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Polarization measurement in the COMPASS polarized target

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Abstract

Continuous wave nuclear magnetic resonance (NMR) is used to determine the target polarization in the COMPASS experiment. The system is made of the so-called Liverpool Q-meters, Yale-cards, and VME modules for data taking and system controlling. In 2001 the NMR coils were embedded in the target material, while in 2002 and 2003 the coils were mounted on the outer surface of the target cells to increase the packing factor of the material. Though the error of the measurement became larger with the outer coils than with the inner coils, we have performed stable measurements throughout the COMPASS run time for 3 years. The maximum polarization was +57% and −53% as the average in the target cells.

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Keywords: Polarized target; COMPASS; NA58; Polarization measurement; NMR

1. Introduction

The large polarized ^{6}LiD twin-target has been used for the investigation of the spin structure of the nucleon in deep inelastic muon–nucleon scattering at the COMPASS experiment at CERN during 2001–2003. A superconducting solenoid magnet produces a 2.5 T longitudinal field, and the nuclear spins are polarized parallel or antiparallel to this field. The target consists of two independently and oppositely polarized cells, each 60 cm long and 3.0 cm in diameter. The cells are filled

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with irradiated ^{6}LiD granulated material. ^{6}LiD was chosen as the target material because of its large fraction of polarizable nucleons and its high polarization [1]. The material preparation and the general target setup were reported in Ref. [2]. The present report will focus on the polarization measurement techniques and the results which are essential to the spin asymmetry measurement in the COMPASS experiment.

2. Continuous wave NMR system

The target polarization measurement system in the COMPASS experiment (Fig. 1) is based on a Liverpool Q-meter [3,4]. A series resonant circuit is made of a coil surrounding the target material, capacitors, and a dumping resistor. Ten parallel circuits allow simultaneous measurements with the coils placed on the cells. The dynamic nuclear susceptibility, $\chi(\omega) = \chi'(\omega) - j\chi''(\omega)$, changes the coil inductance

$$L(\omega) = L_0(1 + \eta\chi(\omega)). \quad (1)$$

Here η is the filling factor and L_0 is the inductance of the empty coil. $\chi''(\omega)$ is seen as the absorption spectrum in the NMR measurement, and the integral of this spectrum is proportional to the polarization [5].

A small modification was done to the conventional Q-meters (Fig. 2). Varactor diodes were added in each Q-meter box [7] for circuit tuning convenience. These varactor diodes are driven by DC voltage from 0 to 10 V and change the capacitance of the circuit from 20 to 550 pF .

Probe coils were designed to tune the circuit to the deuteron Larmor frequency resonance at 2.506 T, namely 16.379 MHz. The coils were made of Cu-Ni tube with wall thickness of 0.1 mm to reduce extra material in the target. Fig. 3 shows the coil designs. Type (a) coils were put inside the cells in 2001. To improve the packing factor of the material inside the target cells, type (b) coils were mounted on the outer surface of the target cells in 2002 and 2003. Small coils (c) or (d) were put inside the cells and used together with coil (b) in order to investigate the radial distribution of the polarization. The coils were oriented perpendicular to each other to reduce their mutual coupling.

The Yale-cards, following the Q-meter box, were used for DC compensation and amplification. The nominal gain can be switched to 1, 207, or 334. Thermal equilibrium (TE) signals around 1 K were measured with gain 207 while for the enhanced signals from polarized nuclei gain 1 was used. The gain factor for each coil was calibrated by comparing Q-curves measured at nominal gains 1 and 207.

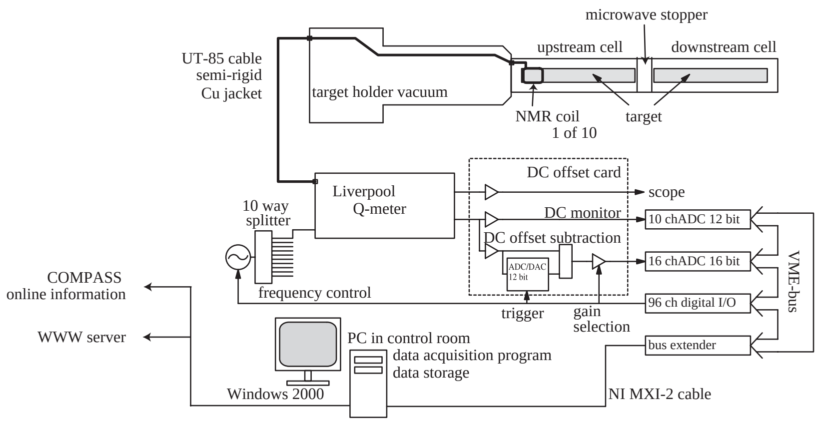

Fig. 1. The NMR data taking system used in the COMPASS experiment. The coils are connected to the Liverpool Q-meters with half-wavelength coaxial cables. The Yale-cards (DC offset card) compensate the DC voltage and amplify detected NMR signals. The digital part is made of VME-bus modules. These are the 16-bit analog-to-digital converters (ADC) for signal reading, 12-bit ADCs for DC voltage monitoring in the Yale-cards and digital-input-output (DIO) board for frequency synthesizer control. The bus extender is used to send the data to a computer.

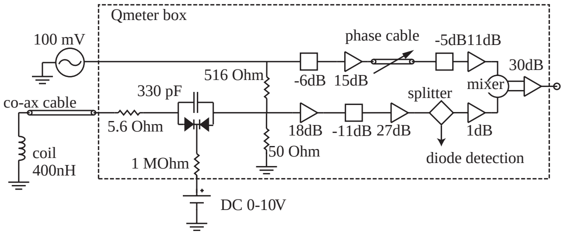

Fig. 2. The Q-meter circuit. The radio frequency voltage from the synthesizer drives the series tuned resonance circuit with a constant current. The varactor diodes enable easy tuning. $\chi''(\omega)$ is extracted by phase sensitive detection.

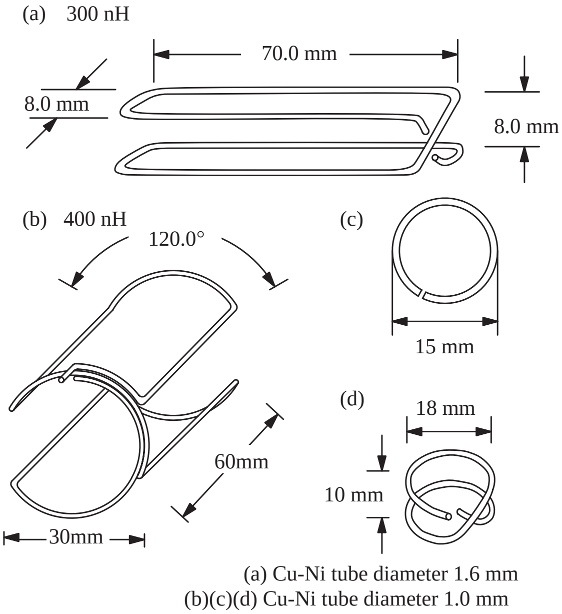

Fig. 3. The coil design (a) was used in 2001 (300 nH), (b) 2002 and 2003 (400 nH), (c) 2002, and (d) 2003.

A VME bus was used for controlling the system and acquiring signals. The data acquisition program was made with LabVIEW. One frequency sweep contains 1000 steps and the voltage is measured 32 times in fast sequence at each step. The sweeps alternate upward and downward in frequency. The sweep up plus sweep down takes 4.9 s with averaging of the measured voltage 64 times at one frequency step.

3. Thermal equilibrium (TE) calibration

At thermal equilibrium between the lattice and spins, the polarization is given by the Brillouin function [6]

$$P_{\mathrm{TE}}(x) = \frac{2J+1}{2J}\coth\frac{2J+1}{2J}x - \frac{1}{2J}\coth\frac{x}{2J}. \qquad (2)$$

Here $x = g\mu_{\mathrm{B}}JH/k_{\mathrm{B}}T_{\mathrm{S}}$, J is the spin, g is the Landé g-factor, μ_{B} is the Bohr magneton, H is the external field, k_{B} is the Boltzmann constant and T_{S} is the spin temperature equal to the lattice temperature T_{L}. Good thermal equilibrium between T_{S} and T_{L} is reached in about 10 h at the calibration temperatures.

Since the integral of the NMR signal is proportional to the nuclear polarization, the enhanced polarization by dynamic nuclear polarization (DNP) method P_{e} is obtained by its signal area A_{e}

$$P_{\mathrm{e}} = G_{207}\, C_{\mathrm{cor}}\frac{P_{\mathrm{TE}}}{A_{\mathrm{TE}}}A_{\mathrm{e}}. \qquad (3)$$

Here A_{TE} is the average signal area during the thermal equilibrium calibration at known temperature around 1 K with polarization P_{TE} (Eq. (2)). G_{207} is the calibrated Yale-card DC gain with nominal value of 207 and C_{cor} is a correction factor ~ 1 to account for the different TE calibration results for the two magnetic field directions.

The TE signal of the deuteron with about 0.05% polarization is small. The integration of one signal cannot be done very precisely due to noisy residual background after Q-curve subtraction. The residual background should not contribute to the integral. Fig. 4 shows a TE signal just after Q curve subtraction. The residual background is almost linear in the 100 kHz frequency width, however, accidental small distortion is still visible in Fig. 4. Different residual background fitting regions give different signal areas.

Typically 40 TE signals were obtained in about 8 h at one stable temperature, and one of the fitting regions sets was applied to these signals to enter the average area in the histogram shown in Fig. 5. This calculation was repeated 100 times

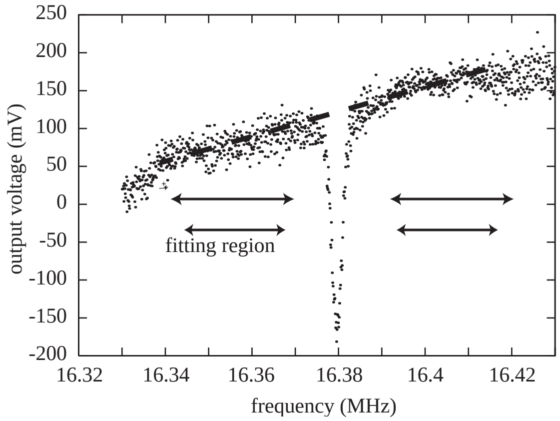

Fig. 4. The choice of fitting region for residual background subtraction in a TE signal from 4096 measurements averaged.

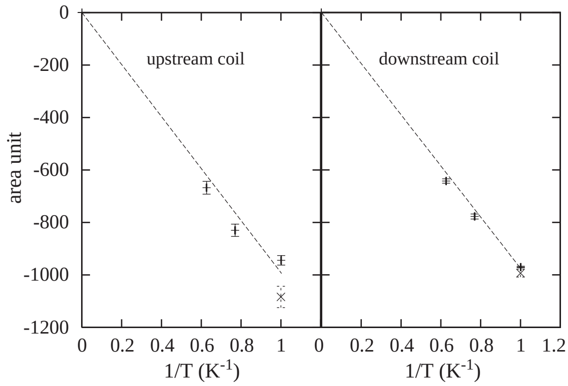

Fig. 6. A plot of inverse temperature versus area unit. The uncertainty in the temperature is typically 2–20 mK. For the area the error bar comes from the standard deviation of the normal distribution fit to the histogram, see Fig. 5.

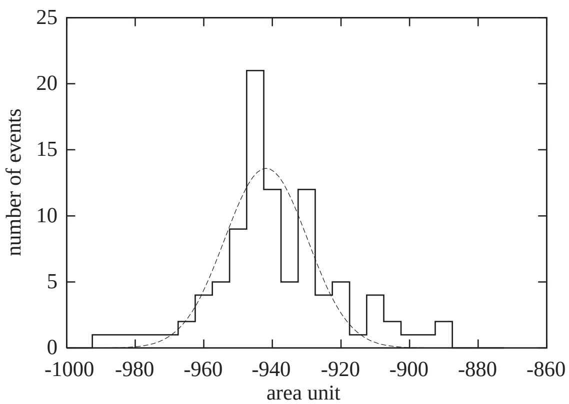

Fig. 5. A histogram of area units calculated from different fittings. Each area unit is the average of about 40 TE signals measured at one temperature.

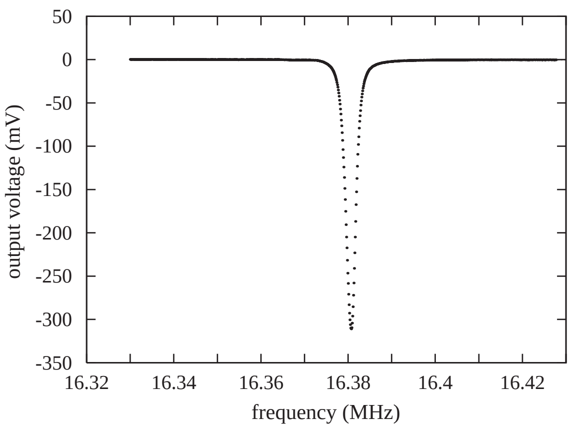

Fig. 7. The +46% polarized deuteron signal by averaging 320 measurements. No wiggles are observed. The DC level is about 3 V, and the modulation $\Delta V/V$ is about 0.1.

with 100 different fitting regions. Fig. 5 is an example of a histogram of these areas. The histogram was fitted with a normal distribution function to determine the most probable signal area at the measured temperature.

The TE signals were measured at two or three different temperatures: 0.97 and 1.44 K in 2001, 1.01 and 1.33 K in 2002, and 1.00, 1.30 and 1.60 K in 2003. The fit to the Curie law $\chi_0 \propto 1/T_L$ for 2003 is shown in Fig. 6. χ_0 is the static susceptibility, satisfying $\chi_0 \propto \int \chi''(\omega)\, d\omega$. The calibration constant, A_{TE} at 1.000 K, is obtained from this fit for each coil.

4. Deuteron polarization results by DNP

A typical DNP enhanced deuteron signal is shown in Fig. 7. The deuteron polarization for the run 2003 is shown in Fig. 8. The negative polarization has always lower absolute values than the positive polarization. The measured polarization varies from one coil to the other, see Tables 1 and 2. This distribution can be changed by fine tuning the field homogeneity only within 70 μT. ^{6}LiD material is very sensitive to the homogeneity of the magnetic field and to the tuning of the microwave frequency during the polarization.

These facts can cause the longitudinal spread in the polarization values along the target cells.

Table 3 summarizes the sources of uncertainty in the polarization measurement. The TE calibration error comes from the fit to the Curie law as shown in Fig. 6. It includes the temperature measurement error and the residual background fitting error for the TE signals. The circuit nonlinearity was estimated from the modulation depth $\Delta V/V \sim 0.1$. The error of the enhanced signal fitting comes from the residual background fitting. The error from field reversal is minimized by using the correction factor C_{cor} for the negative field direction, but a small residual error remains. The influence of a small shift in the magnetic field was tested to see how much it affected the polarization. The Q-curve off-centering reflects the influence due to the drift in the Q-meter and series tuned resonance circuit components. Low frequency gain variation comes from the error in the gain measurement (G_{207}) of the Yale-cards. Tuning difference between on and off status of the microwave is added as a systematic error.

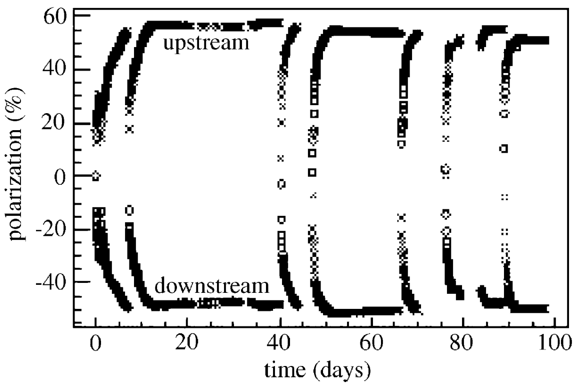

Fig. 8. Target polarization during run 2003. The polarization from the upstream (crosses) and downstream (circles) coils was averaged. The maximum polarizations were +57% and −51% for upstream cell and +54% and −49% for downstream cell. For 2002 the maximums polarization were +55% and −53% for upstream and +57% and −47% for downstream. In 2001 +54% for upstream and −47% for downstream was measured.

Table 1
Coils used in the different years

	Coil 1–4	Coil 5	Coil 6	Coil 7–10
2001	(a)	(a)	(a)	(a)
2002	(b)	N/A	(c)	(b)
2003	(b)	N/A	(d)	(b)

5. Measurement of the isotopic contents

The amount and the polarization of other polarized nuclei in the target material are also important for the spin asymmetry measurement in the COMPASS experiment. NMR measurement is also useful to determine the ratio of the numbers of the other nuclei. ^{6}LiD target material contains also ^{7}Li and protons. The percentage of them was calculated by comparing NMR signal areas of

Table 3
Error ($\Delta P/P$) estimated for the polarization measurement in 2003

	upstream (%)	downstream (%)
TE calibration error	3.38	1.84
Circuit nonlinearity	<0.5	<0.5
Enhanced signal fitting	0.1	0.1
Field polarity	0.2	0.2
Field shift	0.18	0.07
Q-curve off-centering	0.15	0.17
LF gain variation	0.087	0.037
Subtotal	3.43	1.83
Microwave effect	0.1	0.1
Total	3.5	1.9

Table 2
Typical polarization value for each coil (2003). There was no coil 5

coil	1	2	3	4	5	6	7	8	9	10
pol.(%)	55.7	58.5	50.6	58.4	N/A	−45.2	−47.6	−48.9	−49.4	−49.6

^{6}Li, ^{7}Li, deuteron and proton [6]. For example

$$\frac{N_p}{N_d} = \frac{P_d}{P_p}\frac{g_d^2}{g_p^2}\frac{I_d}{I_p}\frac{A_p}{A_d}. \quad (4)$$

N_p/N_d is the number ratio of the proton to deuteron nuclei. The g-factor for each nuclei gives $g_p = 2.7928$ and $g_d = 0.8574$, spin $I_d = 1$ and $I_p = \frac{1}{2}$, A_p, A_d are the integrals of NMR signal. P_d is calculated with TE calibration, but P_p is calculated from P_d assuming that they have equal spin temperature (EST). The validity of the EST was demonstrated in Ref. [2]. The percentage of ^{6}Li and ^{7}Li can be obtained in the same manner. As a result, there is an impurity of $4.21 \pm 0.08\%$ of ^{7}Li in ^{6}Li, and $0.5 \pm 0.1\%$ of protons in deuterons.

6. Summary

We have produced deuteron polarization as high as +57% and −53% in the large ^{6}LiD target of the COMPASS experiment during the last 3 years. The NMR measurement system has proved to work reliably during the about 100 day long runs. The measurement error is different between the upstream and the downstream cells. This is probably due to a ground loop formed on the upstream half by the microwave stopper, NMR cables, thermosensor cables and the ^{3}He filling tube. The change of tuning due to a field reversal is reproducible. By using different calibration constants for positive and negative field directions, the effect from field polarity can be overcome.

Acknowledgements

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