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Communication

Indirect detection of nitrogen-14 in solids via protons by nuclear magnetic resonance spectroscopy

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Abstract

This Communication describes the indirect detection of ^{14}N nuclei (spin $I = 1$) in solids by nuclear magnetic resonance (NMR) spectroscopy. The two-dimensional correlation method used here is closely related to the heteronuclear multiple quantum correlation (HMQC) experiment introduced in 1979 to study molecules in liquids, which has recently been used to study solids spinning at the magic angle. The difference is that the coherence transfer from neighboring ^{1}H nuclei to ^{14}N is achieved via a combination of J couplings and residual dipolar splittings (RDS). Projections of the two-dimensional correlation spectra onto the ^{14}N dimension yield powder patterns which reflect the ^{14}N quadrupolar interaction. In contrast to the indirect detection of ^{14}N via ^{13}C nuclei that was recently demonstrated [Gan, J. Am. Chem. Soc. 128 (2006) 6040; Cavadini et. al., J. Am. Chem. Soc., 128 (2006) 7706], this approach may benefit from enhanced sensitivity, and does not require isotopic enrichment in ^{13}C, although the ^{1}H line-widths may have to be reduced upon selective deuteration.

Keywords: Solid-state NMR; Magic angle spinning (MAS); Nitrogen-14 NMR; Quadrupolar parameters; Quadrupolar interaction; Residual dipolar splitting; Second-order quadrupole–dipole cross term; Amino acids

Although ^{14}N has an isotopic abundance of 99.64%, the large quadrupolar interaction associated with its spin $I = 1$ has so far prevented nitrogen-14 NMR from becoming popular. In liquids, ^{14}N line-widths tend to be very broad due to rapid quadrupolar relaxation, except in small molecules that tumble rapidly or have nearly tetrahedral symmetry [1]. NMR spectra of ^{14}N in powders spinning at the magic angle (MAS) can feature hundreds of spinning sidebands that may span several MHz [2]. Although various methods have been developed to observe double-quantum (DQ) transitions between the $|m = +1>$ and $|m = -1>$ levels [3–5], which are not affected by the first-order quadrupole interaction, none of these techniques have made it possible to study nitrogen-containing materials in a straightforward manner.

The two-dimensional correlation experiments described in this Communication exploit a combination of scalar J couplings and residual dipolar splittings (RDS) [6–8], also known as second-order quadrupole–dipole cross term, between nitrogen-14 and neighboring protons that fulfill the role of "spy" nuclei. The latter couplings should not be confused with residual dipolar couplings (RDC), which are observed in weakly aligned liquid crystalline media [9]. In spinning solids, heteronuclear dipolar interactions ^{14}N–I with I = ^{13}C, ^{1}H, or other "spy" nuclei with spin $I = 1/2$, cannot be averaged out completely by magic angle spinning, because the large quadrupole coupling of the I nucleus prevents its quantization along the direction of the static field. The I resonances feature 1:2 doublets, each of the two components having the appearance of a narrow powder pattern [6–8,10]. The effective residual dipolar splitting D_{RDS} (^{14}N–I) can be defined as the separation between the centers of gravity of these patterns. The RDS is

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used in experiments recently described by Gan [11] and by our group [12,13] for indirect observation of ^{14}N nuclei using ^{13}C as a "spy" nucleus. It is shown that the strength of the RDS is critical for the efficiency of the two-dimensional correlation experiments. The advantage of ^{1}H nuclei arises from the ratio $D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{1}\mathrm{H})/D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{13}\mathrm{C}) = \gamma_H/\gamma_C\,[r(^{14}\mathrm{N}–^{13}\mathrm{C})/r(^{14}\mathrm{N}–^{1}\mathrm{H})]^3 \approx 13.5$ when $r(^{14}\mathrm{N}–^{1}\mathrm{H}) = 1.0$ Å and $r(^{14}\mathrm{N}–^{13}\mathrm{C}) = 1.5$ Å which are typical distances found in amino acids and proteins. In glycine $\mathrm{NH_3^+CD_2COO^-}$, $D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{13}\mathrm{C}) \approx 23$ Hz at 9.4 T assuming colinearity of the dipolar and quadrupolar tensors. The $D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{13}\mathrm{C})$ is much larger than $J(^{14}\mathrm{N}–^{13}\mathrm{C}) \approx 4$ Hz so the magnetization transfer occurs mainly through RDS. On the other hand, it is known that $J(^{14}\mathrm{N}–^{1}\mathrm{H}) \approx 65$ Hz, while $D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{1}\mathrm{H}) \approx 106$ Hz, taking into account the rapid rotation of the $\mathrm{NH_3^+}$ group about its threefold axis which coincides with the N–C axis. This rotation leads to a scaling of the static RDS interaction by a factor of $(3\cos^2\theta\text{-}1)/2$, where $\theta \approx 71°$ is the angle subtended between the threefold axis and the instantaneous position of one of the $r(^{14}\mathrm{N}–^{1}\mathrm{H})$ vectors [14]. Since the two effective dipole–dipole vectors $r(^{14}\mathrm{N}–^{1}\mathrm{H})$ and $r(^{14}\mathrm{N}–^{13}\mathrm{C})$ are parallel due to averaging about the threefold axis, they have the same orientation with respect to the electric field gradient tensor of the ^{14}N nucleus. It is evident that $J(^{14}\mathrm{N}–^{1}\mathrm{H})$ and $D_{\mathrm{RDS}}(^{14}\mathrm{N}–^{1}\mathrm{H})$ are considerably larger than their ^{14}N–^{13}C counterparts.

The remarkably simple pulse sequence of Fig. 1 is reminiscent of heteronuclear multiple-quantum correlation (HMQC) spectroscopy that is commonly used in liquids [15], and that has recently been applied in solids with magic angle spinning (MAS), where the magnetization transfer is achieved via J couplings, under the name of MAS-J-HMQC [16–18]. It is also closely related to the work of Gan [11] and ourselves [12,13] using ^{13}C as a spy nucleus. Note that the RDS is a through-space interaction, while the J coupling is a through-bond interaction. As a consequence, it is possible to correlate neighboring pairs of nuclei using RDS even when the J couplings are negligible.

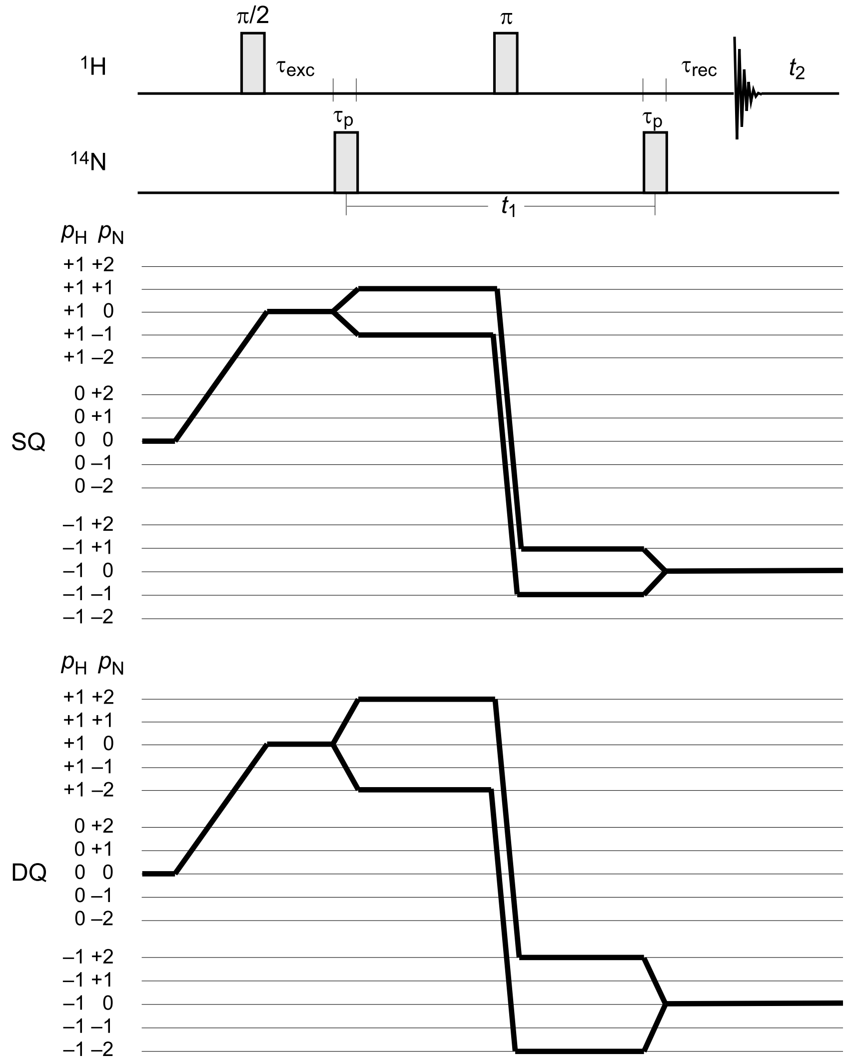

Fig. 1. Pulse sequence and coherence transfer pathway diagrams for the indirect detection of ^{14}N single- or double-quantum spectra by coherence transfer from ^{1}H to ^{14}N and back.