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Target Offline Polarization COMPASS 2022

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(in behalf of the COMPASS Polarized Target Group)

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The COMPASS experiment at CERN used a transversely solid polarized deuteron target with a muon beam to measure the TMD PDFs in SIDIS in 2022.
The target system consists of a 50 mK dilution refrigerator, a 2.5 T solenoid magnet, and three sets of 70 GHz microwave systems. Solid ^{6}LiD beads of the target material were contained in a 3-target-cell of 30-60-30 cm long with 3 cm in diameter. The target material was produced for the first phase of COMPASS which started data-taking in 2002. The longitudinal polarization of the target is obtained by the DNP method with gunn diode oscillators which are newly installed. We collected data from June to November 2022.
The polarization was determined with 10 NMR coils on the cells. The polarization was calibrated with the thermal NMR signal at three different temperatures (1.0, 1.3 and 1.5 K). The analysis of the thermal equilibrium NMR signal is essential to determine the polarization during DNP.
We will present the results of the analysis of the thermal deuteron NMR signals, the relaxation times during the data-taking as well as performance of the new microwave synthesizers.

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1. Introduction

The COMPASS experiment at CERN had been measuring the transverse spin azimuthal asymmetry of charged hadrons produced in semi-inclusive deep inelastic scattering (SIDIS) using a 160 GeV muon beam and transversely polarized proton and deuteron targets in order to study the nucleon spin structure. The Collins and Sivers asymmetries are the amplitudes of 2 of the 8 azimuthal modulations, which are theoretically expected to be present in the SIDIS cross-section for a transversely polarized target.

The COMPASS collected a significant amount of the proton data with a polarized NH_3 target in 2010 [1]. On the contrary the deuteron data with ^{6}LiD (lithium deuteride) was obtained only for short periods in 2002 and 2004 with a small acceptance magnet [2].

Thus, the statistical uncertainties of the deuteron transverse spin asymmetry were considerably larger than those of the corresponding proton asymmetries. The COMPASS collaboration aimed to obtain more deuteron data with ^{6}LiD [4] to improve the statistical uncertainties in 2022. The accurate measurements of the asymmetries with the deuteron target will provide a comprehensive understanding of the nucleon's internal structure.

2. COMPASS Polarized Target Components

The COMPASS Polarized Target consists of various components, which are described below[5].

Magnetic System: A superconducting magnet system is used to generate a strong, homogeneous magnetic field. This magnetic field helps in aligning the spins of the target nucleons and maintaining their polarization during the experiment. The magnet system consists of a 2.5 T solenoid (with 50 ppm homogeneity) with two saddle coils for a perpendicular to beam orientated magnetic field of 0.6 T.

Cooling System: Depending on the experimental conditions, a cooling system is required to control the temperature of the target material. This involves a helium vaporizing mode for the TE (thermal equilibrium) calibration and a powerful mixing mode with ultra-low temperatures in the millikelvin range [5].

Q-Meter: [6–8]The degree of polarization is one of the most important values for later analysis. Therefore, the exact determination of the polarization is of central importance. In general, the cw (continuous wave) NMR method is used to determine polarization. The sensitive part is the Q-meter with a resonance circuit including the conductivity (NMR coil) which is embedded in the target material itself or mounted on the target container. The capacitance is connected via an $\lambda/2$ cable to the coil. To calibrate the Q-meter, the NMR signals are measured at a known temperature and magnetic field in thermal equilibrium (TE). The area under the signal (A_{TE}) is proportional to the polarization (P_{TE}). The dynamic nuclear polarization can be calculated using the rule of three: $P_{dyn} = P_{TE}/A_{TE} * A_{dyn}$.

Polarization System: A polarization system is employed to align the spins of the target nucleons (protons or neutrons). The target materials is contained in three cells with lengths of 30 cm, 60 cm and 30 cm. The cells with a diameter of 4 cm are installed in series with the beam axis. The cells are separated from each other by microwave stoppers (copper mesh) and are dynamically polarized in opposite directions. This means that the spins of the two outer cells are aligned with the opposite sign to the spins of the middle cell. The dynamic polarization is conducted using three different microwave generator diodes (gun diodes) to apply the optimal microwave frequency and energy to the respective cell. The maximum power of the gun diodes is three watts and the frequency can be varied by several hundred megahertz around the Larmor frequency of the paramagnetic centers (70 GHz at 2.5 T).

3. TE calibration

The COMPASS-target [3, 5] has 10 NMR coils installed on the target cells (3 in upstream-, 4 in center- and 3 in the downstream cell). The coils are excited by a signal generator and operated in parallel with 10 Liverpool NMR modules. The signals are freed from offset and amplified with Yale-Boards. Finally, the processed signals are digitized with 16bit ADCs. The baseline (parabola shape) of the frequency scan for every NMR coil is detected at off resonance (shifted magnetic field) and subtracted from the signal in resonance.

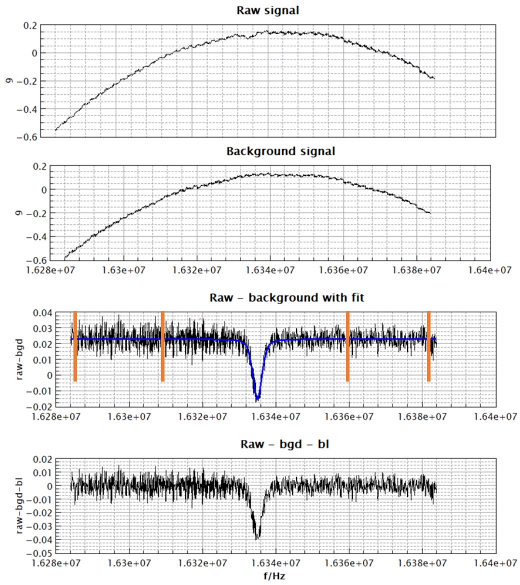


Figure 1: Signal analysis

In figure 1 the processing of the signal is shown. The upper plot shows the raw signal. In the second plot, the background signal,which is subtracted from the raw signal, is depicted and plotted in the third graph plane. A polynomial function is fitted to the data points between the vertical lines in the wings of the signal and again subtracted from the same signal, in order to remove the residuum background. The resulting line is shown in the fourth graph plane. To get the area under the line-shape the data points between the inner vertical lines are summed up. Before the target material is dynamically polarized and the actual physics data acquisition begins, the TE calibration is performed. For this purpose, the TE signals were detected at three different temperatures (0.99, 1.29 and 1.48 K) over several days. Every 10 signals, a background signal was recorded at a magnetic field outside the NMR resonance. Figure 2 shows an example for a build-up curve of coil no. 7 at T = 1K. The area-units, the exponential fit and the mean value for the 50 hours are shown. The dc-offset board is set to a gain of "206"[1]. For the online polarization this TE values are used. After the data-taking run, an additional TE signal was taken in November. The final offline polarization was calibrated with all four values. In figure 3a the TE-polarization values are plotted versus the corresponding TE-areas. Except for coil no. 7 the value in November could not be used because at the beginning of November 2023 there were issues with the transfer cable which couldn't fixed by the end of the run. The final enhancement factors $E = P_{TE}/A_{TE}$ are given in table 3b. The corresponding uncertainties are given in the third column.

[1]The real gain values are determined by fitting the Q-curve with a polynomial function to the Q-curve at gain 1.

In section 5 all sources of the uncertainties will be discuss.

4. Offline polarization

In the field of the 2.5 T solenoid, the target is dynamically polarized. After achieving a high polarization in a comparatively short time, the $^3He/^4He$ mixing cryostat is brought to temperatures below 100 mK, so that the spin is "frozen" and the magnetic field can be reduced to a small holding field. The relaxation times of the target polarization are extended to thousands of hours. Since the polarization of the target must be perpendicular to the muon beam, the holding field is provided by the saddle coils, which is perpendicular to the beam.

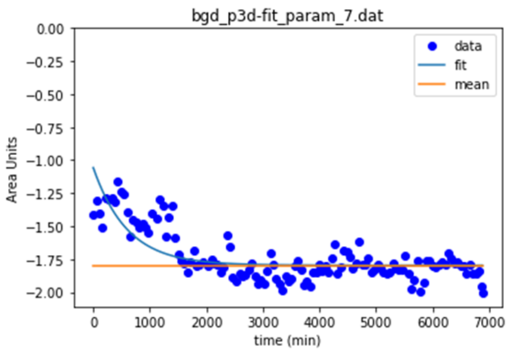
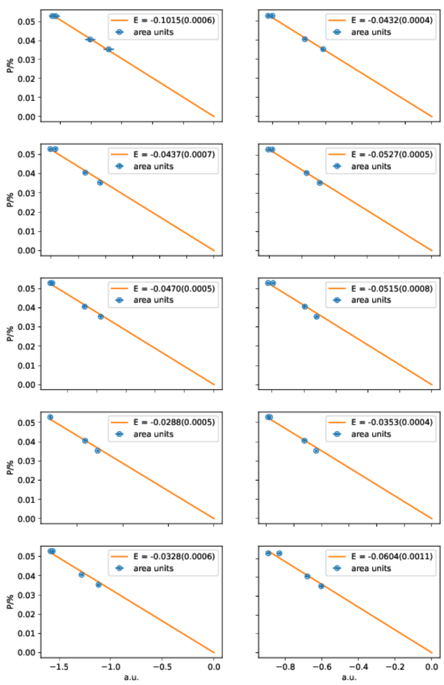


Figure 2: TE build-up curve of coil no. 7 for T = 1K.



(a) TE-Polarization vs TE-area-units

Coil	E	dE
1	-0.10150	0.00064
2	-0.04317	0.00036
3	-0.04373	0.00065
4	-0.05273	0.00048
5	-0.04705	0.00050
6	-0.05151	0.00080
7	-0.02878	0.00049
8	-0.03532	0.00045
9	-0.03284	0.00056
10	-0.06040	0.00115

(b) Enhancement factor E for every coil with April and November TE.

The dynamically polarized signals are recorded with fewer sweeps, but are processed in exactly the same way as the TE signals. Because of the low and less homogeneity holding field of the saddle coils, no polarization measurement is possible. Before the polarization is hold by the saddle coil, the polarization is measured several times and averaged. At the end of data acquisition, the polarization is measured again at 2.5 T. Maximum deuteron polarization values of more than 40 % and lower than -40 % are achieved. The polarization values during data acquisition are interpolated via a linear curve. In order to reduce systematic uncertainties, the polarization is reversed after a block of several weeks. Figure 4 shows the course of the polarization over the entire run in 2022. For physics data analysis not only the deuteron polarization is needed but also ^{6}Li polarization (^{6}LiD). The deuteron and lithium spin system of ^{6}LiD are in close thermal contact and it has been shown that the EST (equal spin temperature) is given [9]. The ^{6}Li polarization is calculated by the fictive temperature (so called spin temperature) from the dynamic D polarization by finding the roots of the function.

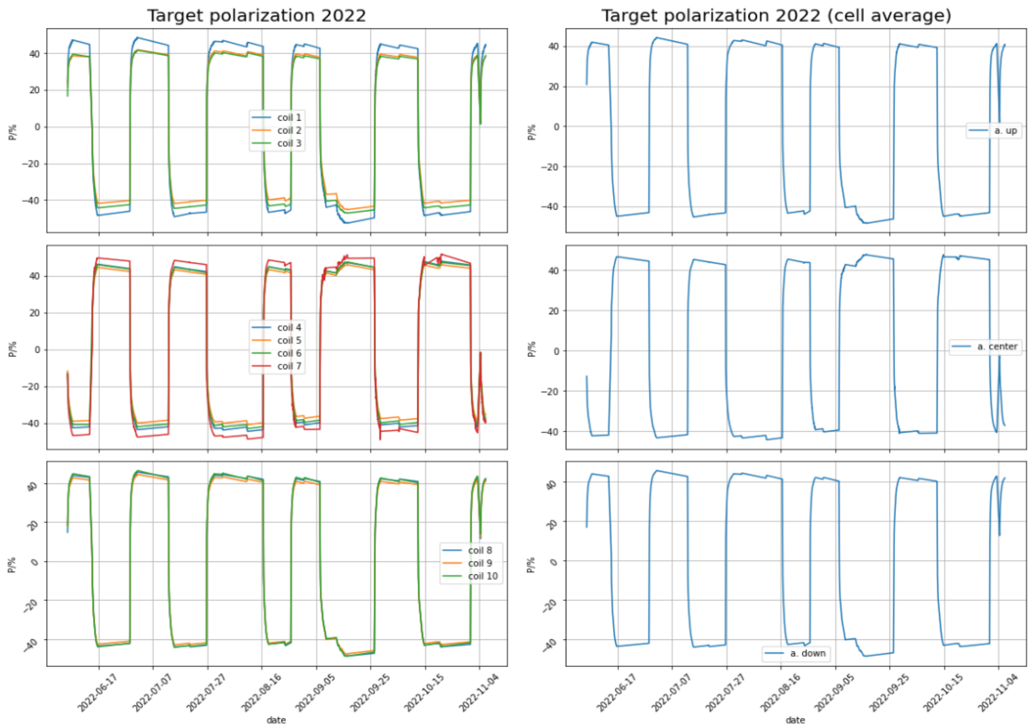


Figure 4: Left plot shows the polarization values for every coil in the targets cells; Right plot shows the average polarization for each cell

5. Uncertainties

In this section the uncertainties will be discussed, estimated and summed up. The accuracy of the gain measurement (dG) depends on the noise of the q-curve and the maximum values are less than $dG = 0.5\%$. The rf resonance circuit and the first amplifier with a 50 Ω input impedance are connected in parallel. This caused some non-linearity as a function of the signal level in series resonant circuits. With the polarization, the inductive resistance x_L changes, and consequently, the the current flowing through the coil changes. The number of spin flips is proportional to the coil current. As a result, positive signals become relatively smaller and negative signals relatively larger

as the signal level increases. This means that positive signals are underestimated and negative ones are overestimated. Non-linearities in the measurement of high dynamic polarization (dNL) can be caused by the serial resonant circuit if the modulation (signal level / q-curve offset) exceeds values of 0.3 %. The measured modulation values are less than 0.1 and therefore the non-linearity is very small and is estimated at $dNL = 0.5\%$.
Additional, dominant uncertainties are the temperature distribution and measurement over the whole target container dT, which is estimated at $dT = 2\%$ and is one of the dominant uncertainties. A further but minor uncertainty is the magnetic field, which can be determined to $dB = 1kHz/16.3MHz = 0.06\%$. The statistical uncertainties for the enhanced signals are negligible. All these uncertainties are of equal value and are geometrically added up to a relative uncertainty of $dP/P = 2.6\%$.

6. Summery

The polarization value was calibrated with three TE – measurements in April before the data-taking and a fourth in November after the data-taking period. The 30-60-30 cm target cell configuration was applied to minimize systematic uncertainties. The two outer cells are polarized with the opposite sign of the middle cell and the polarization were reversed by DNP every few weeks. It was repeated ten times in total. The COMPASS run in 2022 was the last data-taking run and succeeded with a high deuteron target polarization of more than |40|% and a maximum relative uncertainty of 2.6 %.

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