The SLAC E-154 ^{3}He Polarimeter

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Abstract. We describe the NMR and Rb Zeeman frequency shift polarimeters used for determining the ^{3}He polarization in a recent precision measurement of the neutron spin structure function g_1 at SLAC (E-154). We performed a detailed study of the systematic errors associated with the calibration of the NMR polarimeter. A new technique was used for determining the ^{3}He polarization from the frequency shift of the Rb Zeeman resonance.

I INTRODUCTION

The ^{3}He polarimetry system for E-154 was designed to meet the challenges of a precision measurement with a small statistical error. The goal was to measure the ^{3}He polarization with a relative error of less than 5% and a good control over systematic errors. The polarization was measured by two independent methods. The first method used a traditional technique of Adiabatic Fast Passage NMR. The NMR signal was calibrated by detecting the Boltzmann polarization from a sample of water. The second method, used for calibration of the ^{3}He AFP signal, utilized the shift of the Rb Zeeman resonance frequency due to the Rb-^{3}He spin exchange. In each case we investigated several effects which can lead to systematic errors. The two method of polarimetry have comparable errors and are in good agreement with each other.

II NMR POLARIMETRY

Adiabatic Fast Passage (AFP) NMR was used to measure the ^{3}He polarization at regular intervals throughout the run [1,2]. The polarized target

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was placed inside AFP coils, which created an RF field H_1 orthogonal to the holding magnetic field H. The holding field H was swept linearly in time, $H = H_0 + \alpha t$, through the ^{3}He NMR resonance at $H_0 = 28$ G. The sweep rate was optimized to satisfy the AFP conditions. ^{3}He polarization losses per sweep were on the order of 0.1%. The NMR signal, induced in a set of pick-up coils orthogonal to the AFP coils, was measured by a lock-in amplifier as the field was being swept. Under ideal conditions the AFP signal is given by:

$$V(t) = \frac{GH_1\mu_{He}\,[^3\mathrm{He}]\,P_{He}}{\sqrt{(\alpha t)^2 + H_1^2}} \qquad (1)$$

where μ_{He}, $[^3\mathrm{He}]$ and P_{He} are the magnetic moment, density, and the polarization of ^{3}He, and G is the gain of the detection system, which depends, among other things, on the dimensions of the ^{3}He cell and the pick-up coils. The broadening of the signal due to the field inhomogeneity and the lock-in time constant were negligible, and the data were well fit by Eq. (1), with residuals of less than 0.5%.

The NMR system was calibrated by detecting a signal from the Boltzmann polarization of protons in water. This calibration procedure is complicated by several factors. The Boltzmann polarization of protons in our conditions is $P_p = \mu_p H / k_B T = 7.5 \times 10^{-9}$, and their NMR signal is very small. For each set of calibration data we averaged 50 sweeps to reduce the random error to 1%. The shape of the proton AFP signal is different from Eq. (1) because the relaxation time in water is only about 2 sec., and the polarization of protons changes as the magnetic field is being swept. The relaxation process is parametrized by a longitudinal relaxation time T_1 and a transverse relaxation time T_2 [1]. Relaxation during the sweep affects both the height and the shape of the AFP signal. In the past [2] this has been the dominant source of the systematic error. It also makes the signal dependent on the speed and direction of the magnetic field sweep. To properly fit the water signals it is important to know the functional form of the signal.

Naively, one would expect that $T_2 = T_1$ in water, since the correlation time associated with the translation and rotation of the molecules is much shorter than the Larmor period [1]. However, measurements [3,4,7] show that $1/T_2 = 1/T_1 + 0.125\,\mathrm{sec}^{-1}$ for neutral (i.e. pH=7.0) water. The reason for this turns out to be the presence of 0.037% of ^{17}O isotope in natural water [4]. ^{17}O has a nuclear spin of 5/2 and an effective scalar coupling to proton spins. It also has a relatively long correlation time of 10^{-3}sec, so that motional narrowing does not apply. The transverse relaxation time is also affected by the presence of the RF field H_1 [4]. For our conditions $1/T_2\,(H_1) = 1/T_1 + 0.033$ sec^{-1} and the height of the water signal is reduced by 0.4% compared to the case of $T_2 = T_1$. The longitudinal relaxation time T_1 is very sensitive to the temperature and the chemical impurities in water, such as dissolved oxygen [5,6]. We measured $T_1 = 2.4 \pm 0.3$ sec by comparing the size of the water signals obtained while the field was swept up and down through the resonance.

To fit the water signals it is convenient to have an analytic expression for their shape. If we set[1] $T_1 = T_2$ the polarization remains parallel to the effective field in the rotating frame, $\vec{H}_{eff} = (H - H_0)\,\hat{z} + H_1\hat{x}$, and its magnitude is governed by a single differential equation:

$$\begin{aligned} \frac{dP_{eff}}{dt} &= \frac{1}{T_1}\left(P_{eq}(t) - P_{eff}\right) \\ P_{eq}(t) &= \frac{\mu_p}{kT}\left(\frac{H(H-H_0)+H_1^2}{\sqrt{H_1^2+(H-H_0)^2}}\right) \end{aligned} \qquad (2)$$

It cannot be solved analytically. However, if $H_1/\alpha \ll T_1$ one can expand the resulting integral in powers of t/T_1 near the resonance and powers of $\alpha t/H_1$ away from the resonance, and get an analytic, though cumbersome, function for the signal. This function was used in our analysis. Figure 1 shows an averaged water signal with a fit based on equation (2). A simple fit to equation (1) is also shown for comparison. In each case we vary 5 parameters: the height, width, and center of the peak, as well as a linear background. By using a functional form that closely approximates the shape of the signal, we are reducing the sensitivity of the final result to small distortions caused by background fluctuations, etc. The residuals of the fit are consistent with random noise. The signal heights extracted from the sweeps up and down through the resonance are consistent within errors. In contrast, if one uses a simple fit in the form (1), the two heights are different by 20%. Our final result for the water signal height has a 1% statistical uncertainty, and a conservative 1.5% systematic error.

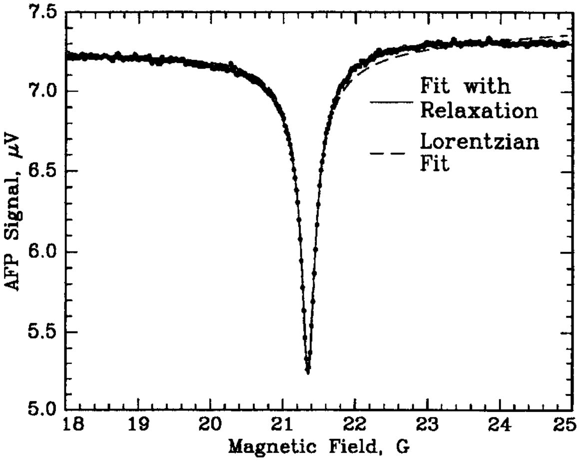

Figure 1: Average of 50 water signals. Solid line fit is based on Eq. (2), broken line fit on Eq. (1)

In using the signal from proton NMR for calibration of the ^{3}He signal, one also has to apply corrections due to slightly different dimensions of the ^{3}He and water cells, which are as large as 20%. To calculate these corrections we used a

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[1] The correction due to $T_2 < T_1$ is applied separately.

complete geometrical model of the pick-up coils and ^{3}He cells. The model also allowed us to predict the absolute size of the water signal with an accuracy of 5%, which was in excellent agreement with the data. The final error of our AFP polarimetry is 3.4%, which comes in roughly equal proportions from uncertainties in the height of the water signal, ^{3}He density, dimensions and position of the cell, temperature of the water cell, and several other sources.

III ZEEMAN FREQUENCY SHIFT POLARIMETRY

The second method of polarimetry uses a ^{3}He polarization-induced shift of the Rb Zeeman resonance (also called Electron Paramagnetic Resonance). The resonance frequency is mainly shifted due to the Rb-^{3}He spin exchange interaction, the same interaction which is responsible for transferring the angular momentum to ^{3}He in spin exchange optical pumping. There is also a small additional shift due to the classical magnetic field created by ^{3}He, which depends on the geometry of the polarized sample. The total shift can be attributed to an additional magnetic field which is given for a spherical sample by the following equation [8–10]:

$$B_{He} = (8\pi/3)\,\kappa_0 \mu_{He}\left[{}^3\mathrm{He}\right] P \tag{3}$$

This field causes a shift in the frequency of the Zeeman resonance by $\Delta\nu = (d\nu(F,M)/dB)\,B_{He}$, where $d\nu(F,M)/dB$ is the derivative of the frequency of the Rb Zeeman transition $(F, M \rightarrow F, M-1)$ with respect to the magnetic field, given by the well-known Breit-Rabi equation [11]. Here F and M are the quantum numbers of the Rb hyperfine manifold. The size of the shift is large (in our case about 20 kHz), and can be easily detected in a typical field of 20 G, where the Rb Zeeman frequency is 9.3 MHz. The constant κ_0, parameterizing the imaginary part of the Rb-^{3}He spin exchange cross-section, has been measured with an accuracy of 1.5% in [9,10]. Its value in the temperature range 100-180°C can be parameterized as follows: $\kappa_0 = 4.52 + 0.00934\,T$ $({}^\circ C)$.

For this experiment we implemented a new method of measuring the frequency shift, which is ideally suited for monitoring the ^{3}He polarization during optical pumping. The system allowed measurements of the polarization without access to the target and proved robust under accelerator conditions. The EPR frequency was detected optically, by monitoring the fluorescence while optically pumping the cell. By applying an RF field at the frequency of the $F = 3$, $M = 3 \rightarrow 2$ transition we partially depolarized the Rb atoms. This, in turn, caused an increase in the intensity of the fluorescence emitted from the cell, which was detected by a photodiode.

The equipment setup for EPR measurements is shown in Figure 2. The RF field was created by a coil mounted on the side of the oven. The fluorescence

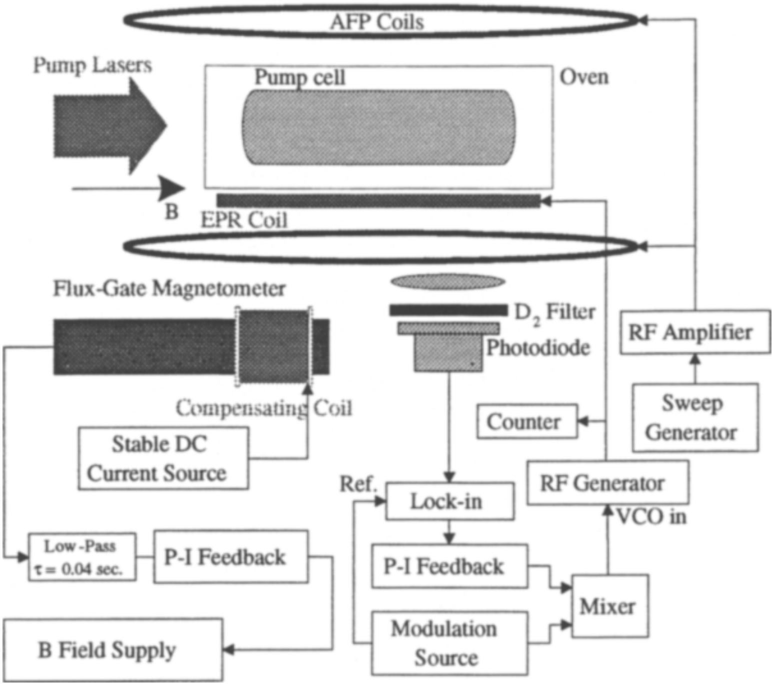

Figure 2: Equipment setup for the frequency shift polarimetry.

from the cell was detected by a photodiode with a D_2 filter to block the scatter from the pumping lasers. The frequency of the RF field was modulated using a Voltage Controlled Oscillator (VCO). The signal measured by the lock-in amplifier referenced to the modulation frequency was proportional to the derivative of the resonance line shape. The feedback circuit adjusted the DC level at the input of the VCO to keep the lock-in signal zero, i.e. locked to the center of the line. To reduce the noise in the frequency measurement the holding magnetic field was stabilized to one part in 10^5 by a feedback system based on a Bartington flux-gate magnetometer.

To isolate the frequency shift due to the ^{3}He polarization we periodically reversed the direction of the polarization. The reversal was done by AFP, only instead of sweeping the magnetic field through the resonance we swept the RF frequency. We utilized the same coils, RF amplifier and generator as used for NMR polarimetry. The measurement cycle consisted of recording the EPR frequency for about 1 min., flipping ^{3}He spins by AFP and recording the frequency for another minute. This procedure was repeated several times. A typical data set is shown in Figure 3. The data are fit allowing a small amount of polarization loss per cycle, which is due to the AFP losses and the decay of the polarization during one half of the cycle, when the lasers are pumping in the direction opposite to the ^{3}He polarization. The quality of the data is very good and the size of the frequency shift can be extracted with a error of less than 0.5%.

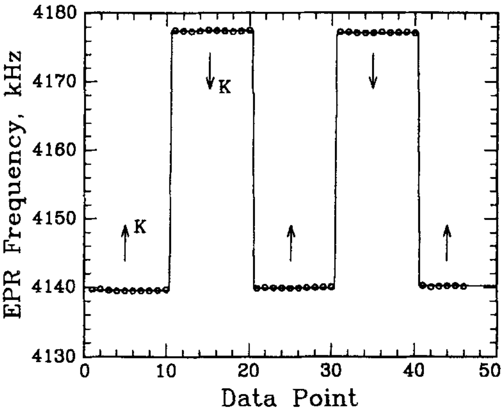

Figure 3: Typical set of EPR data.

Two corrections have to be applied to the frequency shift data. The target pumping cell, where the measurements were performed, was not spherical, so a small additional shift due to the classical magnetic field should be added to equation (3). It resulted in a 4.6% correction and a 1.3% error. The error is due to our limited knowledge of the region in the pumping cell which was sampled by the photo-diode. Also, the frequency shift measures the polarization of ^{3}He in the pumping chamber of the cell. There is a small polarization gradient between the pumping and target cells due to a finite diffusion time. It results in a 3.8% correction and a 1.5% error. The correction was calculated by using a model of diffusion between the target and the pumping cells. The model was checked by measuring the polarization build-up in the target cell in the first hour of a spin-up. The error is due to the uncertainty in the target spin relaxation rates. The total error of the frequency shift polarimetry method is 3%, coming from the uncertainty in the value of κ_0, the density of ^{3}He, and the two corrections described above.

IV POLARIMETRY RESULTS

Since the density of the ^{3}He is the only common parameter for both polarimetry techniques, it was also measured in two independent ways. We calculated the density with an accuracy of 1% using pressure measurements during the filling of the cells. In addition, the density was determined by measuring the width and shift of the Rb absorption lines D_1 and D_2, which are pressure-broadened by ^{3}He. Using the data from [12] as a calibration, the density of ^{3}He in the cells was determined with a error of 1%. The two methods are in excellent agreement.

The polarization of ^{3}He was measured by two independent methods, using Adiabatic Fast Passage and the Rb Zeeman frequency shift. The uncertainties are 3.4% for the AFP method and 3.0% for the frequency shift method. The results of the two methods differ by 5.7%. Since the errors in each case come from many independent sources, in comparing the two methods we combine their errors in quadrature, which gives a total error of 4.6%. Thus, their difference is 1.2 times larger than their combined error, and the two methods are in good agreement. For the final result we averaged the two results and used a conservative 4.8% error.

In conclusion, we described the two methods of ^{3}He polarimetry used in E-154. For the AFP method we considered in detail the effect of thermal relaxation of protons in water. We also described a novel implementation of the Zeeman frequency shift polarimetry suitable for a nuclear physics experiments. Because this technique was used for the first time, several refinements are still possible. The uncertainty due to the classical magnetic field shift can be reduced by restricting the region of the cell sampled by the photo-diode. The error due to the polarization gradient between the target and pumping cells can be reduced by making dedicated measurements designed to study the effect. Because the technique relies on a frequency shift, which can be measured with high accuracy, we believe that with these refinements the error can be reduced below our value of 3%.

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