Polarized $^3$He targets in medium energy physics at MAMI

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Abstract. Experiments with polarized $^3$He targets at the Mainz Microtron (MAMI) involve double polarized photoabsorption or the extraction of the electric form factor of the neutron $G_{e,n}$ via electron scattering, respectively. Polarized $^3$He with an initial polarization of up to 70% at the experimental areas is provided by a polarizer based on the principle of metastability exchange optical pumping (MEOP). In this article both target setups for the photon- and the electron beamlines will be described and a status of the data analysis will be given.

1. Introduction

Polarized $^3$He is used as an effective polarized neutron target in medium energy physics experiments, owing to the large S-state probability [1] where the two protons saturate their spins so that the spin of the neutron is aligned with the spin of the nucleus. This property can be used, e.g., in double polarized quasi elastic electron scattering to extract the electric form factor of the neutron $G_{e,n}$ via the reaction $^3\text{He}(\vec{e},e'n)\text{pp}$.

Furthermore, experimental access to a validation of the Gerasimov-Drell-Hearn (GDH) sum rule[2; 3] of the neutron is possible via double polarized photoabsorption on polarized $^3$He.

A polarizer based on the principle of metastability exchange optical pumping (MEOP), located in the Institute of Physics, provides polarized $^3$He with a nuclear polarization of up to 76% at a flux of more than 1 bar-1/h [4: 5]. After filling at the polarizer, the target cells are brought to the experimental areas in an auxiliary magnetic holding field in Helmholtz configuration powered by a rechargeable battery. This remote type of operation requires long relaxation times of the target cells and a minimization of the polarization losses during the transport.

The experiments that will be described in the following sections have been performed at the MAMI accelerator in Mainz which provides electrons with a maximum energy of 1.6 GeV [6]. Electron scattering experiments (Section 2) with high resolution magnetic spectrometers are performed in the A1 hall, whereas a tagged photon beam in combination with a 4π-detector system is available in the A2 experimental area for the double polarized photoabsorption measurements (Section 3).
Figure 1. Double polarized electron scattering to extract $G_{e,n}$ via beam helicity asymmetries.

2. Polarized $^3$He in the electron beam

2.1. Electron scattering

The differential cross section of electron scattering on extended spin-1/2 structures is described by the Rosenbluth formula:

$$
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left[ \frac{G_e^2(Q^2) + \tau G_m^2(Q^2)}{1 + \tau} + 2\tau G_m^2(Q^2) \tan^2\left( \frac{\theta}{2} \right) \right]
$$

(1)

with $(\frac{d\sigma}{d\Omega})_{\text{Mott}}$ the Mott differential cross section, $Q^2$ the (negative) transferred four-momentum squared and $\theta$ the scattering angle. $\tau = \frac{Q^2}{4M^2}$ is a kinematic factor. The so-called Sachs form factors $G_e$ and $G_m$ characterize the electromagnetic structure. In a special reference frame (the Breit frame) these are the Fourier transforms of the charge distribution and the magnetization density, respectively.

The angular dependence of Equation 1 can be used to separate $G_e$ and $G_m$ (Rosenbluth separation) via measurements of differential cross sections in various kinematical regimes. For an experimental access to the neutron electric form factor $G_{e,n}$ the Rosenbluth method is not applicable as the neutron is uncharged and therefore $G_{m,n}$ dominates over $G_{e,n}$ in Eq. 1. $G_{e,n}$ can be extracted, however, via beam helicity asymmetries. In Figure 1 the schematics of double polarized electron scattering is given. The scattered electron $e'$ is detected in coincidence with the outgoing neutron $n$. The number of events $N^\pm$ divided by the luminosity $L^\pm$ is recorded for the two helicity states ($\pm$) of the incoming electrons $e$. The beam helicity asymmetry $A$ is then defined as

$$
A = \frac{N^+}{N^-} - \frac{N^-}{N^+}
$$

(2)

In plane wave impulse approximation (PWIA) this asymmetry can be related to the electromagnetic form factors $[1]$

$$
A^{\text{PWIA}}(\theta^*, \phi^* = 0) = \frac{aG_{en}G_{mn} \sin(\theta^*) + bG_m^2 \cos(\theta^*)}{cG_{en}^2 + dG_{mn}^2}
$$

(3)

where $\theta^*$ is the angle between the direction of the momentum transfer and the orientation of the nuclear spin of the target. $a, b, c, d$ denote kinematical factors. In the parallel or perpendicular configurations, i.e. $\theta^* = 0^\circ, 180^\circ$ or $\theta^* = 90^\circ, 270^\circ$, respectively, Eq. 3 reduces to

$$
A_\parallel = \pm \frac{bG_m^2}{cG_{en}^2 + dG_{mn}^2} \quad A_\perp = \pm \frac{aG_{en}G_{mn}}{cG_{en}^2 + dG_{mn}^2}
$$

(4)
For the experimental asymmetries $A_{\|}^{\exp}$ the beam and target polarizations $P_e$ and $P_n$ have to be taken into account. In the ratio

$$\frac{A_{\perp}^{\exp}}{A_{\|}^{\exp}} = \pm \frac{a}{b} \frac{G_{e,n} P_e P_n^{\perp}}{P_e P_n^{\parallel}}$$

systematic uncertainties are reduced due to the occurrence of relative polarization values. Only. $G_{m,n}$ has been measured with great precision in different experiments [7], so that $G_{e,n}$ can be obtained from Eq. 5 via a measurement of $A_{\perp}^{\exp}/A_{\|}^{\exp}$.

2.2. Setup

The magnetic guiding field for the polarized $^3$He needs to meet the following requirements. The spin orientation needs to be rotated in the scattering plane for measurements of $A_{\perp}^{\exp}$ and $A_{\|}^{\exp}$. Furthermore, a sufficient homogeneity is required. When the relative field gradient $(dB/dz)/B_0$ is smaller than $5 \times 10^{-4}$ cm$^{-1}$ the corresponding relaxation time due to field gradients $T_{1,grad}^z$ is larger than 1000 hours for cells filled with 5 bar [8].

The target cells with the polarized gas are located in the middle of a box, made from $\mu$-metal and iron plates with coils wound around, providing the magnetic guiding field [9] (see Fig. 2, left). The holes in the box for the primary electron beam and for outgoing particles spoil the perfect homogeneity of the magnetic field which would be obtained in a completely closed box in this configuration. By means of correction coils, a sufficient homogeneity can be regained, however, in the actual setup (see Fig. 2 right).

The target cells are manufactured from fused silica with a wall thickness of 2 mm. They comprise a spherical part with an outer diameter of 9 cm and two cylindrical sidearms resulting in a total length of 25 cm. The entry windows for the electron beam consist of 50 $\mu$m beryllium, covered by a thin layer (0.4 $\mu$m) of aluminum. Cesium coating [10] and a proper demagnetization procedure [11; 12] result in wall relaxation times $T_{1,wall}$ between 100 and 200 hours.

For online polarization measurements two methods are available. A relative method, where the free induction decay (FID) signal is observed after tipping the $^3$He magnetization nonadiabatically by a small angle via a transverse field pulse. The second, absolute, method uses the measurement of the magnetic field generated by a dense sample of polarized gas [13]. In order to get rid off the magnetic holding field which is about a factor 1000 larger than the
Figure 3. The polarization during a single turn (left) and during the complete beamtime (right) for the $G_{e,n}$ measurements.

field generated by the polarized gas, a 180 degree spin flip via adiabatic fast passage (AFP) is involved in this method. Both polarization measurement methods and the corresponding calibrations are described in Ref. [14] and are not repeated here.

2.3. Performance in the beam and status of data analysis

Besides the above mentioned relaxation due to field gradients and the interaction of the polarized gas with the container walls, under real experimental conditions also the relaxation due to the production of $^3$He$^+$ ions in a beam of charged particles [15] and the dipolar relaxation [16] has to be taken into account. For our setup in a 10 $\mu$A electron beam $T_{1}^{\text{beam}}$ amounts to 220 hours$^1$ and $T_{1}^{\text{dipole}}$ is 150 hours at a pressure of 5 bar. Adding up all contributions according to

$$\frac{1}{T_{1}^{\text{total}}} = \frac{1}{T_{1}^{\text{grad}}} + \frac{1}{T_{1}^{\text{dipole}}} + \frac{1}{T_{1}^{\text{beam}}} + \frac{1}{T_{1}^{\text{wall}}}$$

results in a total relaxation time $T_{1}^{\text{total}}$ of 30-40 hours (see Fig. 3 left). The target cells have been exchanged twice per day, the temporal variation of the polarization during the complete beamtime for the $G_{e,n}$ measurements is displayed in the right part of Fig. 3. The initial polarization reached up to 72% and the mean polarization was about 55-60%. More details about the target setup for the electron beam can be found in Ref. [14].

The electric form factor of the neutron $G_{e,n}$ has been measured at $Q^2 = 1.58$ (GeV/c)$^2$. The data analysis which is part of a PhD thesis [17] is in progress. A preliminary data point is consistent with recent measurements [18] at higher $Q^2$ values.

3. Polarized $^3$He in the photon beam

In the A2 experimental area a beam of energy tagged photons is available. The principle of tagging is displayed in the left part of Figure 4. The photons are produced via bremsstrahlung of electrons impinging on a thin radiator (e.g. 10$\mu$m Cu). The electrons are then deflected in a dipole magnet where the bending radius depends on the electron energy that is left after the bremsstrahlung process. Due to the hit position on a scintillator array in the focal plane of the magnet, the electron energy $E_e$ is determined. With the known primary energy $E_0$ the energy of the photon $E_\gamma$ is simply $E_\gamma = E_0 - E_e$ [19]. Circularly polarized photons are generated by bremsstrahlung of linearly polarized electrons on an amorphous radiator [20].

$^1$ The production of $^3$He$^+$ molecular ions has been suppressed by adding a small amount (10$^{-2}$) of N$_2$ as quenching gas.
3.1. GDH sum rule

One aim of the experimental program with the polarized $^3$He target in the photon beam is the validation of the Gerasimov-Drell-Hearn (GDH) sum rule [2; 3] of the neutron. This sum rule has already been derived in the mid 1960s by using very fundamental physics principles, only. It reads

$$\int_{E_\gamma,0}^{\infty} dE_\gamma \frac{\sigma_{3/2} - \sigma_{1/2}}{E_\gamma} = \frac{2\pi^2 \alpha}{m^2 \kappa^2}$$

with $\sigma_{3/2,1/2}$ the total photoabsorption cross sections of circularly polarized photons on longitudinally polarized nucleons (see Fig. 4, right side). The cross section difference is divided by the photon energy $E_\gamma$ and integrated over the complete energy range. This means that the l.h.s. of Equation 7 includes the complete excitation spectrum of the nucleon, whereas on the r.h.s. only static properties like the mass $m$ and the anomalous magnetic moment $\kappa$ appear. $\alpha$ denotes the fine structure constant. An experimental check of the GDH sum rule for the proton has been performed at the accelerators MAMI in Mainz and ELSA in Bonn in the energy range from the threshold up to 3 GeV [21–23]. For an experimental access to the neutron the use of nuclear targets is inevitable. So far, only double polarized data from deuteron targets exist in a limited energy range [24; 25]. Here, the use of polarized $^3$He provides an alternative, and due to the spin structure, more direct access to an experimental validation of the GDH sum rule for the neutron.

3.2. Setup

A sideview of the experimental setup at the photon beam is displayed in Figure 5. During data taking the cell with the polarized gas is located in the middle of the Crystal Ball detector [26].
The magnetic guiding field is provided by a solenoid [27]. Due to lack of space inside the detector, polarimetry is performed outside the detector inside a pair of Helmholtz coils. An automatic transport system has been installed for movement of the cell between the two positions. Inside the Helmholtz coils the decay of polarization is measured via the FID method (see Section 2.2). The complete polarization measurement cycle, including the movement of the cell, is completed within 3 minutes and causes only a 1% relative polarization loss.

The target cells obey cylindrical geometry with a diameter of 6 cm and a total length of 20 cm (see Fig. 6 left side). They are made from quartz glass or pyrex and coated with cesium. Various materials for the entry windows for the photon beam have been tested. Besides tightness for the desired pressures and good properties regarding relaxation, the area density of the window foils should be as small as possible to suppress background events caused by interaction of the photon beam with the window material. 50 \( \mu \text{m} \) Mylar coated with aluminum seemed to be a good choice. It turned out, however, that these foils remain not tight after multiple exposures to high pressures. Consequently water vapor from the surrounding air can diffuse inside the cell and destroy the cesium coating. The high tensile strength metallic alloy Havar is compatible to Mylar regarding background events, though it is not ideal for keeping the \(^3\text{He}\) polarized. The preferred

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solution is 50 μm titanium which resulted in the highest relaxation times so far. The measured $T_1$ times of cell ‘CBD1’ as a function of the pressure inside the cell is shown in the right part of Fig. 6. The $T_1$ times decrease stronger with increasing pressure than expected from dipole-dipole interaction [16] (dashed line). This effect can be attributed to ferromagnetic contaminants [28]. An improved demagnetization procedure led to an increase of the wall relaxation time for cell ‘CBD1’ from 40 to 60 hours (extrapolation of black and red lines in Fig. 6 to zero pressure).

3.3. Performance in the beam and status of data analysis

A first measurement with polarized $^3$He in the photon beam has been performed in July 2009. It has been demonstrated that the complete setup works fine and that polarization losses during handling of the cells can be kept under control. The polarization performance during the complete beamtime is displayed in Figure 7. The polarization has been measured every two hours by means of the FID method. The agreement of the parametrization with the data points shows that there are no additional relaxation terms besides the known ones. The target cells have been exchanged twice per day. During the first part of the beam time only cells with total relaxation times between 5 and 6 hours were available, only, whereas in the last part cells with 20 hour livetime could be used. More details about the target setup for the photon beam will be given in an upcoming paper.

Data have been taken with primary electron energies of 855 and 525 MeV, respectively, covering the energy range of the delta resonance. The analysis of the data is part of a PhD thesis [27]. Preliminary results show a clear signal of the delta resonance.

4. Summary and outlook

In this article the setups for experiments with polarized $^3$He in the electron and the photon beam at MAMI have been described. In the electron beam a measurement of $G_{e,n}$ at $Q^2 = 1.58(\text{GeV}/c)^2$ has been performed. For completeness it should be mentioned that also the reaction $^3\text{He}(\vec{e}, e'\vec{p})d$ has been studied [29] with a similar setup.

In the photon beam the first experiment with a polarized $^3$He target in the energy range of the delta resonance has been performed which demonstrated the functionality of the assembly.
For future experiments the improvement of the mean polarization is worthwhile. A major improvement can be made by installing the new compact polarizer [30] directly at the experiment. This online polarization would allow for quasi constant polarization values around 70%.

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