Communication

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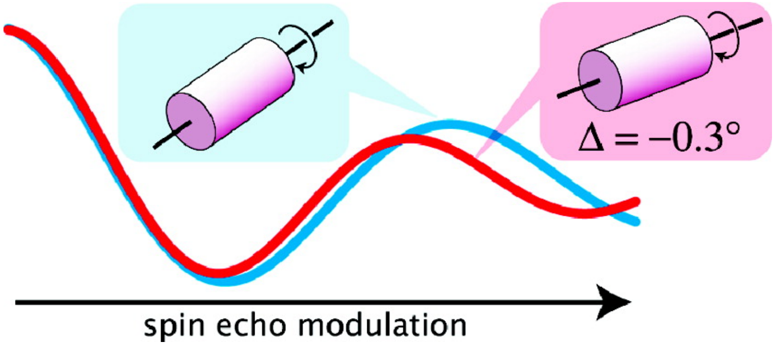

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Residual Dipolar Couplings by Off-Magic-Angle Spinning in Solid-State Nuclear Magnetic Resonance Spectroscopy

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In solution-state NMR, *residual dipolar couplings* (RDCs) are an important source of molecular structural information.[1−3] These interactions are introduced by adding weakly orienting media, such as lipid mixtures or bacteriophage particles, to the isotropic liquid phase. The RDCs are manifested as small changes in the splittings of spectral peaks, which are equal to the *J*-couplings in isotropic phase, but which contain a small dipole−dipole coupling component in an anisotropic liquid. The magnitude of the RDCs may be adjusted by changing the anisotropy of the phase. The most desirable situation is when the RDCs are large enough to give rise to significant changes in the peak splittings, but are too small to cause significant line broadening or strong coupling effects.

In solid-state NMR, magic-angle spinning (MAS) plays a similar role to the rapid isotropic rotation of molecules in an ordinary liquid. MAS involves rapid rotation of the sample around an axis that is at the "magic angle" ($\theta^0 = \arctan\sqrt{2} \cong 54.74°$) with respect to the main magnetic field. Sufficiently rapid MAS averages out the anisotropic nuclear spin interactions, leaving the isotropic chemical shifts and the *J*-couplings. Small *J*-couplings may be estimated robustly in the solid state by determining the modulation frequency for spin echoes induced by a single π pulse, even when the *J*-splitting cannot be observed directly.[4] Spin−echo modulations in MAS NMR have been used to estimate *J*-couplings in, for example, organometallics,[5] hydrogen-bonded systems,[6,7] and the chromophore of a membrane protein.[8]

In this communication, we introduce a solid-state analogue of the solution-state RDC effect. Solid-state RDCs may be introduced by slightly changing the direction of the spinning axis, so that it is not at the exact magic angle with respect to the magnetic field. The solid-state RDCs are manifested as a small perturbation of the spin−echo modulations induced by *J*-couplings. Significant RDCs are introduced even when the spinning angle is only a fraction of a degree away from the magic angle. The magnitude of the solid-state RDCs may be adjusted simply by changing the deviation of the spinning axis from the magic angle. Small axis deviations may be used to obtain RDCs which are large enough to allow the estimation of dipolar couplings, without significantly degrading the spectral resolution and without introducing strongly coupled spin dynamics. Furthermore, the estimation of RDCs may be performed very robustly by using a straightforward rotor-synchronized spin−echo pulse sequence. This method therefore comprises an alternative and a complement to the large class of *recoupling* methods, which also provide dipole−dipole coupling information under magic-angle-spinning conditions, but which require relatively complicated radiofrequency pulse sequences, and encounter complications in heteronuclear spin systems.[9−11]

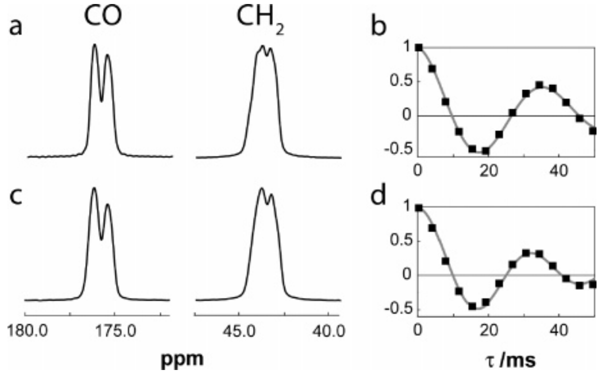

Figure 1. ^{1}H-Decoupled ^{13}C NMR of $^{13}C_2$-glycine powder, at a sample spinning frequency of 13.130 kHz and a field of 7.1 T: (a, b) with exact magic-angle spinning; (c, d) with the spinning axis offset by $\Delta = -0.27°$ from the magic angle. (a, c) Expanded regions of the ^{13}C NMR spectrum. (b, d) Spin−echo amplitudes of the 1-^{13}C peak, as a function of the echo duration τ. The gray lines are the best-fit analytical forms of the modulation curves.

The solid-state RDC effect is demonstrated in Figure 1, which shows ^{1}H-decoupled ^{13}C spectra of $^{13}C_2$-glycine powder. Figure 1a shows spectra from a sample spinning at the exact magic angle with respect to the static field, $\theta = \theta^0$. The ^{13}C resonances are partially split by the $^{13}C-^{13}C$ *J*-coupling of 55 Hz. The *J*-coupling also leads to a clear oscillatory modulation of the signal amplitude with respect to the echo duration τ of a Carr−Purcell echo sequence ($\tau/2 - \pi - \tau/2$), where both $\tau/2$ intervals are always integer multiples of a rotor period (see Figure 1b).

A small change in the spinning angle to $\theta = \theta^0 + \Delta$, where the "misset" is $\Delta = -0.27°$, barely changes the one-dimensional spectral line shapes (see Figure 1c). However, the echo modulation curve shown in Figure 1d has a significantly increased frequency, compared to that in Figure 1b. This frequency shift of the echo modulation is due to the introduction of a RDC by the axis misset. Analytical formulas for the echo modulation curves in the case of off-magic-angle spinning involve Fresnel integrals and are given in the Supporting Information.

The dependence of the echo modulation curves on the deviation Δ of the spinning angle from the magic angle is explored in more detail in Figure 2, which also shows the Fourier transforms of the echo decays. For spinning at the magic angle (Figure 2c), the Fourier transform of the echo modulation curves corresponds to a doublet of sharp peaks with a splitting equal to the *J*-coupling. For off-magic-angle spinning, the peak frequencies shift and the doublet components change their appearance. In all cases, the echo modulation curves are described very well by the analytical formula given in the Supporting Information.

Related phenomena involving off-magic-angle-spinning have previously been described for chemical shift anisotropy and

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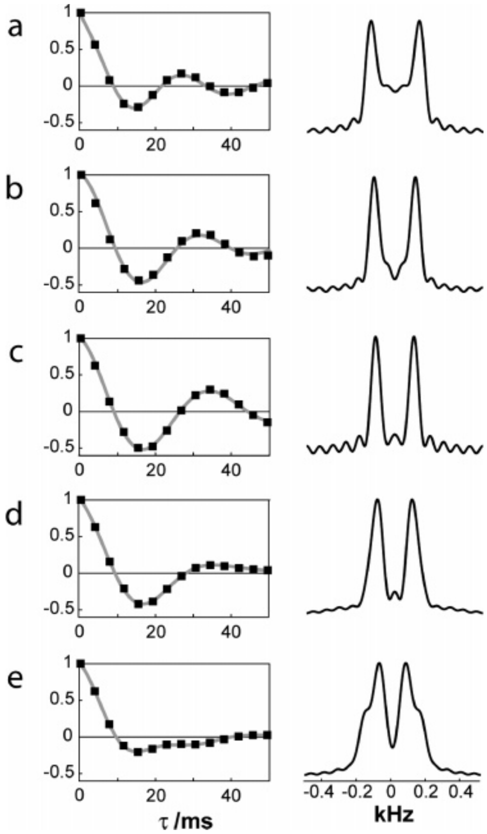

Figure 2. Spin−echo modulation curves for $^{13}C_2$-glycine as a function of echo interval τ (left column) and their Fourier transforms (right column). The spinning angle misset Δ takes the following values: (a) $-0.49°$; (b) $-0.26°$; (c) 0.00; (d) $+0.26°$; (e) $+0.50°$. The gray curves are best fits to the analytical formula.

quadrupole coupling interactions.[12−14] Dipole−dipole couplings have been scaled down in liquid crystals by off-magic-angle spinning, although the physical mechanism is different in that case.[15] In solids, dipole−dipole coupling estimations have been made by off-magic-angle spinning, in combination with multiple-pulse sequences.[16,17] The method described here, in which a simple pulse sequence is used to probe the perturbation of J-modulations by a small axis misset, has a very different philosophy.

It may seem unlikely that small dipole−dipole couplings, which are particularly significant for structural studies, may be evaluated using the method described here. However, one should note that the extremely robust characteristics of spin echoes make it possible to evaluate couplings of only a few hertz.[7] It should be possible to combine the optimal resolution of exact MAS with the structural information of RDCs by executing small-angle jumps in the spinning angle, possibly monitored by using a Hall effect angle sensor.[18] This possibility is discussed further in the Supporting Information.

One of the strengths of the RDC approaches is that the dipolar coupling information is introduced without breaking the weak-coupling approximation. Frequency-selective radiofrequency pulses may therefore be used to isolate individual couplings from a multiple-spin-coupled network.[19,20] The effect described here may therefore facilitate the robust estimation of selected spin−spin couplings in multiple-spin systems. Such an approach could play an important role in solid-state molecular structure determination.

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Supporting Information Available: Full citation for ref 8, experimental details, analytical formulas, full fitting details, spinning-angle determination, and applicability of the phenomenon for measuring smaller dipolar couplings. This material is available free of charge via the Internet at http://pubs.acs.org.

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