POLARIZATION BUILD UP IN COMPASS ^{6}LiD TARGET

J. KOIVUNIEMI, N. DOSHITA, S. GOERTZ, K. KONDO, I. L. GARCIA, W. MEYER, G. REICHERZ

Physics Department, University of Bochum, Bochum, Germany

F. GAUTHERON

Physics Department, University of Bielefeld, Bielefeld, Germany

The CERN COMPASS experiment uses a large double 424 cm^3 cell polarized ^{6}LiD target for the muon program. High nuclear spin polarization $|P| > 50$ % is obtained, typically in five days. The high cooling power of the COMPASS dilution refrigerator helps to build up the polarization fast at temperatures around 300 mK. At lower microwave power with lower spin and lattice temperatures, the polarization build up is slower. We discuss these features of the dynamic nuclear polarization of our ^{6}LiD target.

The COMPASS polarized target and the nuclear magnetic resonance technique to determine the nuclear polarization have been described in recent papers [1–4]. In the ^{6}LiD target material [5], the ^{6}Li is diluted with 4.2 % of ^{7}Li. About 10^{-4} – 10^{-3} paramagnetic centers per nucleus have been created by irradiation in an electron beam [6]. The theory of dynamic nuclear polarization has been discussed in the literature [7, 8] and in recent review papers [9, 10]. High deuteron polarization $|P| > 40$ % in a 2.5 T field is reached in 24 hours with a ^{3}He flow in the dilution cryostat of 80 - 120 mmol/s. The maximum polarization $|P| > 50$ % is reached in five days. For each cell the power of the 70 GHz microwave pumping of the electron spins is reduced from 200 mW in the beginning to 25 mW during the polarization process. At the same time the optimum microwave frequency shifts 40 MHz up (down) for positive (negative) polarization [2]. The dynamic nuclear polarization can also be seen as a nuclear cooling process [11, 12], in which heat is removed from the spin system to the lattice.

The deuteron and ^{6}Li in the target material have nuclear spin quantum number 1. In a homogeneous magnetic field, three energy levels E_+, E_0 and E_- are possible for them if the interaction between the spins is neglected. Each energy level has a population p_+, p_0 and p_- with $p_+ + p_0 + p_- = 100$ %. In the absence of quadrupole splitting, only one narrow nuclear magnetic resonance line, 3 kHz wide, is seen [13], and $E_+ - E_0 = E_0 - E_- = hf_0$. Here f_0 is the nuclear magnetic resonance frequency of the spin system. The intensity of the absorption signal integrated over the frequency is proportional to the population difference [8]

$$I = \frac{1}{f_0}\int_{f_0-\Delta}^{f_0+\Delta} \chi''(f)df = -a\cdot(p_- - p_+) = -a\cdot P, \tag{1}$$

where P is the vector polarization, $\chi''(f)$ the dynamic susceptibility, and $\Delta = 50$ kHz is much larger than the NMR-line width. The constant a is positive and is determined during a thermal equilibrium calibration [3], when the spin temperature is the same as the measured lattice temperature T_L. For positive polarization the signal intensity I is negative since $p_- > p_+$. The nuclear polarization is given by the Brillouin function [11,12]

$$P_J(x) = \frac{2J+1}{2J}coth(\frac{2J+1}{2J}x) - \frac{1}{2J}coth(\frac{1}{2J}x), \tag{2}$$

where the spin number $J = 1$ for deuteron and ^{6}Li, and $J = 3/2$ for ^{7}Li. Here $x = hf_0/k_BT_S$ with k_B the Boltzmann constant and T_S the spin temperature. The thermal equilibrium calibration of the polarization [3] is done around 1 K temperature at the nominal NMR field of 2.506 T, corresponding to the resonance frequency f_0 of 16.379 MHz. The spin-lattice relaxation time is typically 3 hours and a good thermal equilibrium between the spin system and the lattice is reached in about 15 hours. The deuteron polarization from Eq. 2 at $T_S = T_L \sim 1$ K is about +0.05 %.

Typical polarization build up is shown in Fig. 1. The target material is heated up to 0.1 K - 0.3 K by the microwaves [2]. Even if the spin system could be cooled to 0.1 K, the resulting nuclear polarization would still be very low. The electron spin system cools down due to microwave pumping, and heat from the bulk nuclear spin system is transfered to the paramagnetic centers by a nuclear spin diffusion process [9,14]. After the dynamic nuclear polarization the thermal energy of the nuclear spin system has been reduced to $T_S \sim \pm 0.9$ mK. We have carefully checked that during the polarization all the nuclei share the same spin temperature [1]. Thus the calculation of the polarizations of ^{6}Li and ^{7}Li can be done from Eq. 2, using the measured deuteron polarization and the resonance frequencies for ^{6}Li and ^{7}Li in the 2.506 T field. The nuclear heat capacity in a constant field for independent spins is [11,12]

$$C_S/R = (x/2)^2 sinh^{-2}(x/2) - ((2J+1)x/2)^2 sinh^{-2}((2J+1)x/2) \tag{3}$$

with R the universal gas constant. The heat capacity depends on the polarization through Eq. 2. At the maximum polarization values obtained it is 3.1 J/mol·K for D and ^{6}Li and 4.3 J/mol·K for ^{7}Li. The nuclear cooling power can be estimated from the rate of polarization build up $\dot{Q}_S = n\cdot C_S(T_S)\cdot dT_S/dt$. In the beginning it is 100 μW for one target cell and drops fast below 1 μW when polarization $|P| > 20\%$ is reached. This is small compared to the 25 - 200 mW from the microwaves, since the energy needed for electron spin flip is about $5\cdot 10^3$ higher than for nuclear spin flip. The electron spin normally has a very short relaxation time to the lattice phonon system [8]. The lattice heat conductivity is [15]

$$\kappa = 1/3\cdot C_V\cdot v_s\cdot l = 4/5\cdot\pi^4\cdot R\cdot n_V\cdot v_s\cdot l\cdot(T_L/\theta_D)^3, \tag{4}$$

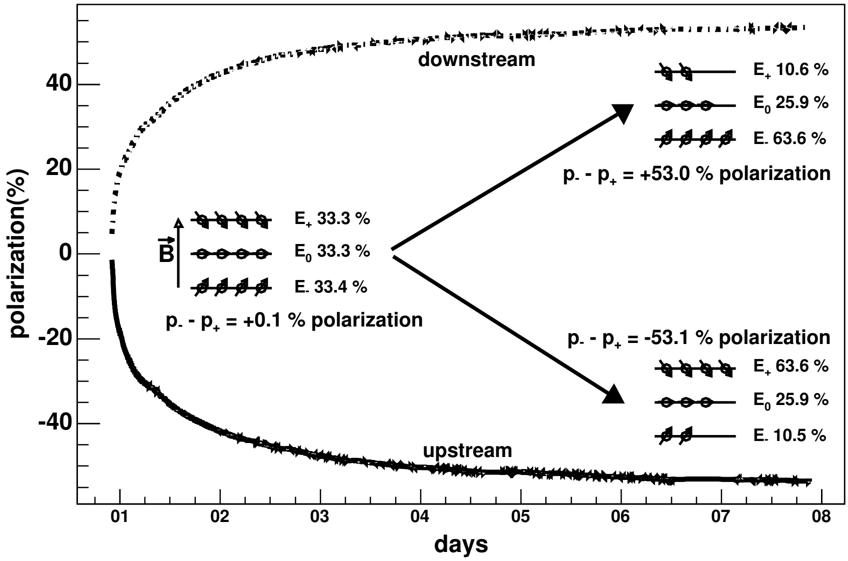

Fig 1. Typical deuteron polarization build up from 2004. Both upstream and downstream target cells are polarized simultaneously. About ±40 % polarization is reached in 24 hours after starting the microwave pumping of electron spins. The build up then slows and the final polarization is reached in about five days from the start. The initial and final level populations for spin 1 deuteron are shown in the figure. The vector polarization $P = p_- - p_+$ is given by the population difference between the lowest and the highest energy levels. Since the gyromagnetic ratio of the deuteron is positive, the minimum energy E_- is achieved when the spin is aligned along the magnetic field. The tensor polarization can be estimated to be $T = 1/2(1 - 3p_0) = 11$ % at the maximum. The highest polarizations correspond to a spin temperature T_S of 0.87 mK or -0.87 mK for negative polarization. From Eq. 2 the polarization of ^{6}Li can be estimated to be ±51.3 % and the polarization of ^{7}Li ±92.4 %.

where C_V is the heat capacity per volume, $\theta_D \sim 1000$ K the Debye temperature [16], v_s sound velocity, n_V the molar density, and l the phonon mean free path. Since the dominant phonon wave length [11] $\theta_D/T_L \cdot 2$ Å ~ 2 μm is much larger than the size of crystal defects, the phonon scattering takes place only at boundaries. Thus l is the crystal size $\sim$ 2 - 4 mm. The probability for a phonon to cross the boundary between ^{6}LiD and helium [11] gives the relaxation time $\sim 70 \cdot l/v_s \sim 10 - 100$ μs. The phonon thermalization at boundaries is fast compared to the single electron spin flip rate $\sim (hf_0N_e)/\dot{Q}_S \sim$ 30 - 300 s, with $\dot{Q}_S \sim$ 0.1 nW/crystal. At the same time the electron spin flips give heat $\dot{Q}_e \sim 400$ nW/crystal. The lattice heat capacity is negligible compared to that of the helium. Thus the high helium temperature limits the achievable maximum polarization [7, 9], and a high ^{3}He flow rate helps to build up polarization faster due to more efficient removal of heat from the paramagnetic centers.

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