Communication

Proton tunneling in a hydrogen bond measured by cross-relaxation field-cycling NMR

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Abstract

A field-cycling NMR pulse sequence is described for studying cross-relaxation between unlike nuclear spins in the solid state. The technique has been applied to study proton tunneling in the hydrogen bonds of a carboxylic acid containing ^{19}F and ^{1}H spins. By studying the *B*-field dependence of the off-diagonal element of the relaxation matrix that characterizes the longitudinal polarizations, an accurate measure of the proton transfer rate is obtained.
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With the advent of techniques in magnetic resonance for enhancing the spin polarization of nuclei [1–3] there is increasing interest in measuring and understanding cross-relaxation and cross-polarization processes connecting different spin-species in the same material. By facilitating the transfer of spin polarization from highly polarized spin systems, such techniques have the potential to substantially increase the sensitivity of NMR and to facilitate the observation of NMR spectra and images from nuclei in low abundance.

Cross-polarization and cross-relaxation processes are mediated by magnetic interactions which connect the two spin-species. In particular, the magnetic interactions must be rendered time dependent to provide an effective mechanism for transferring spin polarization. The time-dependence can be introduced coherently and reversibly through suitably applied rf fields, for example, by using the rotating-frame as with Hartmann–Hahn cross-polarization [4], or, as in the present investigation, by utilizing stochastic fluctuations arising from inherent molecular motion in the material. Since spin polarization is proportional to inverse temperature, substantial gains in polarization can be made by operating at low temperature. However, in cross-relaxation the spectral density characterizing the molecular motion must be sufficiently strong to drive the relaxation processes in order that such gains can be realized. Since classical barrier hopping will invariably be too slow at low temperature, in practice it will usually be necessary to choose or design a molecular system in which quantum tunneling dominates the motion [5,6]; only then will the motion be sufficiently fast.

In this Communication, we describe a new magnetic field-cycling NMR technique for measuring the cross-relaxation between ^{1}H and ^{19}F nuclei in a carboxylic acid in the solid state. The cross-relaxation process is driven by proton tunneling in the hydrogen bonds of the material and the magnetic field dependence provides a direct measure of the proton tunneling rate.

The time dependence of the longitudinal polarizations, $\langle I_z \rangle$ and $\langle S_z \rangle$, of two coupled spin systems (labeled I and S) in the laboratory frame is governed by the well-established differential equations [7],

$$\begin{bmatrix} \frac{d}{dt}\langle I_z \rangle \\ \frac{d}{dt}\langle S_z \rangle \end{bmatrix} = - \begin{bmatrix} \rho_I & \sigma \\ \sigma & \rho_S \end{bmatrix} \begin{bmatrix} (\langle I_z \rangle - I_0) \\ (\langle S_z \rangle - S_0) \end{bmatrix}. \tag{1}$$

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Here, I_0 and S_0 are the longitudinal polarizations at thermal equilibrium and the elements of the relaxation matrix, $\mathbf{R} = \begin{pmatrix} \rho_I & \sigma \\ \sigma & \rho_S \end{pmatrix}$, are spin-lattice relaxation rates determined by homonuclear and heteronuclear magnetic interactions within and between the two spin systems. The cross-relaxation process connecting the two spin reservoirs is governed by the off-diagonal element, σ. In the case where one of the spin species is highly polarized, then the polarization can be transferred to the second spin species via the pathway provided by the off-diagonal element, leading in appropriate circumstances, for example, to nuclear Overhauser effects and NMR signal enhancement of the second spin. In this Communication, we emphasize the cross-relaxation process.

Where molecular motion is responsible for mediating the cross-relaxation pathway, the off-diagonal element is written in terms of the spectral density function characterizing the molecular motion, sampled at the sum and difference Larmor frequencies of the two spins, $\omega_I + \omega_S$ and $\omega_I - \omega_S$. In the hydrogen bonds of carboxylic acid dimers the motion is a stochastic, concerted double proton transfer process characterized by a Lorentzian spectral density function [8], $L(\omega, \tau_c) = 2\tau_c/(1 + \omega^2 \tau_c^2)$, with width determined by the inverse correlation time for the motion, τ_c^{-1}. We may then write [7],

$$\sigma = K(T)(-L(\omega_I - \omega_S, \tau_c) + 6L(\omega_I + \omega_S, \tau_c)), \qquad (2)$$

where [9] $K(T) = C_{IS}\frac{4a}{(1+a)^2}$. In Eq. (2) the two spectral density components appear with opposite sign; this situation arises because double-quantum and zero-quantum transitions compete within the manifold of dipolar coupled spins, driving the cross-relaxation process in opposite directions. The cross-relaxation processes are driven by modulation of the heteronuclear dipolar interactions; C_{IS} is a lattice sum of such dipolar interactions [9] and the Boltzmann factor $\frac{4a}{(1+a)^2}$, with $a = \exp(A/k_B T)$, arises from the energy asymmetry, A, of the two conformations of the hydrogen bonds that are interchanged by the proton transfer process.

Following a disturbance away from thermal equilibrium, the general solutions of the coupled Eq. (1) describing the time-dependence of the polarizations of the two spin species are characterized by two spin-lattice relaxation rates R_1 and R_2 which are eigenvalues of $\mathbf{R}$, namely, $R_{1,2} = \frac{1}{2}\left((\rho_I + \rho_S) \mp \sqrt{(\rho_I - \rho_S)^2 + 4\sigma^2}\right)$ (we adopt the convention $R_2 > R_1$). The solutions are bi-exponential,

$$\langle I_z \rangle = I_0(c_1^I \exp(-R_1 t) + c_2^I \exp(-R_2 t)) + I_0, \qquad (3)$$

$$\langle S_z \rangle = S_0(c_1^S \exp(-R_1 t) + c_2^S \exp(-R_2 t)) + S_0, \qquad (4)$$

where the weighting coefficients c are functions of R_1, R_2, and $\mathbf{R}$, determined by the polarization state of each reservoir at time $t = 0$.

To measure the cross-relaxation matrix element, σ, the strategy developed in this investigation was to polarize one spin species, I, and saturate the second, S at time

$t = 0$. Subsequently the polarization of spins I was monitored as a function of time. With such initial conditions the weighting coefficients characterizing Eq. (3) may be shown to be,

$$c_1^I = \left(\frac{\sigma}{R_2 - R_1}\right)\frac{\gamma_S}{\gamma_I}; \quad c_2^I = -c_1^I, \qquad (5)$$

where γ is the magnetogyric ratio. Hence time-dependence measurements of $\langle I_z \rangle$ provide a means to determine σ from the value of the weighting coefficient that governs the bi-exponential relaxation. This contrasts with more conventional NMR relaxometry measurements where the spectral density information is usually extracted from the spin-lattice relaxation time constants themselves [10].

The cross-relaxation field-cycling NMR pulse sequence designed to implement this scheme is illustrated in Fig. 1.

(a) The spins were polarized at the field B_{pol} to a predetermined level during time interval, τ_{pol}.
(b) The field was switched rapidly to match the rf frequency of the spectrometer to the Larmor frequency of spins S, where the latter were saturated with a burst of $\pi/2$ rf pulses.
(c) The field was rapidly switched to the magnetic field, B_r, where the polarizations were allowed to evolve for the period τ_r.
(d) The field was rapidly switched to match the rf frequency of the spectrometer to the Larmor frequency of spins I, where the polarization of the latter was measured with a single rf pulse.

Experiments have been conducted in the solid state at low temperature on tetrafluoroterephthalic acid (TFTA: $C_6F_4(COOH)_2$) where we assign spins I to be ^1H and spins S to be ^{19}F; Fig. 2. This di-carboxylic acid molecule forms infinite chains linked by pairs of bridging hydrogen bonds.
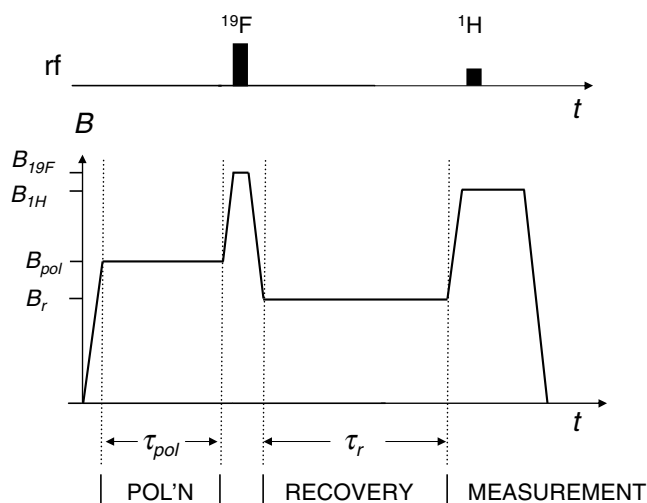

Fig. 1. The cross-relaxation field-cycling NMR pulse sequence. Following polarization of the nuclear spins, the ^{19}F spins are saturated with a burst of $\pi/2$ pulses shortly before the B-field is switched to B_r. Following recovery, the ^1H polarization is measured with a single rf pulse.
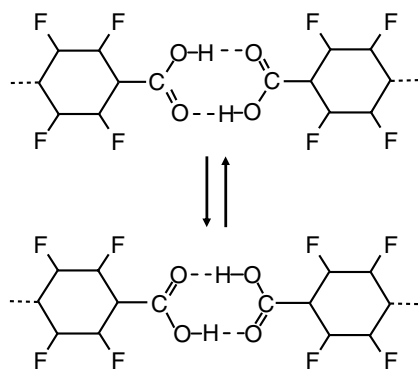
Fig. 2. Concerted double proton transfer in the di-carboxylic acid, TFTA.

Within each pair of hydrogen bonds, there are two possible tautomeric configurations which can interchange by double proton transfer within the hydrogen bonds. In such infinite chains, experimental evidence to date is able to identify motion within a single pair of hydrogen bonds [11], however, coordinated motion along the chain involving many such hydrogen bond pairs has not yet been separately identified in experiments. Therefore, for the purpose of discussion we identify a dimer as a single pair of TFTA molecules. The concerted double proton transfer process leads to a modulation of both homonuclear ^1H–^1H dipolar interactions and heteronuclear ^{19}F–^1H dipolar interactions. Changes in both internuclear distances and in the angle made by the internuclear vector with respect to the applied B-field are responsible for this modulation. ^1H–^1H interactions are dominated by the intra-dimer internuclear vector connecting the two acid protons in the bridging hydrogen bonds. Of more importance to this study are the numerous ^{19}F–^1H dipolar contacts, both intra- and inter-dimer, involving ^{19}F nuclei on the phenyl ring and the hydrogen bond protons.

Measurements were made using a custom-built field-cycling NMR spectrometer [9,12]. To facilitate fast field-switching, the main B-field was provided by a superconducting solenoid with low inductance. The spin-lattice relaxation behavior was observed to be bi-exponential at all B-fields studied and temperatures below 50 K; the ratio of the two rates, R_2/R_1 was typically 10–15 depending on field and temperature. In Fig. 3, the polarization-recovery curve, $\langle I_z(\tau_r)\rangle$, for a cross-relaxation field-cycling NMR experiment is presented; the temperature was 20 K and $B_r = 0.35$ T. In order that Eq. (5) applies, it was necessary for the initial polarization of spins I to match the thermal equilibrium polarization, I_0, at the field B_r; this condition was tailored experimentally by selecting appropriate values of τ_{pol} and B_{pol}. In Fig. 3, following the saturation of spins S, the polarization $\langle I_z \rangle$ initially decreases with rate R_2 as polarization is transferred to spins S via the cross-relaxation pathway; thereafter $\langle I_z \rangle$ recovers toward its thermal equilibrium value at the field B_r with rate R_1. Fitting Eq. (3) to the data, with weighting coefficients determined by Eq. (5), enables the value of σ to be determined. The
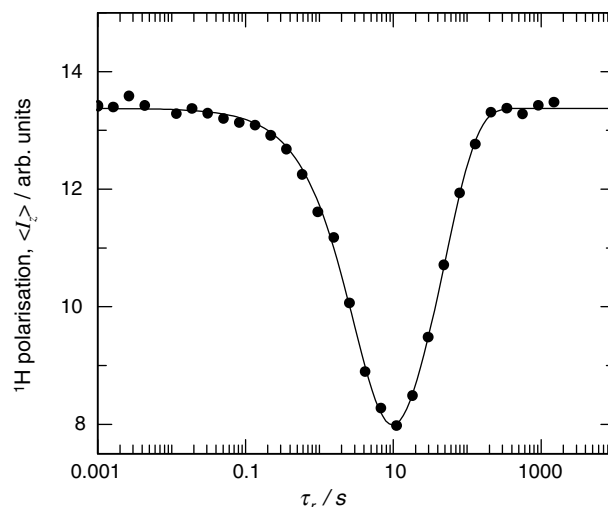

Fig. 3. The ^1H polarization $\langle I_z \rangle$ recorded as a function of τ_r in TFTA using the pulse sequence illustrated in Fig. 1. ($T = 20$ K, $B_r = 0.35$ T). The solid line is the fit with Eq. (3) using weighting coefficients, Eq. (5). For this field and temperature, the relaxation rates are $R_2 = 0.29 \pm 0.01$ s^{-1} and $R_1 = 0.020 \pm 0.001$ s^{-1}.

experiment was repeated for different values B_r permitting the magnetic field dependence of σ to be mapped out, as presented in Fig. 4 at the temperature $T = 20$ K. For fields $B \geqslant 80$ mT, a free fit was made to the polarization curves to extract R_1, R_2, and σ: the values of the relaxation rates agreed within experimental error with those determined in a separate series of measurements using a conventional single-nucleus pulse sequence. In this field regime, the uncertainties were of order 2–5% and dominated by random scatter. For fields $B \leqslant 50$ mT the relaxation rates were increasing and the NMR signal, proportional to field, was
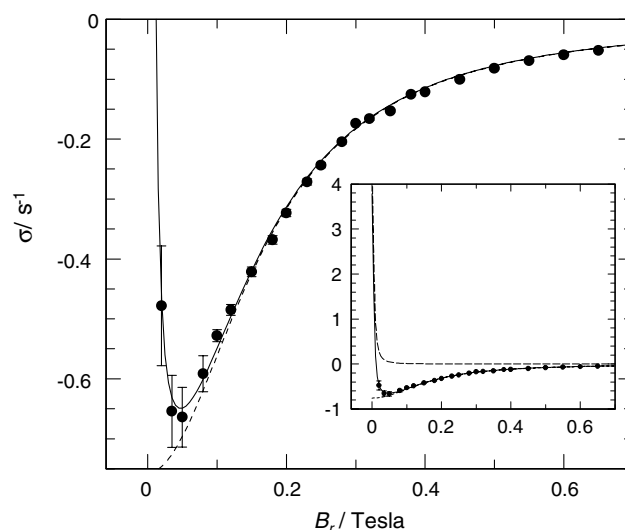

Fig. 4. The B-field dependence of the cross-relaxation time constant, σ, recorded at $T = 20$ K. The solid line is the fit with Eq. (2) from which the correlation rate for proton transfer, $\tau_c^{-1} = (2.66 \pm 0.08) \times 10^6$ s^{-1}, is determined. Inset: the spectral density components, $L(\omega_I - \omega_S, \tau_c)$ (short dash) and $L(\omega_I + \omega_S, \tau_c)$ (long dash), have opposite signs and significantly different widths when plotted as a function of B-field.

becoming very small; both trends made the measurements more challenging. To minimize uncertainties for the lowest three field values, the fits to the polarization-recovery data were constrained with values of R_1 and R_2 determined in separate measurements using conventional single-nucleus pulse sequences. In this field regime, $B \leqslant 50$ mT, the errors in σ were dominated by systematic uncertainties in R_2 leading to the larger error bars.

In this particular system, for the range of B-field studied, Fig. 4 reveals that σ is a negative quantity; consequently, we conclude that the spectral density component $L(\omega_I - \omega_S, \tau_c)$ arising from zero-quantum transitions and characterized by the difference Larmor frequency, dominates the cross-relaxation process. Eq. (2) was fitted to the σ data in Fig. 4, resulting in the solid line. For ^{1}H and ^{19}F, ω_I and ω_S differ by only 5.9%, consequently in a plot versus B-field, since Larmor frequency is proportional to B, the Lorentzians $L(\omega_I - \omega_S, \tau_c)$ and $L(\omega_I + \omega_S, \tau_c)$ have very different widths. As the fit shows, in the field range studied for this heteronuclear system, the data is indeed dominated by the Lorentzian arising from the difference in Larmor frequencies. The Lorentzian $L(\omega_I + \omega_S, \tau_c)$ would only become fully observable at very low B-field, beyond the range of the current experiment; inset Fig. 4. From the fit we determine the inverse correlation time for concerted double proton transfer in the hydrogen bonds of TFTA at 20 K to be $\tau_c^{-1} = (2.66 \pm 0.08) \times 10^6$ s^{-1}. Unlike many conventional studies of molecular dynamics by spin-lattice relaxation, this measurement has been determined wholly from an investigation of the cross-relaxation process. At the temperature recorded, the proton transfer dynamics are dominated by incoherent tunneling in the ground state of the double minimum potential. It is noteworthy that the proton transfer rate is nearly fifty times slower than similar processes in the model compound, benzoic acid [6,13]. That this much slower motion is accessible to the B-field range studied in these cross-relaxation field-cycling NMR experiments is due to the fact that the spectral density is sampled at the difference Larmor frequency which for ^{1}H–^{19}F is relatively small.

The field-cycling NMR techniques described in this Communication provide an experimental procedure for directly studying cross-relaxation processes in magnetic resonance. As a wider range of polarization transfer experiments are developed to improve the sensitivity of NMR and MRI, the methodology described in this Communication, including importantly the study of the magnetic field dependence, may be applied to provide insight into the mechanisms responsible for mediating the coupling between the two spin systems. It is note-worthy that quantum tunneling plays a vital role in the cross-relaxation process in this case since in its absence, if the dynamics had been dominated by classical barrier hopping, the coupling between the two spin-reservoirs would have been vanishingly small at these temperatures. Furthermore, we have shown how the techniques have the potential to be applied in new ways to study molecular dynamics in systems where heteronuclear spins are coupled, as with the direct measurement of spectral density components that characterize the off-diagonal element of the relaxation matrix; in this case the study enabled the measurement of proton tunneling in the hydrogen bonds of TFTA.

Acknowledgments

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