued on the outer heat shield for cooling purposes.

9. NMR

Since the value of the nucleon polarization contributes directly to the result of the GDH-experiment, it had to be determined with high accuracy. For its measurement the continuous-wave nuclear magnetic resonance method (NMR) was used [12]. For this purpose the target material was surrounded by a small coil working as a sensing probe of a series Q-meter. This RF circuit was driven at the nucleon Larmor frequency to induce transitions between the nucleon Zeeman levels of the material under study. By this interaction the material exchanged energy with the Q-meter, leading to a linear dependence of the coil impedance $Z(\omega)$ on the complex magnetic susceptibility χ of the material:

$$Z(\omega) = R + i\omega L[1 + \eta\chi(\omega)],$$
$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega). \quad (5)$$

The parameter η represents the effective filling factor of the target material in the coil, L the inductance when $\chi = 0$ and ω is given by the frequency of

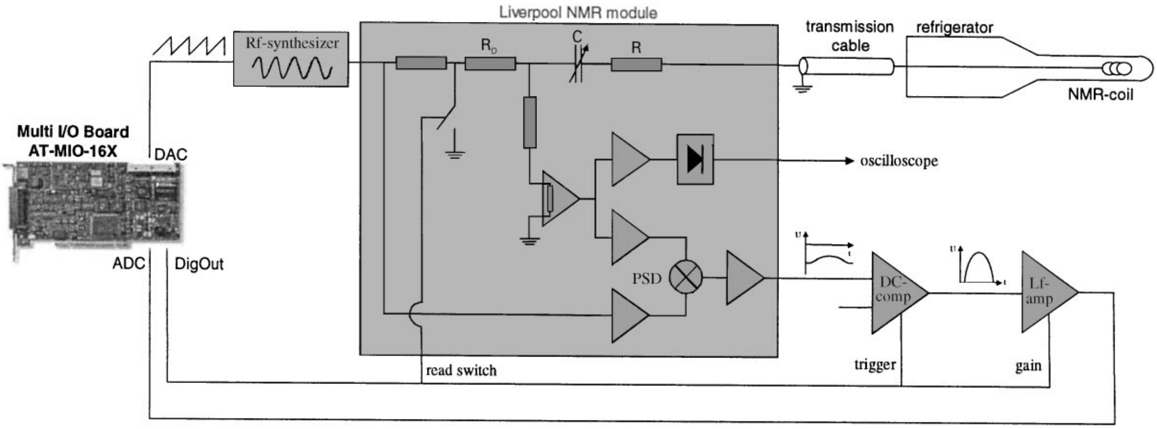

Fig. 7. Set-up for the NMR-measurement with the series Q-meter.

the RF oscillator. The real part of the complex susceptibility (dispersion) represents the resulting inductance, whereas the imaginary part (absorption) is determined by the energy exchange caused by the nucleon Zeeman transitions. Since the energy exchange (and the number of transitions) depends on the population of the nucleon Zeeman levels, the absorptive part of the susceptibility is a direct measure of the polarization of the target material. The Zeeman levels are broadened by the spin–spin interaction of the nucleons, so the imaginary part of χ has to be integrated over the resonance region:

$$P = c \int_{\Delta\omega} \chi''(\omega)\, \mathrm{d}\omega \tag{6}$$

The proportional factor c for the spin polarization was obtained by a calibration measurement in thermal equilibrium (TE-measurement) at a known temperature and magnetic field – corresponding to a Larmor frequency of the nucleon ω_0 – using the Curie law ($P_{\mathrm{TE}} = \tanh(\hbar\omega_0/2kT)$). Knowing c, the polarization can also be calculated after the microwave pumping process of the DNP.

In Fig. 7 a schematic diagram of the series Q-meter circuit is shown: The coil in the refrigerator was connected by a coaxial transmission line to the room temperature electronics of the LIVERPOOL NMR module [13]. In order to reduce influences by an additional capacity and inductance, the length of the transmission line was adjusted to an integer number of half-wavelengths at the nucleon Larmor frequency. In addition it was temperature-stabilized by a water circuit (as were the room temperature electronics) to minimize electronic shifts. The LIVERPOOL NMR module contains a RF amplifier (gain = 42 dB) a phase sensitive detector (PSD) and a LF amplifier (gain = 30). The use of wide-band RF amplifiers (10–250 MHz) was necessary for the signal-to-noise ratio. The phase sensitivity of the PSD was used to detect the absorptive part of the signal alone. The amplitude of the output signal varied up to 500 mV with a DC-offset of -1.5 V. After subtraction of the measured DC-offset, the signal was adapted by a LF amplifier (gain = 10) to the input of a 16-bit ADC to achieve high resolution. In order to measure the whole line width of the NMR signal the oscillator swept the RF-frequency in 500 steps over the resonance region. This measurement was controlled by a programmed Multi I/O-Board that read out a voltage ramp to sweep the frequency of the osciallator and stored the measured ADC values in a buffer. This technique provided a fast measurement of 75 ms/sweep. The PC used in this NMR measurement corrected the digitized signal for the parabolic background due to the Q-meter curve. This background was determined in a separate measurement, where a change of the magnetic field was used to shift the NMR signal out of the frequency scan ($\chi(H) = 0$). To improve the signal-to-noise ratio,

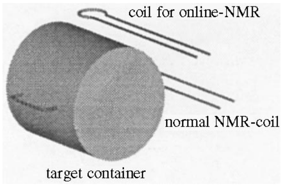

Fig. 8. Target container with the two NMR-coils.

especially for the very small signals at thermal equilibrium, the signal-averaging method was used. This required a fast measurement, as the signal was recorded up to 2000 times.

The design of a NMR-coil depends on the target material, the target size, the Larmor frequency of the nucleons (depending on the magnetic field) and the desired quality factor. The quality factor had to be large enough to obtain a clear NMR signal, but small enough to stay within the linear region of the NMR-module. For these reasons also the wire of the NMR-coil was coated by a Teflon tube. This tube kept the target material away from the strong RF field close to the wire and thus limited the size of the signal.

The coil used for the detection of the proton signal consisted of one turn with an inductance of about 75 nH. For the detection of the deuteron signal a more sensitive coil was required due to the smaller size of the signal (smaller g-factor) and its more complicated line shape (quadrupole splitting). Thus a saddle coil was built, consisting of eight turns and an inductance of about 440 nH.

The calibration of the proton NMR was performed by measurements of the polarization in thermal equilibrium at three different temperatures, so that the proportional factor c could be determined by linear regression. These measurements were performed at temperatures around 1 K running the refrigerator in the ^{4}He-mode, since in this range temperatures can easily be measured with high precision and the polarization build-up times are short.

The uncertainty in the determination of the proton polarization was mainly due to the calibration measurement. The main error sources of a single TE-measurement were the determination of the temperature and the noise of the signal: The temperature was measured using a carbon resistor (Allen Bradley) with a statistical error of $\pm 0.5\%$ and a systematic uncertainly in the calibration of $\pm 1\%$. The magnetic field was calculated using the Larmor frequency of the protons to an accuracy of 10^{-4}. By averaging over 1000 measurements the statistical noise of the small TE signal was reduced to below $\pm 2\%$. The uncertainty based on the dispersive part of the NMR signal depends on the tuning of the PSD and is negligible. Thus the statistical error of the calibration factor c given by linear regression of three TE-measurements at different temperatures is $\pm 0.5\%$. This error also includes the statistical error of the temperature measurement and the error resulting from thermal drifts in the Q-meter electronics during the measurement; it does not include the systematic uncertainty in the calibration of the resistor. Thus, the total error of a TE measurements was $\pm 1.1\%$.

The enhanced proton signals taken as 2.5 T were about 300 times larger than the TE signals. Thereby, the noise is of minor importance and the average of 100 measurements was sufficient to lower the corresponding statistical error to less than $\pm 0.1\%$. However, the larger signal size increased the influence of nonlinear effects in the amplifier. By using a wide frequency scan (500 kHz) and a small modulation – the relation of the signal size to the DC-level – this error was reduced below $\pm 0.5\%$. Thus the total error for the proton polarization at 2.5 T from the statistical error of the enhanced signals and the uncertainties of the calibration measurement amounted to $\pm 1.3\%$.

Due to its small size ($B = 2.5$ T, $T = 1$ K $\Rightarrow$ $P_d = 0.05\%$), the deuteron signal in thermal equilibrium could not be taken with a sufficient precision using this small type of saddle coil out of the target container. Thus, the deuteron polarization was determined by the relationship of the two peaks of the NMR signal (so-called R-ratio method) [14]. The line shape of the deuteron signals was fitted using the parameters of the Liverpool NMR module. By this fit the two peaks resulting from different Zeeman transitions could be analyzed precisely. These polarization values based on R-ratio method were in good agreement with the dedicated values of the uncalibrated integral of Eq. (6) as the linear dependence in Fig. 9 shows. The upper limit for the resulting uncertainty in this

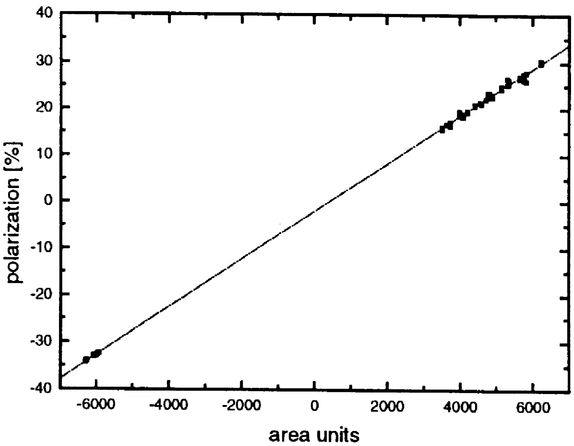

Fig. 9. Deuteron polarization by the R-ratio method versus the uncalibrated integral of Eq. (5).

determination of the deuteron polarization is $\pm 4.5\%$.

In former experiments with frozen-spin targets the polarization could not be determined during the frozen-spin mode (data taking period), since the magnetic field of the holding coils formerly used was not homogeneous enough to allow a NMR measurement. Thus the polarization had to be interpolated exponentially between the starting and the end values of this period. The homogeneity of the new internal holding coil ($< 10^{-3}$ over the target are) allowed for the first time an online measurement of the proton polarization in a frozen-spin target lowering considerably the systematic error of the target polarization. This online measurement was performed by a second NMR circuit that was tuned to the lower field of the holding magnet. However a NMR measurement always causes a depolarization effect whose strength is related to the size of the signal. In order to minimize this effect a smaller coil – compared to the normal NMR circuit – was placed outside the target container (Fig. 8), leading to a reduction in the magnetic susceptibility by a factor of approximately 100. During the data-taking of the GDH-experiment the proton polarization was determined every hour with a statistical error of $\pm 0.2\%$ for a single measurement, with the same systematic error as that of the normal NMR measurement,

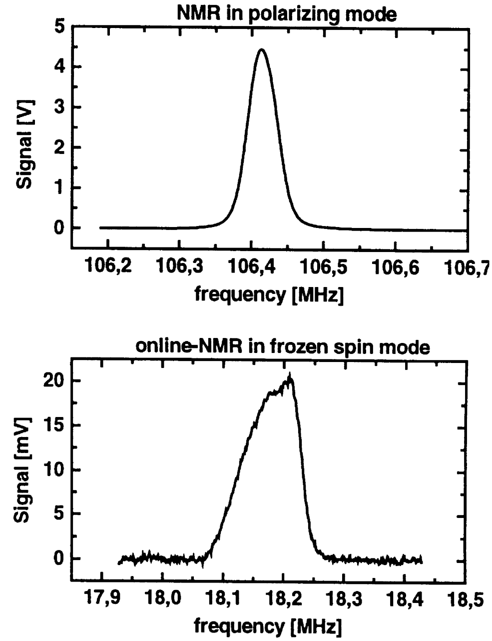

Fig. 10. Enhanced signals taken at 2.5 T using the polarizing magnet (upper diagram) and at 0.4 T using the internal holding coil (lower diagram).

since it was calibrated by it. Typical NMR signals are shown in Fig. 10. For the deuterons an online measurement of the polarization with this coil was not possible due to the very low resonance frequency of deuterons (2.8 MHz) at 0.4 T, which could not be detected by the Liverpool NMR module.

10. Target material

The main requirements on the target material were a high maximum polarization as well as a short build-up time and long relaxation time. Apart from these conditions the absence of polarized background nuclei was also of major importance, since the GDH experiment determined the spin dependence of the total photoabsorption cross section. For these reasons 1-butanol was chosen as target material, since the residuals carbon and oxygen are spinless particles. Furthermore it provided easy handling, especially in comparison to ammonia. The diluation factor – the fraction of polarized protons (deuterons) – of ammonia is 30% higher than that one of butanol (0.135) leading to an increase of statistics, but this benefit was of minor importance at a total beam time of only 600 h. The radiation damage of butanol was negligible at a tagged photon beam of 5×10^5 γ/s. The process of the DNP required the presence of paramagnetic radicals in the vicinity of the nuclear spin. Therefore, the butanol was chemically endowed by 0.5 wt% porphyrexide dissolved in 5 wt% water resulting in 1.82×10^{19} electron spins per cm^3. Butanol doped by porphyrexide had been preferred, since it had been shown in test measurements to be most temperature stable (e.g. compared to TEMPO-doped butanol) [15], which was an important characteristic during insertion of the target material in the refrigerator along with the easy handling. The target material was frozen into spherical beads of 2 mm size. A glassy state of the beads obtained by shock freezing in liquid nitrogen provided the homogeneous distribution of the paramagnetic centers. The beads were placed in a PTFE-container of 2 cm in length and in diameter. The effective filling factor of the target material was 62%. In another experiment related to the experimental check of the GDH sum rule of the deuteron and the neutron perdeuterated butanol was used as target material.

11. Data acquisition and computer control

Concerning the computer aided control the polarized target system presents a diverse range of requirements: For the NMR-measurement a high-speed data acquisition with excellent precision is needed to ensure high accuracy in short time of measurement by the signal-averaging method. Therefore the NMR-measurement is performed autonomously by a programmable Multi I/O board providing 100 k Samples/s and 16-bit resolution. The supervisory control and analysis of the measured values is done by a PC that extracts the data stored in a FIFO buffer of the slot-board. The Slow-Control of the refrigerator, the microwaves, and the superconducting magnets has to provide a wide variety of connectivity options. Devices such as GPIB, Multi I/O-board and serial port are used to connect frequency counters and generators, power supplies, level meters, pressure gauges, mass spectrometer and resistance bridges for the measurement of temperatures to a PC. The third component of the computer control represents the automation of critical processes concerning the vacuum system, the polarizing magnet and the ^{4}He-support. For failsafe operation these control functions are accomplished by programmable logic controllers (PLC), which are connected by the Suconet-K-bus network to a SCADA application running on a PC for monitoring and supervising purposes. The PLC controlling the vacuum system is connected by the industrial network Interbys-S to over 800 Input and Output points spread across 11 racks for conditioning the digital and analog signals related to pumps, motors, valves, manometers and other sensors. this system also integrates the frequency converters and performs motion control of four stepper motors, which are used for the precise and reliable positioning of the inlet valves metering the helium flow in the refrigerator.

The three different data acquisition and supervision systems are integrated in a common concept capable of providing a customized and therefore intuitive graphical user interface, network communication, real-time and historical trending, data-logging, alarming and data-linking to other applications for analyzing and reporting purposes [16,17]. With this solution it became possible to give all collaboration members access to real-time information about the polarized target system and to have remote-control anywhere on a LAN or GAN (Internet) independently of the used platform. The whole application was developed in G, the object-oriented graphical programming language of LabVIEW. Since it consists of a modular open system architecture it is very flexible and can easily be expanded. Besides accomplishing the immediate requirements it also provides for the future needs of new experiments.

12. Performance

With this set-up a maximum polarization of 87.7% for protons and of 35.3% for deuterons was

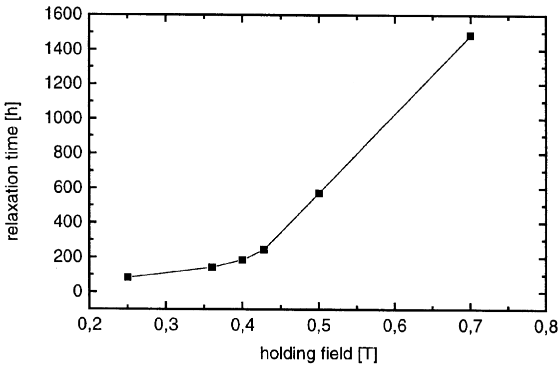

Fig. 11. Relaxation time of butanol at 60 mK.

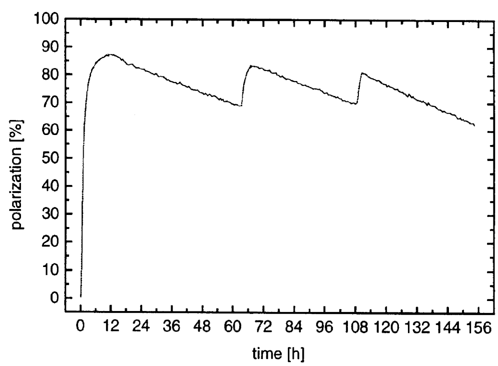

Fig. 12. Proton polarization during three typical frozen-spin cycles.

achieved at build-up times of about 2 h. The relaxation time of the proton polarization at the operational parameters in the frozen-spin-mode of 50–60 mK and 0.42 T exceeded 200 h (deuterons > 150 h) [18]. In Fig. 11 the dependence of the relaxation time of the proton polarization on the magnetic field is given.

Between May and October 1998 the GDH collaboration took data on the proton for more than 700 h and on the deuteron for 200 h. The electron beam polarization was 70–75%, so that the photon polarization exceeded 50% in the upper half of the bremsstrahlung spectrum. In order to use this energy range the experiment ran at two different electron energy settings: 850 and 525 MeV. The starting value of the target polarization in the 'frozen-spin mode' was 80–85% for protons and 30–33% for deuterons. The polarization was refreshed every two days and reversed for consistency checks. Fig. 12 shows a typical development of the proton polarization during the experiment.

13. Conclusion

The new target concept extended the suitability of a polarized solid state target to use for the measurement of spin dependent total cross sections. Due to the horizontal design of the refrigerator and the application of a thin internal holding coil, only 3.3% of 4π in the backward region is hidden by the cryogenic components, and the system provides a symmetric mass distribution in azimuth. The compact design of the front end of the refrigerator and the small fringe field of the internal holding coil enables the placement of detector components directly around the vacuum jacket of the refrigerator at a radial distance of 23 mm and a longitudinal distance of 70 mm from the target. It has been shown that high polarization values for protons and deuterons could be reached. Temperatures below 60 mK in the frozen-spin mode led to long relaxation times so that the nucleon polarization had to be refreshed only once every two days, resulting in more efficient data-taking. At 50–60 mK the refrigerator provided a sufficient cooling power for tagged photon beams with a rate of up to 10^7 γ/s. The concept of loading the target material with an insert allowed quick changes (less than one hour) of the target sample in the ^{4}He-mode. For this purpose a special technique was developed to insulate the mixing chamber with a cold indium seal from the vacuum of the beam tube. The measurement of the target polarization was done very accurately for photons as well as for deuterons by the NMR technique. The homogeneous field of the internal holding coil allowed for the first time in a scattering experiment with a frozen-spin target the determination of the target polarization during data-taking. In this way the systematic error of the target polarization was considerably lowered in comparison to former experiments where the target polarization had to be interpolated between the starting and the end values of the frozen-spin period [1]. In almost 1000 h of data-taking the whole system has been shown to work reliably. The development and successful operation of the polarized target has thus made an important contribution to the feasibility of the first experimental test of the GDH sum rule.

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