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Large enhancement of deuteron polarization with frequency modulated microwaves

Spin Muon Collaboration (SMC)

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Abstract

We report a large enhancement of 1.7 in deuteron polarization up to values of 0.6 due to frequency modulation of the polarizing microwaves in a two liter polarized target using the method of dynamic nuclear polarization. This target was used during a deep inelastic polarized muon–deuteron scattering experiment at CERN. Measurements of the electron paramagnetic resonance absorption spectra show that frequency modulation gives rise to additional microwave absorption in the spectral wings. Although these results are not understood theoretically, they may provide a useful testing ground for the deeper understanding of dynamic nuclear polarization.

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Measurements of deep inelastic scattering of polarized muons from polarized protons and deuterons determine the spin dependent structure functions of the nucleon which allow fundamental tests of quantum chromodynamics and of models of nucleon structure [1]. The precision of these experiments is strongly related to the polarization of the target nucleons. Therefore, the large enhancement of our deuteron target polarization which we discovered during the data-taking for deep inelastic muon scattering [2] had a significant impact on our experiment at CERN. The discovery was associated with a faulty regulator of the high voltage power supply of a microwave source. After
The large enhancement of deuteron polarization in our target due to FM came therefore as a surprise. Fig. 1 shows the typical time evolution of the deuteron polarization \(P_\text{D}\) without and with FM. For this figure the cathode voltages were modulated at 1 kHz with a \(=50\,\text{V}\) peak-to-peak amplitude leading to a FM amplitude \(\Delta f = 20\,\text{MHz}\) for the 69 GHz microwave source. The maximum deuteron vector polarizations under these conditions were 0.43 and 0.49.

The EPR spectrum was measured in our target at a constant frequency by scanning the magnetic field. Such a spectrum, shown in Fig. 2 without FM, was obtained using a 220 Ω Speer composite carbon resistor as a bolometer, located in the dilute phase of the mixing chamber outside the target material [15]. The input power to the microwave cavity \(Q_{\text{in}}\) is the sum of \(Q_{\text{MAX}}\), the power absorbed by the material in the EPR process, and \(Q_{\text{NR}}\), the non-resonant power absorbed into the cavity. The power absorbed by the bolometer \(Q_{\text{SP}}\) is a constant fraction \(r\) of \(Q_{\text{NR}}\). It can be expressed as \(Q_{\text{SP}} = c(T_{\text{SP}} - T_{\text{HE}})\) where \(T_{\text{SP}}\) is the temperature of the bolometer, \(T_{\text{HE}}\) is the temperature of the dilute phase and \(c\) is a constant [16]. During the EPR measurement the input power \(Q_{\text{in}}\) remains constant and we can neglect the variations of \(T_{\text{HE}}\). Consequently the relation \(Q_{\text{IN}} = Q_{\text{MAX}} + Q_{\text{NR}} = Q_{\text{MAT}} + (c/r)(T_{\text{SP}} - T_{\text{HE}})^4\) shows that \(Q_{\text{MAT}}\) is a linear function of \(T_{\text{SP}}^4\). The broad absorption band seen in Fig. 2 is due to the anisotropy of the \(g\)-factor of the EDBA-Cr(V) electron spin. The highest positive and negative polarizations without FM were obtained at frequencies \(f_0 = 69.090\,\text{GHz}\) and \(f_0 = 69.520\,\text{GHz}\), respectively.

The EPR spectra with better resolution at the edges of the absorption band are shown in Figs. 3a and 3b, both with and without FM. The data points with FM were...
obtained using a modulation amplitude $\Delta f = 4$ MHz to keep a good resolution in our spectra. In order to measure the small change in EPR absorption due to FM a novel technique of making consecutive measurements of the bolometer resistance with and without FM at each field step was employed. In Figs. 3c and 3d we display the difference $\Delta T_{SP} = (T_{SP})^2 - (T_{SP})^2 = (Q_{MAT} - Q_{MAT}^2)/\gamma$. These data demonstrate that FM increases $Q_{MAT}$ in the edges of the EPR spectrum. Note that the structures in Figs. 3a and 3b which extend down to 69.00 GHz and up to 69.60 GHz are almost entirely eliminated in the presence of FM even though the amplitude of FM is small compared to their width.

In Fig. 4 we show the difference $\Delta T_{SP}$ as a function of the frequency of FM for different input power levels $Q_{IN}$ with an FM amplitude $\Delta f = 30$ MHz at 69.090 GHz where $\Delta T_{SP}$ reaches a maximum. This difference grows with the modulation frequency up to a maximum value (indicated by the arrows) and then remains constant. The frequencies at which the additional EPR absorption reaches its maximum value increase roughly linearly with $Q_{IN}$. A study of the polarization growth rate was performed at high negative $P_{IM}$ values for a setting of $Q_{IN}$ close to the one which was used for curve 2 of Fig. 4. The rate increased with modulation frequency and reached a maximum value of $-0.8\%$ per hour when modulating at 10 Hz. At this $Q_{IN}$ value, $\Delta T_{SP}$ reaches a maximum at this frequency which suggests strongly that the additional EPR absorption due to FM is what leads to the enhanced DNP.

In further measurements, we have established that the highest positive and negative polarizations with FM were obtained using $\Delta f = 30$ MHz at $f_{MW} = 69.090$ GHz and $f_{MW} = 69.540$ GHz, respectively. The gain in maximum polarization due to FM is 1.7 and the increase in polarization speed is about 2. The homogeneity of the deuteron polarization throughout the target volume was investigated.
Two radially superimposed coils measuring polarization at radii of 1.5 and 0.5 cm showed a deuteron polarization ratio from the small to the large coil of 1.20 before and 1.06 after applying FM [3]. A study of the deuteron NMR line asymmetry [3] provided us with an upper limit ΔPd, for the spatial variation of Pd. Typical values for ΔPd were 0.30 without FM and 0.15 with FM which confirmed that FM improves the uniformity of polarization.

The large enhancement has been confirmed recently in our new 2.51 target [17] where maximum deuteron polarizations of 0.46 and −0.60 were observed using FM. In spite of the improved magnetic field uniformity of 3 × 10⁻⁶ of the new target, the optimum Δff f for FM was about 0.5 × 10⁻⁴ as in the previous target with 10⁻³ field uniformity. Also we find that Δff f is large compared to the target magnetic field inhomogeneity in both targets. We conclude that the mechanism by which FM improves polarization has little to do with the field nonuniformity. For protons FM increased the polarization, typically from 0.75 to 0.85, and to maximum values as high as 0.95 [18].

The existing theory [19–21] provides a qualitative understanding of the DNP for our target material; however, the large polarization enhancement due to microwave FM may require additional mechanisms. An example is the cross-relaxation within the system of electron spins which has been assumed to be fast. It has been suggested [22] that a slow cross-relaxation may lead to a lack of thermal equilibrium among electron spins and hence to unequal spin temperatures for different nuclei which results in lower nuclear polarization. FM may counteract this effect by increasing the number of electron spins which are saturated.

A possibly related effect is the local depletion of the electron spin packets which has been observed for materials whose EPR lines are broadened by hyperfine interactions when irradiated at fixed frequency. With FM, this local depletion can be avoided and a migration of spin packets occurs towards the wings of the EPR band [23]. This may result in a stronger EPR absorption in the wings.

Since the aim of our experiment was to measure spin-dependent asymmetries in polarized deep inelastic scattering, we did not attempt a more detailed study of the effect of FM on the target polarization. Our observations of the EPR absorption were used as a guide to optimize the parameters of the FM.

In conclusion, we discovered a large increase in deuteron polarization due to frequency modulation which is of great value for our high energy physics experiment. We found that an amplitude of FM of ≃30 MHz and a frequency of 1 kHz improved the deuteron polarization growth rate by a factor of 2 and resulted in deuteron polarizations as high as 0.60 with improved spatial uniformity over the target volume. Relations of this large FM effect to features of the EPR absorption mechanism were found and may provide useful information to a deeper understanding of dynamic nuclear polarization.

References