Polarized target for COMPASS experiment

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1 Introduction

COMPASS is one of the few experiments currently running at CERN.
The experiment investigates the structure of nucleons by scattering a beam of leptons off a target of nucleons. If the energy of the lepton beam is high, deep inelastic scattering takes place, and the lepton has enough energy to break apart the nucleons. Nucleons consist of quarks which are kept together by gluons due to strong interaction. The gluons can spontaneously break into quark-antiquark pairs producing the so called sea quarks. The internal structure of the nucleon spin can be studied using both polarized beam and target.
The COMPASS experiment uses a 100-190 GeV polarized muon beam with a polarized nucleon target of solid granulated ^{6}LiD.
Other experiments, (SMC, SLAC, HERMES), before COMPASS have provided evidence that the quarks carry only a small fraction (20-30%) of the nucleon spin, and this is the reason why further work at the COMPASS experiment (and the RHIC experiment in U.S.A. also) is now aiming to understand the spin structure of the nucleon. The missing part of the nucleon spin should be explained by the gluon spin or/and the angular momentum of partons.
One of the main goals of COMPASS is to measure the gluon polarization and its contribution to nucleon spin with a statistical accuracy of 10%. The data taking started in 2002.

2 Theory and physics

The angular momentum sum rule tells us that if we sum over the momenta of all the partons in a nucleon, we must reconstruct the total momentum of such nucleon. Therefore, the nucleon spin can be decomposed in terms of contributions from quarks and gluons as follows:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g \tag{1}$$

where $\Delta\Sigma$ is the spin of quarks, Δg is the spin of gluons, and L_q and L_g correspond to the orbital angular momentum of quarks and gluons respectively.
From theory and experiments we know that, at high Q^2, about half of the nucleon's longitudinal momentum is carried by the gluons.
The COMPASS experiment explores the gluon polarization in the nucleon by a direct method which studies the open charm leptoproduction (OCLP) via photon-gluon fusion process shown in figure 1.

Muons in the longitudinally polarized beam are scattered off nucleons in the polarized target to an outgoing muon and a hadronic final state X. A virtual photon emitted from the muon beam interacts with a gluon from a nucleon in the target. In this process, a charm-anticharm pair is produced in the centre of mass of the photon and gluon system.

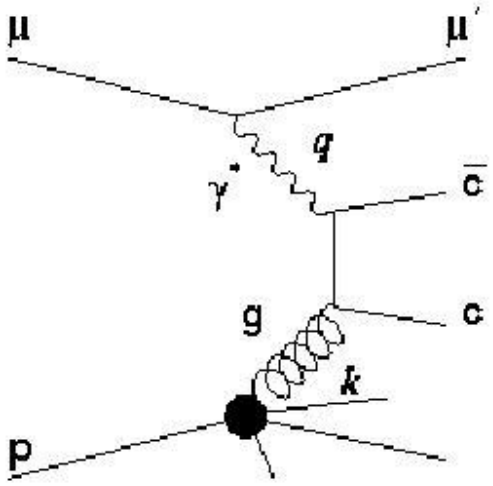

Figure 1: The process of open charm leptoproduction

The gluon contribution to nucleon spin is obtained from the double spin asymmetry A_1 of open charm leptoproduction:

$$A_1 = \frac{\sigma(\rightarrow\Leftarrow) - \sigma(\rightarrow\Rightarrow)}{\sigma(\rightarrow\Leftarrow) + \sigma(\rightarrow\Rightarrow)} \tag{2}$$

where $\sigma(\rightarrow\Leftarrow)$ and $\sigma(\rightarrow\Rightarrow)$ are the cross sections of open charm leptoproduction in the antiparallel and parallel spin configurations of the beam to the target respectively.
The experimentally measurable double spin asymmetry, A_2 is given by the expression:

$$A_2 = \frac{N(\rightarrow\Leftarrow) - N(\rightarrow\Rightarrow)}{N(\rightarrow\Leftarrow) + N(\rightarrow\Rightarrow)} \tag{3}$$

where $N(\rightarrow\Leftarrow)$ and $N(\rightarrow\Rightarrow)$ are the counting rates of OCLP in the antiparallel and parallel spin configurations as before.
A_2 is related to A_1 by the following expression:

$$A_2 = A_1 P_B P_T f \tag{4}$$

where P_B is the beam polarization, P_T is the target polarization, and f is the dilution factor, ie. the fraction of polarizable nucleons in the molecule of ^{6}LiD.
The evaluation of the counting rates of OCLP is based on the invariant mass reconstruction of the short-living hadrons from their decay particles.
Therefore, the gluon contribution to nucleon spin can be obtained from comparison between the cross section of OCLP when the muon spin and the target spin are parallel, and that of the configuration in which the muon spin and the target spin are anti-parallel.

3 COMPASS experimental set-up

3.1 COMPASS spectrometer and muon beam

The spectrometer has several kinds of detectors for tracking, identification and energy measurement of the outcoming particles from the scattering events.
The kinematics of muons, before and after the scattering must be determined, and the rest of the outgoing hadrons must be detected for better statistics and systematics.
The energy of the incoming muon is measured by BMS, located at the end of the beam line.
Scattered muons are mainly detected by scintillating fibers installed inside or near the beam region.
Large magnets SM1 and SM2 are used to produce the magnetic bending of particle tracks. Numerous detectors, including calorimeters, are used to measure the momentum of the resulting particles and to determine their trajectory.

The muon beam has a fixed helicity state with about 10^7muons/s in time average.
The polarization of the muon beam is naturally obtained, based on the parity violation in the weak decay of the charged pions or kaons. The sign and degree of the muon polarization can be chosen by selecting the corresponding muon energy.
The beam size is about σ_x , $\sigma_y = 8$mm, and it decides the diameter of the target cells, which should be minimized in order to avoid multiple scattering of the produced particles for the detection of short living hadrons.

3.2 COMPASS polarized target apparatus

The target has a dilution refrigerator providing low temperature and high cooling power at 50-300mK, a superconducting solenoid producing a magnetic field of 2.5T, two 70GHz microwave systems for dynamic nuclear polarization (DNP), and the nuclear magnetic resonance (NMR) signal detection system for the polarization monitoring. The side view of this apparatus is shown in figure 3.

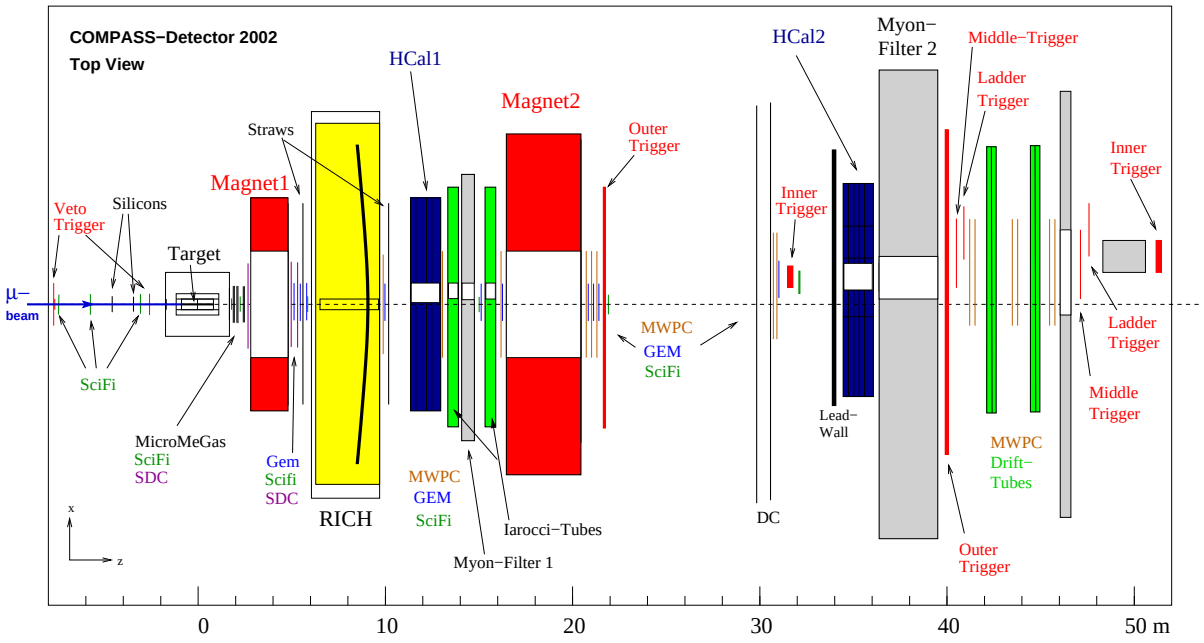

Figure 2: COMPASS general experimental set-up.

The target material is placed in two large 60cm long and 3.0cm diameter cells, one having opposite polarization to the other one.

The microwave cavity is separated into two halves and fed by the two microwave systems that produce simultaneous dynamic nuclear polarization in the two target cells. The two cells are polarized longitudinally with respect to the traveling direction of the muon beam in opposite signs to each other. Polarization build-up is achieved with frequency modulation of the microwaves. The magnetic field produced by the superconducting solenoid can be rotated to allow spin reversal of the two target cells, in order to measure the double spin asymmetry. This field rotation is done every 8-12 hours and can be performed in about 30 minutes.

Four NMR coils are placed around each of the target cells to allow the measurement of the nuclear polarization inside the target. One small NMR coil (coil 6) is placed inside the downstream cell to study the difference between the measurements inside and outside the target cell. Deuteron NMR signals are recorded in 1-30 minutes intervals during the data taking. All the NMR coils are read out simultaneously and can be used to check the spatial uniformity of the polarization.

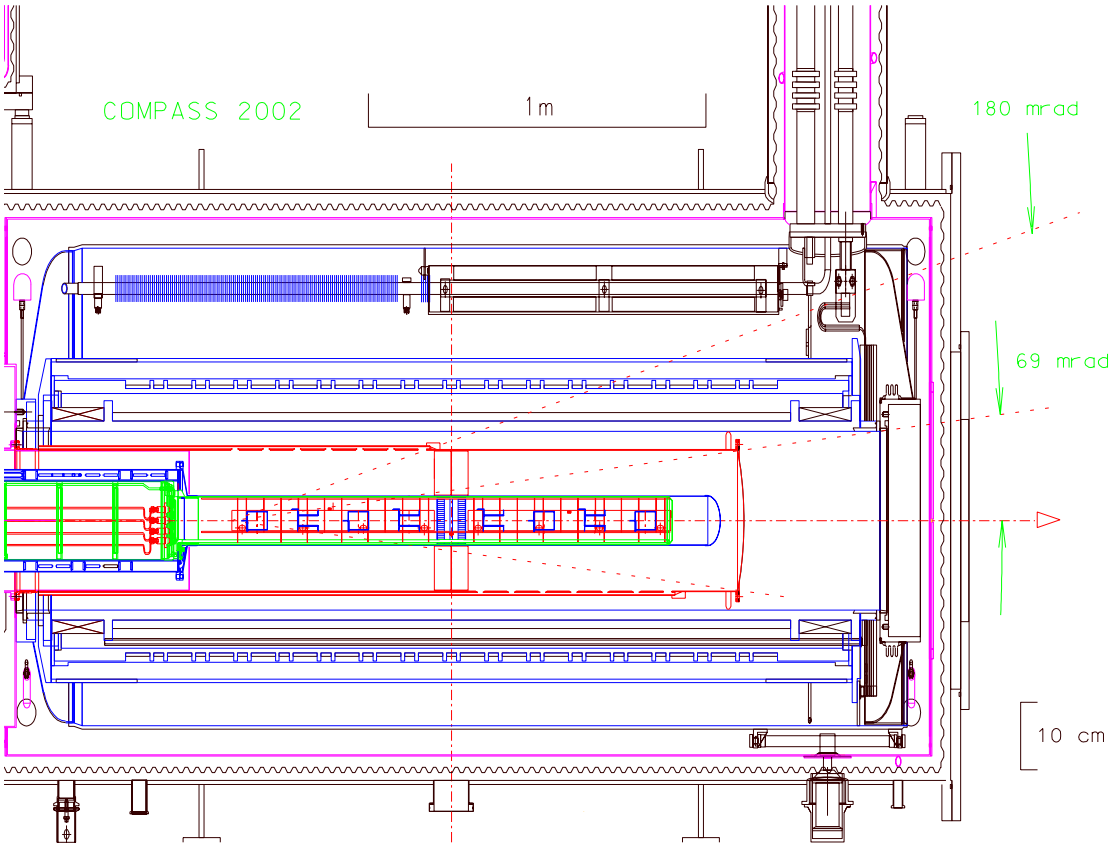

Figure 3: Side view of the COMPASS polarized target apparatus. The muon beam traverses from left to right.

4 COMPASS polarized target

4.1 Dynamic nuclear polarization (DNP)

At thermal equilibrium (TE) the nuclear polarization is too small, (about 0.05 % at 1.0K and 2.5T), so it needs to be largely enhanced for particle physics experiments. High nuclear polarization in the target is obtained via dynamic nuclear polarization (DNP) process, in which microwaves are used to artificially enhance the polarization above the TE polarization.

The material of the target, ^{6}LiD, is a crystal with face-centered cubic structure that can be seen in figure 4. By irradiating granules of the crystal with an electron beam at low temperature, paramagnetic F-centers are produced (about $10^{-3} - 10^{-4}$ F centers per nucleus). An F-center consists of a vacancy in the anion sub-lattice of the crystal, in which a free electron is captured. Unpaired electrons coming from F-centers play a key role in the DNP process.

In the experimental conditions, at a magnetic field of 2.5T and a temperature of 1K, the unpaired electrons have a polarization of about 96%, while that of the nuclei is below

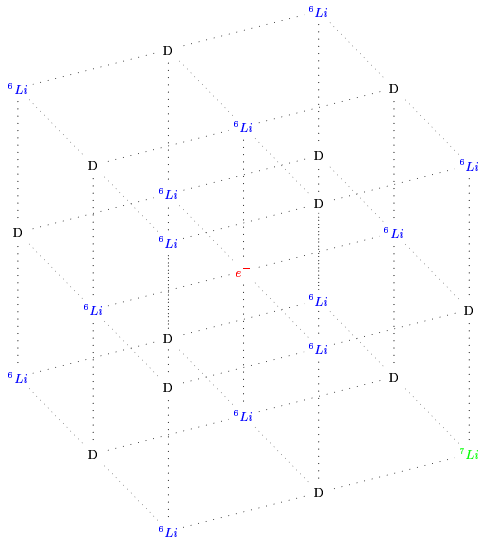

Figure 4: Target material ^{6}LiD crystal structure. The lattice constant is 4 $\dot{A}$.

1%. DNP transfers the high electron polarization to nuclear spins.
An external source of microwave energy is used to induce simultaneous reversals of both electronic and nuclear spins. If this reversals are forced and the strength of the source is such that the rate at which they occur is much greater than the nuclear relaxation rate, then nuclear polarization can be built up. The electron spin will relax back to its thermal equilibrium state before the nuclear spin can have the time to do so. Polarization build up during time can be seen in figure 5.

4.2 The choice of the target material

The small cross section of OCLP and the limited beam intensity make it necessary to use a large target, but, at the same time, the detection of short living hadrons demands a small diameter of the target cell.
Since a free nucleon polarized target does not exist, compound nuclei must be used for scattering of different particles on nucleons. The binding energies of these nuclei need to be as small as possible. Some of the smallest binding energies in nature are those of the deuterium and the ^{6}Li nucleus.
^{6}LiD material is chosen for its large fraction of polarizable nucleons and for the high effective nuclear polarization that the molecule can reach (50% for both ^{6}Li and D at 2.5T magnetic field). This means that the beam time needed to achieve a certain statistical accuracy in the asymmetry measurement is reduced as the accuracy is proportional to the square of the spin polarization.
Therefore, the ^{6}LiD target high polarization and the simple shape of the NMR deuteron spectrum allow an easy and accurate measurement of the polarization value.

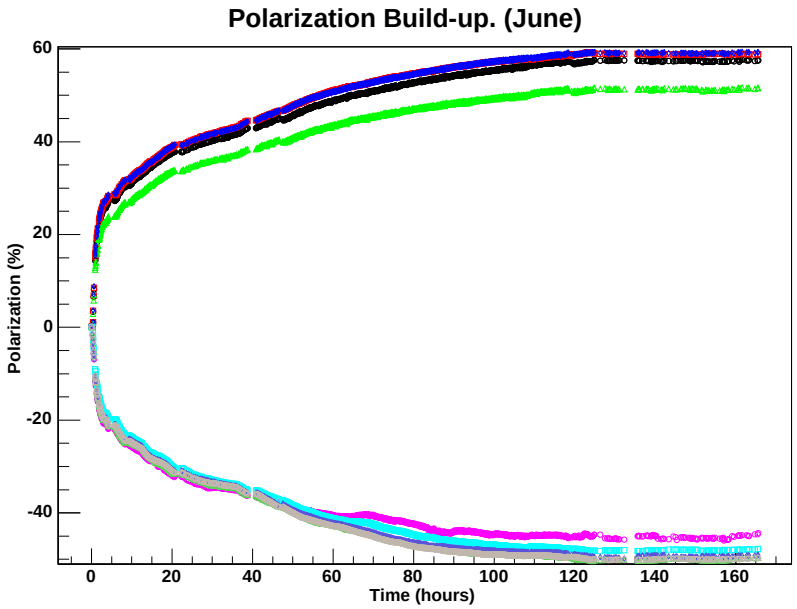

Figure 5: Polarization build-up in time. June 2003.

5 NMR Measurements

The target polarization is measured by nuclear magnetic resonance (NMR). The determination of the polarization of the target must be done precisely because it affects the evaluation of the gluon contribution to nucleon spin.

The resonant peak for deuteron at 2.5T magnetic field takes place at a frequency of 16.35MHz. In the COMPASS experiment the NMR signals are recorded with a frequency window of 100KHz.

The target polarization at thermal equilibrium is proportional to the area S of the NMR signal:

$$P = C \cdot S \tag{5}$$

where the factor C can be calibrated by detecting the NMR signal at thermal equilibrium (TE) and measuring its area S_{TE}, given that the polarization P_{TE} at thermal equilibrium can be analitically calculated from the Brillouin function at a known temperature. Hence:

$$C = \frac{P_{TE}}{S_{TE}} \tag{6}$$

The polarization P_{dyn} after dynamic nuclear polarization can be determined by the area method using:

$$P_{dyn} = \frac{P_{TE}}{S_{TE}} \cdot S_{dyn} \tag{7}$$

by detecting the NMR signal and calculating its area S_{dyn}.

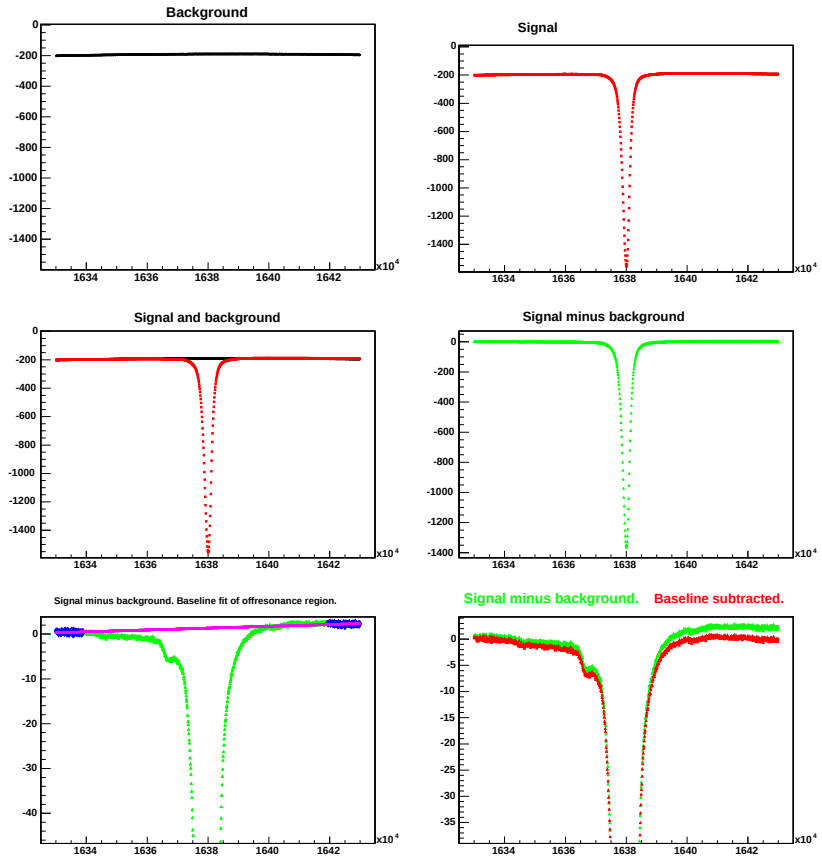

Figure 6: Analysis of NMR signals. From top to bottom and left to right: background; signal; signal and background together; signal after background has been subtracted; baseline fit of off-resonance region; comparison between signal, and signal after baseline has been subtracted.

If the magnetic field is shifted from the nominal value, the NMR signal does not appear on the curve, and we get only the background. When the nominal magnetic field is set, the NMR signal appears on the curve. By subtracting the background signal from the raw NMR data one can obtain the NMR signal. There is a small residual baseline left, however. The residual baseline can be subtracted from the signal by fitting a straight line to off-resonance region. This curve can be integrated to obtain the area of the TE signal, S_{TE}, at a known temperature. Measurements for TE calibration are made at three different temperatures, 1.00K, 1.30K and 1.60K.The different stages of the analysis of NMR signals are shown in figure 6.