FEATURES OF DYNAMIC NUCLEAR POLARIZATION IN IRRADIATED LiD TARGET MATERIAL

Y. KISSELEV, N. DOSHITA, ST. GOERTZ, K. KONDO,
W. MEYER, G. REICHERZ
Physics Department, University of Bochum, 44780 Bochum, Germany.
E-mail: yuri.kisselev@cern.ch

G. BAUM, F. GAUTHERON,
Physics Department, University of Bielefeld, 33501 Bielefeld, Germany.

J. BALL, A. MAGNON
CEA Saclay, DAPNIA, 91191 Gif-sur-Yvette, France

Relaxation times with measured dependency on the nuclear polarization and spectral resolved spin radiation were observed for LiD in the large COMPASS twin target at CERN. The record deuteron polarizations (-53% and +57%) reached in the target may be restricted not only by the material properties but also by the target environment.

Nuclear polarization of irradiated LiD is obtained by the Dynamic Nuclear Polarization (DNP) method. As follows from theory[1], the maximum nuclear polarization depends mainly on the EPR-line structure of F-centers and the different relaxation mechanisms contacting the electron and nuclear spin species with the relatively "warm" lattice.

The actual target is located in a complex environment. Polarized spins have inductive couplings with the NMR coils, microwave (MW) cavity walls, cables and sense wires. These couplings enable radiation or damping losses; usually there are MW dielectric losses and heat transport difficulties during the DNP process. As a consequence, the maximum polarization can also depend on the design of the target environment.

The COMPASS twin-target operates at 2.5 T field in $0.065 \div 0.25$ K temperature region. Its material incorporates an atomic fraction of 0.953 for ^{6}LiD, 0.044 for ^{7}LiD and 0.003 for ^{6}LiH in the total weight of 175 grammes per cell. Due to the high polarizations reached and the large molar spin numbers $n_D \approx n(^6Li) \approx 21, n(^7Li) \approx 0.95, n(H) \approx 0.065, n(e) \approx 0.007$, the nuclear subsystems possess a large heat capacity given by:

$$C(\mu_{I,S}) = n_{I,S} \cdot R \cdot x^2 \frac{dB_{I,S}(x)}{dx} \ , \tag{1}$$

where R is the gas constant, B_I is the Brillioun function, $x = \mu_{I,S}B/(kT_s)$, $\mu_{I,S}$ is the magnetic moment of I, S-spins, B=2.5 T field, k is Boltzmann constant and T_s is the spin temperature. At 50% deuteron polarization ($T_s \approx 0.9$ mK) Eq. 1 yields of the order of 60 J/K for D(I=*1*), 60 for ^{6}Li(I=*1*), 5 for ^{7}Li(I=*3/2*), 1 for ^{1}H(I=*1/2*) and only about 0.02 for S-spins. We could observe an energy release using Speer 220 bolometers and NMR

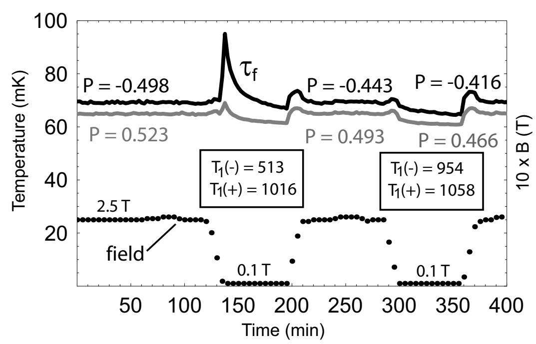

Figure 1. Bolometer detection of the fast energy release of spin energy with $\tau_f \approx 18$ min during the first exposure with clear indication of very different relaxation times of $T_1(-) \ll T_1(+)$ for the opposite deuteron polarizations; a fast energy release is absent in the second exposure and here $T_1(-) \approx T_1(+)$.

polarization measurements. Fig. 1 shows the measured dynamics of the temperatures, the deuteron polarizations and the measured relaxation times (T_1) for the two sequential one-hour exposures of the target at 0.1 T and at about 65 mK. One can see that the bolometer of the negatively polarized cell detects a fast energy release with $\tau_f \approx 18$ min just during the first exposure; it is absent in the second expousure. This shows an additional mechanism of the energy release, needed to explain the dependency of the measured relaxation times on the sign of polarization.

To determine the mechanism of the fast process we estimate the average energy released from D and ^{6}Li during the τ_f-period.

$$\Delta W \approx 2 n_D N_A \mu_D B \cdot \Delta P_D, \tag{2}$$

where factor 2 takes D and ^{6}Li into account, N_A is Avogadro's constant. Setting $\mu_D \approx \mu_{Li} \approx 4.3 \cdot 10^{-27}$ J$\cdot T^{-1}$, the difference of polarization of $\Delta P_D = 0.055$ measured by NMR at B=2.5 T before and after the first exposure, we obtain the energy of $\Delta W \approx 0.15$ J. This gives the average power of $\Delta W/\tau_f \approx 14\ \mu W$ which is negligible in its influence on the temperature of ^{3}He / ^{4}He mixture. On the other hand, the bolometer sensitivity of the order of $10^{-9}\ W$ allows the detection of radiation on such a level. Thus we conclude that we see radiation losses from the polarized LiD.

Figure 2 shows the first observation of the spectro-resolved radiation in LiD, received by bolometer, without additional applied fields to the material. Its pulse components have the approximate duration of $\tau_R \approx 0.1$

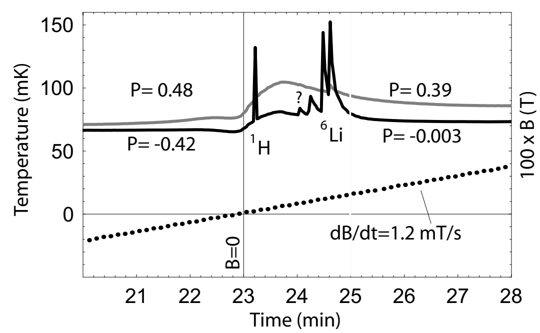

Figure 2. The spectro-resolved spin radiation (from the left to right): ^{1}H (28.9 mT), non-identified (90.1 mT), ^{7}Li (101 mT), D (121 mT), ^{6}Li (127 mT).

min, hence $\tau_R \approx 0.1 \ll \tau_f \approx 18 \ll T_1 \approx 1000$ min. This means that the spin-lattice relaxation is switched off and only the alternating local fields of LiD lead to these resonances. Assuming that Zeeman nuclear energy equals the energy of dipole-dipole interactions of electron spins $h\nu_I = \xi \cdot \mu_S^2/r_{SS}^3$, where h is Plank's constant, ν_I are Larmor frequencies of I- nuclear species, ξ is a fitting parameter, μ_S is the electron magnetic moment, r_{SS} is the effective radius per electron spin, $r_{SS}^3 = 3/(4\pi N_S)$ and $N_S = 9.8 \cdot 10^{-21}$ cm^{-3} is the S-spin concentration in LiD, we finally obtain $\xi = (0.5 \div 1.0)$ which explaines the position of resonances in Fig. 2. It follows that the spin species radiate in sequence, all at aproximately the same frequency of about 1.0 MHz. The first spike in Fig. 2 belongs to the proton spins having the highest gyromagnetic ratio, then comes ^{7}Li, D and ^{6}Li.

The point is that MHz-radiation is not possible without the inductive coupling of polarized spins with a resonance system[2]. This coupling produces an additional channel for the fast spin energy dissipation through the conductive losses in the circuit. In our tests the effect is seen as the fast losses in Fig. 1 and as the background and the resonances in Fig. 2.

Two mechanisms enable explanation of detected radiation[3]: the thermal induced superradiation (SR) and the maser like generation (MG). SR acts during the radiation time τ_R of the order of T_2, where $T_2 \approx 3 \cdot 10^{-4}$ s is the transverse relaxation time of D and ^{6}Li estimated by NMR line shapes. In our case, however, $\tau_R \approx 6 \gg T_2 \approx 3 \cdot 10^{-4}$ s, so that SR is absent or our slow control system with the resolution of 2 s disables its indication.

The MG explaines radiations shown in Fig. 1 and 2. MG is lasting during crossing over the bandwidth of the resonance circuit, which is easily estimated as the product of the field rate into τ_R or $1.2\ mT/s \cdot 6\ s =$ 7.2 mT or 47 kHz for deuteron spike. This yields the circuit quality factor of $Q_{circ} = 10^6/4.7 \cdot 10^4 \approx 20$. The main difference between radiation shown in Fig. 1 and 2 comes from their start temperatures of the electron dipolar subsystem of about $-4 \cdot 10^{-5}$ and -10^{-7} K respectively which determines the intensity of alternating local fields.

We estimate the minimum threshold product $(\eta \cdot Q)_{min}$, where η is the filling factor, at which this process starts to act against the deuteron polarization build up, we have[2]

$$(\eta Q)_{min} = ((2\pi)^2 M_0 \gamma_D T_2)^{-1} \approx 2.1, \tag{3}$$

where M_0 is the average magnetic moment per unit volume, in our case $M_0 \approx 6.1\ \mu T$ at 50 % polarization, $\gamma_D \approx 6.54\ Hz/\mu T$ is the gyromagnetic ratio. Setting $\eta_{coil} \approx 0.25$ for the NMR coils and $\eta_{cav} \approx 0.016$ for the MW cavity yield $Q_{min} \approx 9$ and ≈ 130 for NMR coils and for MW cavity respectively. Eq. 3 does not depend on the magnetic field, also the observed value of $Q_{circ} \approx 20 > Q_{min}$ is satisfied just for NMR coils but not for the MW cavity. From this it can be argued that a high enough Q_{coil} might be a reason of the lower negative polarization of ($\mid -53 \mid$ %) in comparison with positive (+57%) polarization reached in our 2001-2004 measurements.

References

1. A. Abragam, M.Goldman, *Nuclear Magnetism: Order and Disoder*, Clarendon Press, Oxford, (1982).
2. N. Blombergen and R.V. Pound, *Phys.Rev.* **95**, 8 (1954).
3. Yu.F. Kisselev, *Phys. of Part. and Nucl.* **31**, 354 (2000).