Polarization measurement in the COMPASS polarized target:

NMR detection coils' magnetic field Summer Student Report August 27, 2004

Drosoula Giantsoudi National Technical University of Athens

1 Introduction

COMPASS is a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN. The present purpose of this experiment is to study the spin structure of the nucleon with the prime goals to determine the contribution of the gluon polarization to the nucleon spin and to perform a first measurement of the transversity structure function.

The experiment was constructed in 1998-2000 and commissioned in 2001. The first physics run took place in 2002. After the 2004 run the experiment will continue after the CERN accelerator shutdown. The COMPASS collaboration comprises about 200 physicists from 26 institutes and 12 countries.

2 The COMPASS spectrometer

2.1 Spectrometer concept

The COMPASS detector is conceived as a two-stage spectrometer (Fig. 2.1). The largeangle spectrometer (LAS) just downstream of the target covers an aperture of ± 180 mrad while the small-angle spectrometer (SAS) subsequently detects particles within the inner ± 30 mrad. Both sections comprise magnets SM1 and SM2 providing field integrals of 1 and 4.4 Tm, respectively. Tracking in the beam region is provided by scintillating fiber (SciFi) and silicon detectors and in the intermediate region up to 20 cm from the beam by MicroMeGas and Gem detectors. Large area outer tracking is covered by drift chambers (SDC, W45), multi-wire proportional chambers (MWPC), and straw tubes. Iarroccitype tubes (MW1) and drift tubes (MW2) track the muons downstream of the hadron absorbers.

The trigger system is based on the scattered muon. Information from 8 trigger scintillator hodoscopes located in the SAS and from both hadron calorimeters from within 600 ns a trigger signal on the basis of target pointing and energy transfer.



Figure 2.1: The COMPASS spectrometer in 2002

2.2 The Polarized target

COMPASS uses solid polarized proton and deuteron targets in the muon program. The target material is ⁶LiD (see Fig.2.3). The nuclear spins are polarized with dynamic nuclear polarization (DNP), based on microwave saturation of impurity electron spins near their paramagnetic resonance in a 2.5 T longitudinal field. The two target cells have the length of 60 cm and a diameter of 3 cm and they are polarized in opposite directions. The ³He/⁴He dilution refrigerator reaches temperatures of 50 mK in frozen spin mode.



Figure 2.2: The polarized target



Figure 2.3: Target material: LiD or LiH

3 Dynamic Nuclear Polarization

3.1 The basic principle of DNP

The (vector) polarization P of a spin system with spin I and magnetic moment μ under the conditions of thermal equilibrium is given by the Brillouin Function \mathscr{B}_I

$$P = \frac{\langle I \rangle}{I} = \frac{N(I) - N(-I)}{\sum_{m=-I}^{m=+I} N(m)} = \mathscr{B}_I \left(\frac{\mu B}{2k\mathscr{T}}\right)$$
(3.1)

wherein B and \mathscr{T} are the external magnetic field and the temperature. From the last equation (3.1) it is clear that, in order to obtain a sizable polarization of the spin system, the ratio of the magnetic energy μB and the thermal energy $k\mathscr{T}$ has to be as large as possible. In the case of a nuclear spin system a magnetic field of some Tesla and a temperature in the order of 1 K produces a polarization only a fraction of a percent, unlike an electron spin system for which these conditions are sufficient for an almost complete alignment of the spins. This is because the magnetic moment of a nucleus is three orders of magnitude lower than that of an electron.

In these cases, in order to avoid to push the field and temperature values to its technical limits, the technique of dynamic nuclear polarization is used, in which at moderate magnetic fields and temperatures the high electron polarization is transferred to the nuclei via a microwave induced excitation of coupled electron-nucleus Zeeman transitions. For that a certain amount ($\sim 10^{-3}$ per nucleus) of unpaired electrons have to be implated into the otherwise diamagnetic solids, either via chemical doping or by an exposure of the substance to ionizing radiation.

3.2 The mechanisms of DNP

Unpaired electrons in a solid state host material experience several different interactions with different strength from one material to the other. These effects are:

1. Anisotropy of the g-factor due to a non-vanishing angular momentum of the unpaired electron.

- rying nuclei.
- 3. Dipole-dipole interaction among the unpaired electrons.

In general all three interactions appear at the same time and they lead to a broadening of the Zeeman transition energy, when the electron system is exposed to an external magnetic field. Accordingly the ESR line appears as a complicated superposition of the individual effects.

There are several models which try to describe the DNP properties of the material Which one is the more correct in each case is given by the relation between the width σ of the ESR line and the size of the nuclear Larmor frequency ω_I . Only when $\sigma \ll \omega_I$ it is possible to excite the forbidden transitions $|\downarrow\downarrow\rangle \rangle \rightarrow |\uparrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle \rightarrow |\downarrow\uparrow\rangle$ in the four level scheme of the solid effect separately. In this case the microwave frequencies leading to the highest nuclear polarization values are given by the electron Larmor frequency plus or minus the nuclear Larmor frequency.

If this condition is not fulfilled, both transitions take place simultaneously and the final nuclear polarization is not only lower but the corresponding 'optimum' microwave frequencies are located more outside of the electron Larmor frequency. A natural extension of the solid effect model to the case, in which the NMR line width and the nuclear Larmor frequency are of similar size, is given by the 'differential solid effect'. In this model it is assumed that the unpaired electrons can be grouped to 'spin packets' each experiencing a different strength of the inhomogeneous interactions.

This model neglects the effect of the homogeneous coupling – the dipole-dipole interaction – among the electrons themselves, which, though it is only a minor effect concerning the ESR line shape, it changes drastically the mechanism of dynamic nuclear polarization. Due to the presence of the dipole-dipole interaction members of different spin packets can perform mutual spin flips, while the energy difference is compensated by a change of the dipolar energy. Under the influence of the dipole-dipole interaction the electron system responds as a whole to both the microwave radiation and the phonon bath of the lattice. In this case only the spin temperature theory corresponds to the mechanism of dynamic nuclear polarization.

4 Polarization measurement in the COMPASS polarized target

Continuous wave nuclear magnetic resonance 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 (see Fig.4.1). In 2001 the NMR coils (see Fig.4.2) 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.



Figure 4.1: 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.

4.1 Nuclear Magnetic Resonance

Nuclear Magnetic Resonance (NMR) exploits the interaction of nuclei with magnetic fields. A strong static field is applied to polarize the nuclear magnetic moments, time-dependent magnetic rf fields are used to stimulate the spectroscopic response. In NMR spectroscopy, the polarizing magnetic field is required to be highly homogeneous. In most cases, the inhomogeneous part of the field is linearly dependent on space, so that the field gradient is constant.

The strength of homogeneous static magnetic field B_0 is of the order of 0.5-21 T. It defines the NMR frequency $\omega_0 = 2\pi\nu_0$

$$\omega_0 = -\gamma B_0 \tag{4.2}$$

where γ is the gyromagnetic ratio, and B_0 is the magnitude of the strong magnetic field B_0 . For excitation of the spectroscopic response, a weak, time-dependent magnetic field B_{rf} perpendicular to the static field is required. When the weak field $B_{rf}(t)$ oscillates with the nuclear resonance frequency, energy can be transferred from the oscillating field to the nuclei and vice versa. Typical NMR frequencies are in the rf regime between 10 and 900MHz. The strength of the excitation field is of the order of 1mT and less.

In the COMPASS experiment the strength of B_0 is ≈ 2.5 T, so the NMR frequency is ≈ 16 MHz for deuterium. The weak field is generated by saddle coils placed around the target, as described in the following paragraph.



Figure 4.2: The coil design (a) was used in 2001 (300 nH), (b) 2002 and 2003 (400 nH), (c) 2002, and (d) 2003.

4.2 Continuous wave NMR system

In the COMPASS experiment a series resonant circuit is made of a coil (see fig 4.2) 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 $L(\omega) = L_0(1 + \eta\chi(\omega))$. 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.

Probe coils were designed to tune the circuit to the deuteron Larmor frequency resonance at 2.506 T, namely 16.379 MHz. The coils are made of Cu-Ni tube with wall thickness of 0.1 mm to reduce extra material in the target.

My task in this project was to calculate the magnetic field produced by one of these coils in order to estimate the filling factor of the material. In first place, an attempt to do the calculation analytically was made. This was quite easy for the points being on the axis of symmetry (z-axis), based on simple principles of geometry and on the fundamental equation for magnetic field calculations

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{\vec{I} \times \hat{r}}{r^2} dl, \qquad (4.3)$$

wherein \vec{B} is the magnetic field, because of the current \vec{I} of the coil, μ_0 is the permeability of vacuum and \hat{r} is the unitary vector of distance and r is its modulus. This way, and

magnetic field due to the linear parts of the coil:

$$\vec{B}_{//}(x=0,y=0,z) = \frac{\sqrt{3}}{2} \frac{\mu_0 I}{\pi R} \left(\frac{0.06-z}{\sqrt{(0.06-z)^2 + R^2}} + \frac{z}{\sqrt{z^2 + R^2}} \right) \hat{j}$$
(4.4)

Here the z-axis is the symmetry axis of the coil, and R is the radius of the coil (R = 0.015m). The plot of this component of the magnetic field is shown in figure 4.3. Due to



Figure 4.3: The y-component of the magnetic field as a function of z-coordinate, due to the linear parts of the coil.

the curved parts, the field was calculated as following:

$$\vec{B}_{\cap}(x=0,y=0,z) = \frac{\sqrt{3}}{2} \frac{\mu_0 IR}{\pi} \left(\frac{0.06-z}{[(0.06-z)^2 + R^2]^{3/2}} + \frac{z}{[z^2 + R^2]^{3/2}} \right) \hat{j}$$
(4.5)

So, in total, the magnetic field on the axis of symmetry is given by the formula:

$$\vec{B}(x=0,y=0,z) = \frac{\sqrt{3}}{2} \frac{\mu_0 I}{\pi} \Big[\frac{1}{R} \left(\frac{0.06-z}{\sqrt{(0.06-z)^2 + R^2}} + \frac{z}{\sqrt{z^2 + R^2}} \right) + R \left(\frac{0.06-z}{[(0.06-z)^2 + R^2]^{3/2}} + \frac{z}{[z^2 + R^2]^{3/2}} \right) \Big] \hat{j}$$
(4.6)

As one can notice, because of the geometry of the coil, the magnetic field on the axis of symmetry is totally transverse.

Problems occurred when an attempt was made to calculate the magnetic field in points not belonging to z-axis or outside the coil, where the symmetry does not simplifies the

the help of ROOT and C++.

A quite simple code, with the main principles of the method we should use to calculate the magnetic field in the plane x = 0, was provided by my supervisor and my task was to check it and to develop it so that it would calculate the magnetic field in the planes y = 0 and z = 0, and the magnetic flux in planes x = 0 and y = 0, too. The final code (plotsaddlefield6.C) is presented in the last pages of the report and, as a result of it, the following plots occurred (see Fig.4.4). The real value of the magnetic field is given by multiplying the program's results by a constant:



$$C = \frac{\mu_0 I}{4\pi} \approx 10^{-7} I \tag{4.7}$$

Figure 4.4: Transverse magnetic field and flux in different planes of the coil

The functions used in this program have occurred by the fundamental formula 4.3 as following. Taking the current as having a constant modulus Eq.4.3 can be transformed into:

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{\vec{dl} \times \hat{r}}{r^2}$$
(4.8)

change in the current direction. r is the distance between a random space point and the space point on the coil that produces the magnetic field. So if we represent as $\vec{r_1} = (x_1, y_1, z_1)$ the coordinates of the space point where we want to calculate the magnetic field and as $\vec{r} = (x, y, z)$ the coordinates of the space point on the coil that produces the magnetic field, the last equation 4.8 becomes as:

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \vec{df}$$
(4.9)

wherein:

$$\hat{\boldsymbol{r}} = \frac{\vec{\boldsymbol{r}}}{r^3} \qquad \vec{\boldsymbol{r}} = \vec{r} - \vec{r_0}$$
(4.10)

and

or

$$\vec{df} = \frac{\vec{dl} \times \hat{r}}{r^3} \tag{4.11}$$

$$\vec{df} = \frac{[(z-z_0)dy_0 - (y-y_0)dz_0]\hat{i} + [(x-x_0)dz_0 - (z-z_0)dx]\hat{j} + [(y-y_0)dx_0 - (x-x_0)dy_0]\hat{k}}{[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2]^{3/2}}$$
(4.12)

Here the integration is during the parts of the coil (4 linear parts and 4 curved) and the space coordinates of the coil parts are used as variables of integration. So, according to the coil's structure not all the coordinates change during each part of it. So for the linear parts the function to integrate will be:

$$\vec{df} = \frac{\left[-(y-y_0)dz_0\right]\hat{i} - \left[(x-x_0)dz_0\right]\hat{j}}{\left[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2\right]^{3/2}}$$
(4.13)

While for each one of the curved parts the function to be integrated will be:

$$\vec{df} = \frac{\left[-(z-z_0)dy_0\right]\hat{i} + \left[-(z-z_0)dx_0\right]\hat{j} + \left[(y-y_0)dx_0\right]\hat{k}}{\left[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2\right]^{3/2}}$$
(4.14)

Especially for the calculation of the curved parts, because of cylindrical symmetry of the coil, we can replace dx_0 and dy_0 by their equals in cylindrical coordinates, $-Rd\phi sin\phi$ and $Rd\phi cos\phi$, where the angle ϕ increases anticlockwise. We must notice here, that we had to take under serious consideration the direction of integrating during these parts in respect to the current direction inside them. Also, we should mention that we are interested only in the transverse components of the magnetic field, neglecting the \hat{k} component which is parallel to the main axis of the coil.

According to these last remarks the final form of the function for the curved parts is:

$$\vec{df} = \frac{\left[-(z-z_0)Rd\phi\cos\phi\right]\hat{i} + \left[(z-z_0)Rd\phi\sin\phi\right]\hat{j} + \left[-(y-y_0)Rd\phi\sin\phi\right]\hat{k}}{\left[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2\right]^{3/2}}$$
(4.15)

Actually, 4.13 and 4.15 are the functions that we used and integrated by the code and this is the reason why the results should be multiplied by the constant 4.7 to get the quantitatively correct ones.

has a very small value and that's why it is not easy to detect the polarization of the material outside of it. Another remark is that, though the magnetic field should have negative value in some space points, according to the theory, we see that the plot contains only positive values and this is because we plot the absolute value of the strength of the transverse magnetic field only.

As one may see in the plots, the field goes to 0 outside of the coil. If we take as useful magnetic field the one that is from z-coordinate equal from -0.08 m to 0.08 m, where the magnetic field is bigger than zero (see Fig. 4.5), then we can conclude that we can measure only a volume of $\pi R^2 \times 0.16m^3$, where R is the radius of the coil R = 0.015m. So the volume that we measure is about: $1.131 \times 10^{-4}m$



Figure 4.5: Transverse magnetic field and flux in different planes of the coil

Other than the plots, the code also gives as a result the magnetic flux in the planes y = 0and x = 0 which are correspondingly fluxy= 0.641751Vs and fluxx= 0.36275Vs. Their sum give a result which is what we expected divided by 3. This may happen because we didn't take under account the flux in the field z = 0 or maybe the method that we used **Another task** An NMR signal simulation program was provided by my supervisor and I had to run it several times, changing the parameters so that the final result could be as similar as possible to the experimental one. The program (fccmomslineshapeDA.C) calculates the second moment for deuterium with all possible neighbors (D, ⁶Li, ⁷Li and proton). The value of the second moment depends on the orientation of the crystal with respect to external 2.5 T field. The crystal orientation is chosen randomly by setting the Euler angles. The second moment and given center frequency are then used to add one more NMR-signal to the simulated TE-signal. For the TE-signals the amplitude is kept constant, i.e. we assume that the polarization is same everywhere. The field inhomogeneity of the 2.5 T field, about 10-100 ppm is simulated by adding a small random fluctuation to the center frequency of the NMR-signal. For the polarized crystals the center frequency f_0 and the second moment M2 are exactly the same as for the crystals in TE-calibration. Their polarization (around 50%) has small uncertainity however.

After adding all the signals from the 1000 polarized crystals we get a simulated polarized signal seen by the NMR-coil (see Fig. 4.6). The polarization is then calculated by dividing the area of the simulated polarized signal by that of the simulated TE-signal. The results are written into a file 'simulpols'. The resulting histogram can be plotted by a second program (histlineshape2.C). By trying different uncertainties in the center frequency and in the polarization I tried to produce similar results that we see in our experiment.

The following histograms have occurred by executing with different parameters (uncertainties in the center frequency and in the polarization.

While changing the parameters of the execution, the shape of NMR simulated signal was the same. By plotting each histogram for different parameters we had the result shown in fig 4.7-4.11.



Figure 4.6: Simulated polarized signal seen by the NMR-coil



Figure 4.7: Monte Carlo simulating histogram: uncertainty in center frequency=500Hz, uncertainty in polarization 5%.



Figure 4.8: Monte Carlo simulating histogram: uncertainty in center frequency=500Hz, uncertainty in polarization 7%.



Figure 4.9: Monte Carlo simulating histogram: uncertainty in center frequency=1000Hz, uncertainty in polarization 4%.



Figure 4.10: Monte Carlo simulating histogram: uncertainty in center frequency=1000Hz, uncertainty in polarization 7%.



Figure 4.11: Monte Carlo simulating histogram: uncertainty in center frequency=1000Hz, uncertainty in polarization 4.5%.

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