A Polarization Method of Quadrupole Nuclei

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We discuss a possible use of a frozen proton target for polarization of quadrupole nuclei by means of their spin-spin interaction with polarized protons. A principle opportunity to focus spins of these nuclei into the pure quantum state is shown by using π-pulse or adiabatically fast reverse of proton polarization at the frequency equal to the central frequency of quadrupole resonance.

1 Introduction

The nuclear moment study of radioactive isotopes and their hyperfine interactions might be enriched by utilizing the dynamic nuclear polarization technique (DNP). In diamagnetic materials, for example, in ammonia (NH_3) at 2.5 T field (H_0) and temperatures of about 0.2 K, DNP allows ± 90% and higher proton polarization [1] (P_p). On the other hand, DNP ultimate polarization proves to be rather low for the nuclei having larger charges and, as a rule, large quadrupole moments. So, the ^{14}N polarization (P_n) in NH_3 is only about ± 15% [1]. The transmission of high proton polarization to the low polarized spin species has been investigated by many authors [2].

Here we consider the enhancement of polarization when there is no effective mechanism to establish thermal equilibrium (Boltzmann) distribution within the spin system because a strong quadrupole interaction with the crystalline field causes severe inhomogeneous broadening of NMR-line. It will be shown that spins of quadrupole nuclei can be directed to the pure quantum state. The proposed method was elaborated [3] to upgrade heavy nuclear targets as well as to use the existent frozen targets for the study of magnetic structure of implanted isotopes.

2 Polarization of quadrupole nuclei.

Recently strong enhancement of ^{14}N-polarization ($I = 1$) in NH_3 has been obtained by SMC-collaboration [1] at CERN by using the cross-relaxation between ^{14}N and ^{1}H spins after their nuclear demagnetization. For this purpose the 2.5 T initial field of the SMC-target was adiabatically reduced to 0.056 T low field and immediately raised back. At 0.056 T the frequency of quadrupole resonance (ω_0) of ^{14}N-nuclei coincides with Zeeman frequency (ω_p) of protons ($\omega_0 = \omega_p$), then the dipolar coupling between species should provide a common temperature of the spins. Proton spins were cooled down to 39 μK whereas, due to the field independent quadrupole interaction, ^{14}N-temperature was found to be much higher (230 μK). Finally, thermal mixing resulted additional strong cooling down of ^{14}N-spins, that enhanced P_n from 15 % to 40 %. A more accurate understanding of the above experiment follows from

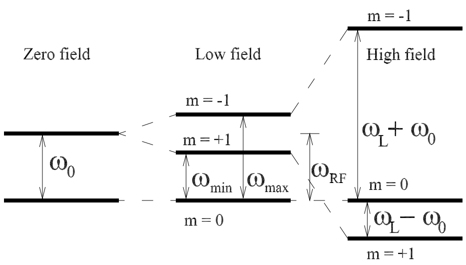

Figure 1: Energy diagram of $I = 1$ spin system at $\theta = 0$.

Fig. 1 which shows the energy level diagram of ^{14}N spins at the zero, low, and high magnetic field (the proton levels are not pointed). The levels correspond to the zero angle (θ) between the principal axis of the electric field gradient tensor and H_0. It is seen that the maximum of the considered enhancement is reached, when the population of the upper sublevel $m = -1$ is zeroed due to the low field cross-relaxation at $\omega_p = \omega_{max}$. Here crossing $\omega_p = \omega_{min}$ should be avoided. As a consequence, the final distribution of spins over magnetic sublevels becomes undetermined.

To solve this problem, we propose a new scheme of the experiment. Assume for the simplicity $\theta = 0$, $I = 1$, and the 100 % initial proton polarization. Generalization of the method for polycrystalline materials and an arbitrary spin was published elsewhere [3]. This time, according to the new scheme, we reduce the field crossing sequentially both frequencies $\omega_{max} = \omega_p$ and $\omega_{min} =$

ω_p (see Fig. 1). Now the cross-relaxation sets $m = \pm 1$ populations to zero and the only state of $m = 0$ gets a non-zero post-passage population resulting to $P_n = 0$ at the lowest field. The high ^{14}N polarization should be reached if we exchange the populations $m = 0$ and $m = -1$ during the following increase of the magnetic field. To fulfil this procedure, the π-pulse reverse of the proton spins should be done in the frequency $\omega_{RF} = \omega_0$ (see Fig. 1). After the reverse, the repeated cross-relaxation at $\omega_{max} = \omega_p$ results in the required exchange of $m = 0$ and $m = -1$ populations and the highest possible value of $P_n \approx P_p$. Since at further increase of the field the state $m = -1$ does not cross over other sublevels, all the spins will remain in the same quantum state. Besides the π-pulse, the reverse of the proton spins can be also done adiabatically by the strong rf-field in $\omega_{RF} = \omega_0$ frequency.

Cross-relaxation provides fast rate of polarization [4] of the order of

$$W = (\gamma_n/\gamma_p)^2 (T_2 \cosh(\xi \frac{\Delta_c}{\Delta_H}))^{-1} \tag{1}$$

where $\gamma_n/\gamma_p \cong 7 \cdot 10^{-2}$ is the ratio of the nuclear gyromagnetic constants, $T_2 \cong 10^{-5}$ s - the transverse relaxation time of protons, Δ_c - the frequency detuning between spins, Δ_H - the width of proton line and $\xi \approx 1$ - a free parameter. Assuming $\Delta_c = \Delta_H$, the estimate is $\tau = W^{-1} \cong 3$ ms.

As we know, the proposed method has never been used while studying the angular distribution of $\beta - \gamma$-radiation and for the polarization of heavy nuclei. It provides positive and negative spin temperatures at relatively high $(0.2 \div 0.3)$ K lattice temperatures when the dilution refrigerator can produce a considerable cooling power of $10 \div 100$ mW. Within these limits the refrigerator can work for the on-line implantation of isotopes in the host matrix. In comparison with a ferromagnetic matrix, the dielectric ones are transparent to 10^{11} Hz and higher frequencies without remarkable warming-up of the materials at ultralow temperatures. The dielectrics are evidently preferable due to negligable local fields, $\sim 10^{-3}$ T, that simplifies data interpretation. The method can find a wide application in the phase analysis, study of P-T-parity violation, and in neutron, high energy, hyperfine interaction physics.

References

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