High Precision Measurement of the Polarization in a Large Target

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Abstract

The individual error sources of the proton polarization measurement during the SMC '93 run were carefully analyzed. Main error groups were the calibration temperature, the NMR signals in thermal equilibrium and those of the enhanced polarization, and the LF gain ratio. After corrections to the raw polarization values, the overall error amounts to $\Delta P/P = 2.1\%$. The averaging of the polarization values, the correlations between the errors and the polarization homogeneity throughout the large target were also considered, resulting in a final relative accuracy of 3%.

1 Introduction

The SMC experiment aims at measuring the spin dependent structure functions by deep inelastic scattering of longitudinally polarized muons off polarized proton and deuteron targets [1, 2]. A general description of the SMC polarized solid state target can be found in the references above and in [3]; Ref. [4] gives an overview of the NMR system used to measure the nucleon polarization. The target consists of two separated cells of 60 cm length and 5 cm diameter, which are polarized in opposite directions via the dynamic nuclear polarization process. The exceptional size of the target has made it more susceptible to possible radial or longitudinal polarization inhomogeneities, and thus requires a multi-channel Q-meter circuit, in our case consisting of 8 large and 2 small NMR probes embedded in the target material, to determine the proton polarization throughout the target.

In principle the dynamic polarization value is derived by comparing the enhanced signal area $\int S_{\rm enh}$ with that of the thermal equilibrium (TE) signal:

$$P = G_{\rm LF} \cdot \frac{\int S_{\rm enh}(\omega)\, d\omega}{\int S_{\rm TE}(\omega)\, d\omega} \cdot P_{\rm TE} \quad , \qquad (1)$$

with the ratio $G_{\rm LF}$ of the LF-amplifier gain factors and the natural polarization for a spin-1/2 particle $P_{\rm TE} = \tanh(\hbar\,\omega_\circ/2\,k\,T)$ (Curie law), where k is the Boltzmann constant, $\omega_\circ$ the Larmor frequency of the proton. Besides the already mentioned polarization inhomogeneity, Eq. 1 indicates the main groups of uncertainties we have to face:

- *Calibration temperature errors*
- *TE signal errors*
- *Enhanced signal errors*
- *Gain ratio errors*

2 The temperature calibration errors

Ref. [5] gives a general description of the dilution refrigerator including the thermometry system. The TE-signal is derived at temperatures around 1 K in order to get fast polarization build up times and temperature values which are easy to measure accurately. The most exact temperature determination around 1 K we would have extracted from the ^{3}He vapour pressure measurement. Unfortunately the ^{3}He-bulb was blocked soon after target loading. So alternative methods have been used during several TE-calibrations:

- *Speer* carbon resistors with 4-wire AC bridge measurement for the first calibration
- ^{4}He vapour pressure inside the still and RuO resistors for all other calibrations

To improve the Curie - law method the still heater has been used to change the calibration temperature in small steps around 1 K. Table 1 gives an overview of the main error sources. A leading error, $\Delta T_{\rm noise}$, originates from the readout noise of the *MKS Baratron* used for the vapour pressure measurement, especially for the low pressures around 1 K. Other errors linked to this device are the scale offset, $\Delta T_{\rm off}$, due to the reference vacuum and an observed bias of the amplifier, $\Delta T_{\rm range}$, when switching to different ranges. In addition, substantial errors arise due to the necessary extrapolation of the ITS 90 temperature scale below 1.25 K, $\Delta T_{\rm ITS}$, and due

Temperature Errors				
	Temperature			
Origin	**1.0 K**	**1.2 K**	**1.4 K**	**1.6 K**
$\Delta T_{\mathrm{range}}$	3.0 mK	3.0 mK	3.0 mK	3.0 mK
$\Delta T_{\mathrm{offset}}$	3.0 mK	1.0 mK	0.3 mK	0.1 mK
ΔT_{ITS}	5.0 mK	2.5 mK	1.0 mK	1.0 mK
$\Delta T_{\mathrm{therm}}$	3.0 mK	1.0 mK	0.2 mK	0.1 mK
ΔT_{ADC}	1.0 mK	0.5 mK	0.2 mK	0.1 mK
$\Delta T_{\mathrm{creep}}$	0.4 mK	0.2 mK	0.1 mK	0.1 mK
ΔT_{cont}	0.3 mK	0.3 mK	0.3 mK	0.3 mK
ΔT_{stab}	3.0 mK	3.0 mK	3.0 mK	3.0 mK
$\Delta T_{\mathrm{noise}}$	8.0 mK	4.0 mK	2.0 mK	2.0 mK
$\mathbf{\Delta T_{tot}}$	**11 mK**	**7 mK**	**5 mK**	**6 mK**
$\mathbf{\Delta T/T}$	**1.1 %**	**0.6 %**	**0.4 %**	**0.4 %**

Table 1: Main error sources for the temperature estimation as a function of T.

to the uncertainty in thermomolecular corrections of the pressure reading. The stability in time during the TE signal averaging ($\sim$4 min) was found to contribute with $\Delta T_{\mathrm{stab}} = \pm 3$ mK. Minor influences were estimated for the ADC resolution of the pressure reading, the film creep of superfluid ^{4}He inside the manometer tube, and the contamination of the ^{4}He with ^{3}He. Other possible items, like pressure differences due to the still pumping, field dependencies, or intrinsic heating of the resistance sensors, have been evaluated to be negligible. These temperature errors result in an overall polarization error of

$$\Delta P_{\mathrm{temp}} = 0.8\,\% \qquad \text{for the calibrations } 2 - 4.$$

The first TE calibration has to be treated in a different way as already mentioned; the main error source is here the calibration of the *Speer* resistor:

$$\Delta P_{\mathrm{temp}} = 2.1\,\% \qquad \text{for calibration } 1,$$

as the first calibration has been done exclusively around 1 K.

3 The TE signal errors

As the thermal equilibrium polarization of protons at 1 K is around 0.25 %, the appropriate NMR signal areas are 400 times smaller than those of the enhanced signals, thus making detection more difficult. For that reason the noise reduction is extended by 10$\times$ longer signal averaging (number of sweeps $n = 2000$), which reduces the statistical noise like $\sim \sqrt{n}$, but which on the other hand increases the influence of thermal drifts in the Q-meter parameters. In Table 2 we list the main uncertainties of the TE signal, resulting in an total error of the TE signal area of ± 1.1 %. Note that the *noise* is the only statistic error source, while all others are systematic ones. For two of the main error sources,

TE Signal Errors	
Origin	**Value**
Polarity	0.60 %
Magnetoresistance	0.50 %
Background	0.40 %
Long term drift	0.40 %
Q-curve jumps	0.30 %
Noise	0.30 %
Relaxation	0.20 %
Short term drift	0.10 %
$\mathbf{\Delta P_{TE}/P}$	**1.1 %**

Table 2: Main error sources of the TE signal ('background' and 'polarity' are residual errors after correction).

namely for the proton background signal of the empty target containers and for a field polarity effect on the calibration coefficients, corrections were applied. The container's NMR signal was found to be in the order of 1 % of the TE signal size, but with a relatively large uncertainty. The influence of the field polarity on the signal areas, most probably caused by the stray field on the RF 10-way splitter used to feed the individual NMR probes from a single synthesizer, is illustrated in Fig. 1. Other main sources of uncertainty on the TE signal are slight tuning changes at the 1.5 % higher baseline field due to magnetoresistance of the coils and cables inside the cryostat, drifts of the Q-meter circuits in time, noise, and observed small irregular jumps in the Q-curves, for which no satisfactory explanation could be given so far. There is also a small contribution due to the change in the TE polarization caused by the baseline taking at a different field together with the finite relaxation time in the order of minutes.

4 The enhanced signal errors

As the enhanced signals are much larger than those of the TE, some of the so far discussed error sources are of minor interest, namely the noise, the background, and the magnetoresistance. But there are also additional error sources for the enhanced signals:
Some of the biggest problems of the polarization measurement arise from the large modulation depth of the highly enhanced signals, that is the signal height relative to the RF-level outside the resonance. This modulation can exceed 60 % for the negative signal, which leads to a non-linear distortion of the line shapes and thus to a wrong estimation of the signal area. Please refer to Ref. [6] for a more detailed analysis. The correction to be

made on the polarizations due to our simulation of the Q-meter circuit is in the order of 5 % with a residual uncertainty of up to 0.9 %.
Another correction was necessary for the observed signal shifts caused by the internal magnetization of the aligned magnetic moments. Figure 2 shows the measured changes in the signal areas due to the frequency dependence of the Q-meter response function and due to the signal cut-off.
Other items are the linearity of the BRM[1] used in the *Liverpool* Q-meters to receive the real part of the output voltage, some observed sudden tuning changes, and a possible contribution from the hyperfine-broadened protons in the EHBA-Chromium (V) complex, which could not be measured. In Table 3 the leading error sources of

Enhanced Signal Errors		
Source	**400 kHz**	**600 kHz**
Nonlinearity	0.90 %	0.60 %
BRM linearity	0.60 %	0.60 %
Offcentering	0.50 %	0.40 %
EHBA-signal	0.15 %	0.15 %
System drifts	0.30 %	0.15 %
Tuning jumps	0.50 %	0.50 %
$\mathbf{\Delta P_{enh}/P}$	**1.2 %**	**1.0 %**

Table 3: Remaining systematic error sources of the enhanced signal after corrections for 400 and 600 kHz sweep width, respectively.

the enhanced signals are summarized for the two sweep widths used through the '93 run, adding to an overall error of 1.2 and 1.0 %, respectively.
The LF amplifier gain ratio between TE and enhanced signal turns out to be an additional source of error in the order of 0.5 %.

5 Polarization homogeneity and averaging

The polarization values given by the individual coils were averaged for each target cell and over the time of one data run (typically 0.5 h) considering the following points:

- The coils do not sample the whole target volume and is different for the small and the big coils.
- Correlations between the polarization errors have to be taken into account not only for the coils of one half regarding the averaged value, but also for the difference of upstream and downstream cells (which is the relevant parameter for the measured observable). At last the correlation in time for a given error has to be considered.
- Only the entirely uncorrelated part of the error will shrink like $1/\sqrt{n}$ of the the number of used coils, n.

[1] Balanced Ring Modulator

In addition, it has to be analyzed, whether the different readings of the individual coils reflect a substantial inhomogeneity throughout the target cells. While the longitudinal homogeneity has less impact due to the 'averaging' by the beam, a large radial dependence of the polarization would cause serious systematic problems. There are several physical reasons which might affect the polarization homogeneity in the target volume:

- **Magnetic field flatness:** Small deviations from the main field of 2.5 T can lead to differences in polarization build-up time and final values in parts of the target. This deviation should not exceed a few Gauss, as shifts of the microwave center frequency of 10 MHz result in a slight depolarization for values of P beyond 90 %. However, the superconducting solenoid provides a magnetic field flatness of $\Delta B/B < 10^{-4}$, so that this influence is largely diminished.
- **Microwave distribution:** The absorption of the microwaves by the paramagnetic centers of the target may lead to a attenuation of the microwave strength towards the center of the target. This would cause a troublesome radial inhomogeneity. Fortunately the optimal microwave frequencies for positive and negative DNP are situated slightly beneath the ESR line, e. g. our target is highly transparent.
- **Microwave leakage:** A microwave leakage through the microwave stopper between the two target cells might cause a drop of the polarization towards the inner ends because of the opposite spin directions in the two halfs. This effect has been investigated, showing no significant microwave leakage.
- **NMR saturation:** The RF field of the proton larmor frequency used for the NMR system destroys a small part of the polarization. Feeding high RF power directly inside the coils results in a strong depolarization within a few seconds. However, the appropriate choice of the circuit parameters leads to a negligible depolarization: The relaxation time caused by the NMR system is in the order of several hundred hours.
- **Superradiance:** The superradiance [7, 8] has destroyed the negative polarization substantially during every field reversal used to change the spin direction every 5 h before it was discovered, how to prevent this effect by means of an inhomogeneous

field created by the solenoid's trim coils during the ramp down of the field. Moreover, the superradiance takes place at particular NMR coils, destroying thus the polarization very locally and creating inhomogeneities in excess of 40%.

After corrections the largest differences inside a given cell is below 3 %. To probe a possible radial inhomogeneity, two small coils have been installed in the upstream target, one centered and the other perpendicular $\sim$1 cm off center. The readings from these coils also do not differ significantly, nor from the averaged value neither from each other.

6 Summary

Table 4 gives an overview over the applied corrections to the polarization values, the number of magnitude and the residual error. Not included are special treatments of the temperature measurements themselves, like the thermomolecular correction. Summarizing the contributions of all investigated error sources, the final error of the averaged polarization for upstream and downstream cells is given in Table 5. If we include the small inhomogeneity observed by the different probes, the overall error of both target halfs averaged over the whole run turns out to be:

Summary of the Corrections		
Correction	**Magnitude**	**Residual**
Background	1.0%	0.4%
Polarity	2.0%	0.6%
Gain	2.0%	0.5%
Offcentering	0.6%	0.5%
Nonlinearity	4.0%	0.8%

Table 4: Summary of the applied polarization corrections and the residual error.

Error of the Coil Averages		
Period	σ_{tot} **(up)**	σ_{tot} **(down)**
May – Jun.	2.8 %	2.7 %
Jun. – Sep.	2.1 %	1.8 %
Sep. – Nov.	2.2 %	1.7 %
Nov. – Dec.	1.9 %	1.7 %

Table 5: Final error of the averaged coils for upstream and downstream target during the '93 proton run.

$$\mathbf{\Delta P_{tot}/P = 3.0\,\%} \quad ,$$

where the mean polarization value throughout the data taking was $\bar{P} = 84\,\%$.

References

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FIGURES:

1. The influence of the field polarity shown by the ratios of enhanced polarization before and after a field reversal (∘) and for the ratios of the polarity dependent TE signal areas (+) for each NMR channel.
2. Relative polarization change as a function of the off-centering frequency $\Delta\omega$ for the coils # 2 (∘), # 3 ($\bigtriangledown$), and # 6 ($\bigtriangleup$) at 600 kHz sweep width.