Journal of Magnetic Resonance 209 (2011) 300–305

Contents lists available at ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Suppression of probe background signals via B_1 field inhomogeneity

Jian Feng [a,b,*], Jeffrey A. Reimer [a,b]

[a] Ernest Orlando Lawrence Berkeley National Laboratory, Materials Sciences Division, Berkeley, CA 94720, USA
[b] Department of Chemical & Biomolecular Engineering, University of California at Berkeley, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 27 August 2010
Revised 24 January 2011
Available online 3 February 2011

Keywords:
Probe background
B_1 inhomogeneity
Dephase
Nutation frame
DEPTH

ABSTRACT

A new approach combining a long pulse with the DEPTH sequence (Cory and Ritchey, Journal of Magnetic Resonance, 1988) greatly improves the efficiency for suppressing probe background signals arising from spinning modules. By applying a long initial excitation pulse in the DEPTH sequence, instead of a $\pi/2$ pulse, the inhomogeneous B_1 fields outside the coil can dephase the background coherence in the nutation frame. The initial long pulse and the following two consecutive EXORCYCLE π pulses function complementarily and prove most effective in removing background signals from both strong and weak B_1 fields. Experimentally, the length of the long pulse can be optimized around odd multiples of the $\pi/2$ pulse, depending on the individual probe design, to preserve signals inside the coil while minimizing those from probe hardware. This method extends the applicability of the DEPTH sequence to probes with small differences in B_1 field strength between the inside and outside of the coil, and can readily combine with well-developed double resonance experiments for quantitative measurement. In general, spin systems with weak internal interactions are required to attain efficient and uniform excitation for powder samples, and the principles to determine the applicability are discussed qualitatively in terms of the relative strength of spin interactions, *r.f.* power and spinning rate.

1. Introduction

Background signals arising from instrumental hardware materials, such as probe stator and rotor tips, significantly interfere with the qualitative and quantitative analysis of NMR spectra. In principle, a simple scheme for removing the background is to subtract the spectrum acquired in absence of the sample from that obtained with the sample present. This strategy, however, is practically difficult to perform, since the inevitable manual adjustments of the hardware, along with the sample replacement, can potentially change the electronic and mechanical conditions, or even the effective magnetic field. Post Fourier-Transform phasing also largely depends on the investigator's incidental determination and observation, which could further introduce additional arbitrary errors when calculating difference spectra. The preferred method by NMR spectroscopists, therefore, is to suppress *in situ* the background signals from the probe hardware by utilizing appropriate pulse sequences.

Based on differences between the sample and the probe hardware, either in the spin physical properties or their response to external pulses, a number of NMR pulse sequences have been applied to the suppression of background signals [1–3]. For example, the spin-echo sequence is frequently used to "filter" spins exhibiting a short T_2. This strategy is effective if the active spins within the sample possess much longer T_2 than those within probe hardware. A widely employed technique for suppressing probe background is the DEPTH sequence [1,4], which is typically composed of one $\pi/2$ initial excitation pulse, and two consecutive π pulses imbedded with the EXORCYCLE phase cycling [5], as illustrated in Fig. 1a, where $\theta = \pi/2$ for original DEPTH sequence. The EXORCYCLE phase cycling functions to eliminate those coherence components that result from the imperfect π pulses, and the efficiency of background suppression is determined by relative strength of B_1 field experienced by sample versus background spins (refer Ref. [4] for a quantitative description). This method is therefore constrained to probes with large differences in B_1 field strength between the inside and outside of the coil. The composite pulse in Ref. [2] and the scheme proposed in Ref. [3] essentially rely on the same principle in terms of the B_1 field strength as that for DEPTH sequence, hence have similar restrictions to application.

In the present paper we report a different approach to the probe background removal, namely dephasing of spins during nutation. We consider a long initial excitation pulse in the DEPTH sequence to dephase in the nutation frame (i.e., *xz* or *yz* plane) the unwanted coherence from probe hardware. The background suppression efficiency is determined by the B_1 field gradient outside the coil, instead of the B_1 field strength. This method is thus not restricted to probes with large differences in B_1 field strength interior and

* Corresponding author at: Department of Chemical & Biomolecular Engineering, Tan Hall/Reimer Lab (Rm D93), University of California, Berkeley, CA 94720, USA.
E-mail address: jifeng@berkeley.edu (J. Feng).

1090-7807/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.jmr.2011.01.023

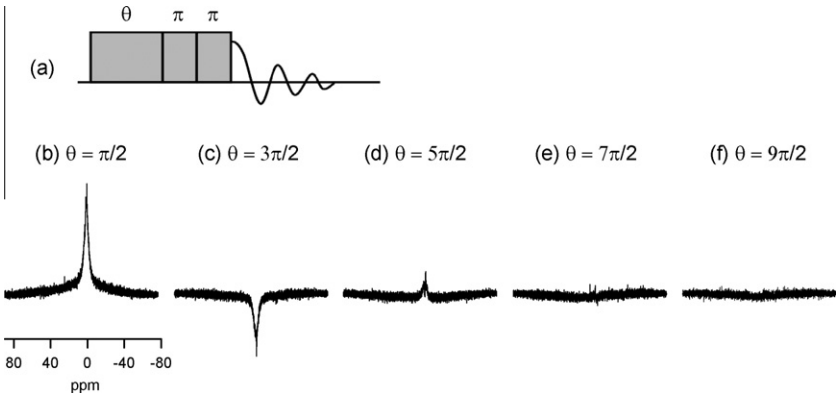

Fig. 1. (a) Modified DEPTH sequence whereby the length of the first pulse is not fixed at $\pi/2$; the phase cycling for all the pulses remains the same as the original DEPTH sequence [1,4]. (b–f) ^{1}H spectra of the empty probe, acquired with the sequence shown in (a). The initial excitation pulse length (θ) is varied, as denoted above each spectrum. The nutation angles refer to the calibration with respect to samples, and are nominal for background signals. For present experimental setup, $\pi/2$ pulse corresponds to 3.45 μs. All spectra were acquired with 2 s repetition delay and 320 scans.

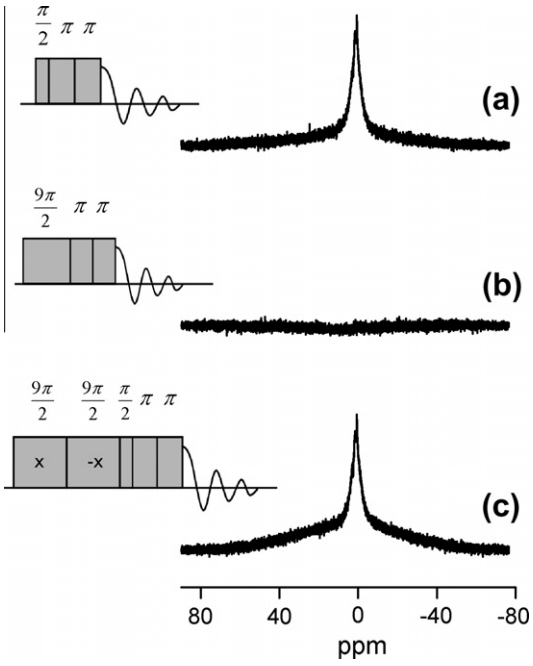

Fig. 2. ^{1}H NMR spectra of the empty probe acquired with: (a) conventional $\pi/2$-DEPTH sequence; (b) $9\pi/2$-DEPTH sequence; (c) DEPTH sequence containing $9\pi/2$ refocusing pulses. Insets show the corresponding pulse sequence used to obtain each spectrum (note that the phase cycling is according to the original DEPTH sequence [1,4]). All spectra were collected with 2 s repetition delay and 320 scans.

exterior to the *r.f.* coil. We demonstrate the advantage of this new strategy via ^{1}H background removal, arguably the most annoying background for NMR spectroscopists. The proposed method, however, is generally applicable to other nuclei. The limitation and potential applications for this new strategy are also considered.

2. Experimental

All the NMR experiments were performed on a 300 MHz (7 T) Tecmag Discovery spectrometer. A Doty XC triple channel probe configured for 5 mm (outer diameter) rotors is used to demonstrate the background removal efficiency for various NMR techniques. The stator of this probe is made of silicon nitride which contains ^{1}H impurities and gives rise to broad, complex background signals. This probe configuration is referred as the default probe through the rest of the paper. Zirconia rotor and Torlon spinning tips are assembled for magic angle spinning (MAS) experiments, and also produce some ^{1}H background signals. The ^{1}H *r.f.* irradiation power is typically 72.5 kHz, corresponding to a 3.45 μs 90° excitation time.

A Doty CRAMPS ^{1}H probe configured for 4 mm (outer diameter) rotors, in combination with Zirconia rotor and Kel-F spinning tips, is used to obtain ^{1}H NMR spectra containing low ^{1}H background signals.

3. Results and discussion

Fig. 1 demonstrates well the efficacy of applying a long initial excitation pulse in the DEPTH sequence (Fig. 1a), instead of a $\pi/2$ pulse, to eliminate probehead background signals. The ^{1}H NMR spectra in Fig. 1 were obtained from an empty Doty 5 mm XC triple channel probe (see details about the configuration in Section 2), which is the default probe referred in the rest part of the paper. It should also be noted that the spin flip-angles denoting the pulse length in Fig. 1, such as θ and π, are calibrated with respect to samples inside the coil, and are nominal for background signals. For the present probe, whereas the conventional $\pi/2$-DEPTH sequence can suppress background signals to some extent, residual components largely remain (Fig. 1b), arising from the spins outside the coil experiencing relatively strong B_1 fields. We find these residual background signals gradually decay as the initial pulse (θ) becomes longer, as shown in Fig. 1c–f. For application on real samples, the optimal length of the initial excitation pulse can be determined at a specific odd multiple of the $\pi/2$ pulse, depending on the individual probe design, so as to preserve signals inside the coil while minimizing those from probe stator or spinning tips. For example, $9\pi/2$ is an appropriate pulse length for suppressing the background from the stator of the Doty probe, while an $11\pi/2$ pulse is required for efficient background repression if Torlon tips are used for solid sample spinning. We noticed that the change of *r.f.* offset can give rise to slight difference in background patterns obtained with a long initial pulse, so the setup of carrier frequency when performing experiments on real samples should be consistent with that for the calibration on empty probe.

It can be inferred by comparing the spectra in Fig. 2 that, the major mechanism accounting for the background signal decay upon a long excitation pulse in the DEPTH sequence is coherence dephasing in the nutation frame caused by B_1 field inhomogeneity

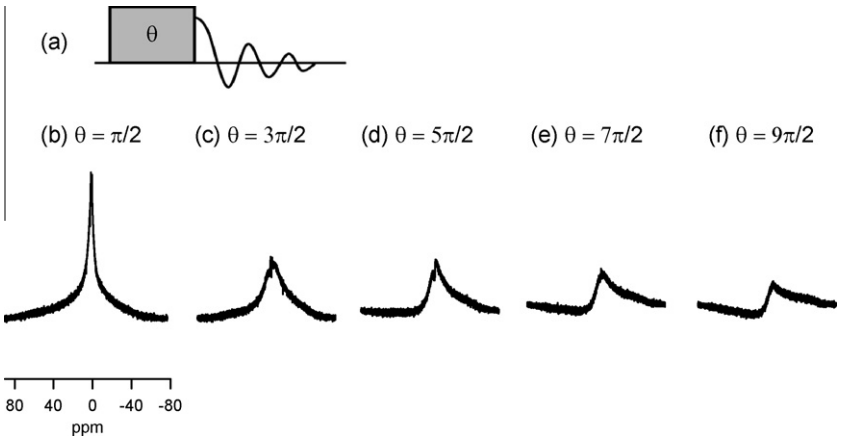

Fig. 3. (a) Single pulse sequence (CYCLOPS phase cycling), employed for subsequent ^{1}H spectra. (b–f) ^{1}H spectra of the empty probe, acquired with variations of excitation pulse length, as denoted above each spectrum. The nutation angles refer to the calibrations for the sample (spins inside the coil), so are nominal to spins outside the coil. A $\pi/2$ pulse length corresponds to 3.45 μs experimentally. All spectra were collected with 2 s repetition delay and 320 scans.

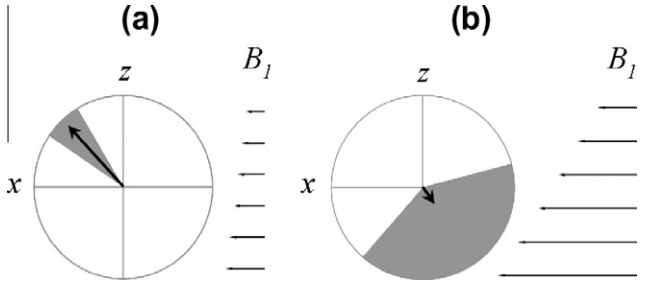

Fig. 4. Plots illustrating the background signal dephasing in nutation frame. Spins experiencing weak B_1 and small B_1 field gradient (a) nutate and dephase slower than those manipulated by strong B_1 and large B_1 field gradient (b). Bold arrows denote the net magnetization for respective coherence, while the gray shading represents the extent of dephasing. Thin arrows indicate the B_1 field strengths.

outside the coil, rather than the short spin–spin relaxation time in rotating frame, $T_{2\rho}$. Fig. 2 contains a set of ^{1}H NMR spectra for the empty probe, where the spectra in Fig. 2a and b were acquired with $\pi/2$-DEPTH and $9\pi/2$-DEPTH sequences respectively, while the pulse sequence used to obtain Fig. 2c includes two additional $9\pi/2$ pulses in the conventional DEPTH sequence, as shown in the corresponding inset. Comparison of these three spectra indicates that the background signals suppressed by the $9\pi/2$ pulse in DEPTH sequence, i.e. Fig. 2b, can nearly be identically restored by a subsequent pulse with equal length but reversed phase (Fig. 2c). The second $9\pi/2$ pulse functions to refocus the coherence back to z-direction if $T_{2\rho}$ of the spins outside the coil is sufficiently long. The recovered signal intensity (Fig. 2c) is consistent with what was obtained with the $\pi/2$-DEPTH sequence (Fig. 2a), suggesting that the B_1 inhomogeneity outside the coil, instead of a short spin–spin relaxation time in rotating frame, $T_{2\rho}$, is the major reason for the intensity loss of the spectrum shown in Fig. 2b. The slight differences between the spectra in Fig. 2a and c presumably are the result of the strong hetero- or homo-nuclear dipolar couplings associated with some of the ^{1}H spins within the stator material.

Although the initial long pulse in DEPTH sequence (i.e., θ in Fig. 1a) can comprehensively dephase the background coherence in nutation frame via B_1 field inhomogeneity, the subsequent EXORCYCLE π pulses are nonetheless indispensable to attain efficient elimination of background signals. Fig. 3 shows that the background signals obtained solely with the single pulse excitation decay much slower with increasing pulse length (θ) than those obtained with modified DEPTH sequence (Fig. 1), indicating that some background components are more efficiently suppressed by the EXORCYCLE π pulses. For present probe, therefore, the B_1 fields outside the *r.f.* coil can be qualitatively distinguished as two classes, namely: strong B_1 fields with large B_1 field gradient, and weak B_1 fields with small B_1 field gradient, as illustrated in Fig. 4. The "strong B_1 fields" are comparable to or moderately weaker than the B_1 fields inside the coil, so the corresponding background signals can not be removed by the EXORCYCLE π pulses in DEPTH sequence (see Ref. [4] for the quantitative description), as shown in the spectrum of Fig. 1b. The associated large B_1 field gradient, however, can dephase in nutation frame the corresponding background coherence relatively fast, and reduce the signal intensity to noise level, in terms of the present experimental conditions, with a $9\pi/2$ excitation pulse (Fig. 1f). In comparison, the "weak B_1 fields" are far weaker than those inside the coil, and the corresponding background signals can be effectively suppressed by the EXORCYCLE π pulses. The associated small B_1 field gradient makes the corresponding background coherence dephase slower in the nutation frame, and remain significant in the $9\pi/2$ single pulse spectrum (Fig. 3f). The long initial excitation pulse and the EXORCYCLE π pulses thereby function complementarily to eliminate the background signals arising from both strong and weak B_1 fields, and the combination proves to be most efficient for background suppression on present probe.

We use a liquid D_2O (Aldrich, 99.9 atom% D, CAS # 7789-20-0) to demonstrate the advantage and effectiveness of this scheme over other established background suppression techniques on the present probe. The ^{1}H single pulse spectrum (Fig. 5a) contains a narrow peak around 5 ppm arising from water, and a broad complex component from the probe hardware, which is apparently centered around 1.2 ppm and span more than 40 ppm. Fig. 5b shows that although the conventional DEPTH sequence with a $\pi/2$ initial excitation pulse exhibits the ability to suppress the background signals by about 50%, the remaining part is nonetheless significant compared with the ^{1}H signals from D_2O. As a comparison, replacing the first $\pi/2$ pulse with a $9\pi/2$ pulse can lower the background signal to the noise level at present acquisition condition (Fig. 5c). ^{1}H spectra in Fig. 5d and e were acquired with the XY-4 composite pulse [2] and the scheme described in Ref. [3] respectively, which, similar to the conventional $\pi/2$-DEPTH sequence, cannot suppress those background components arising from "strong B_1 fields" outside the coil.

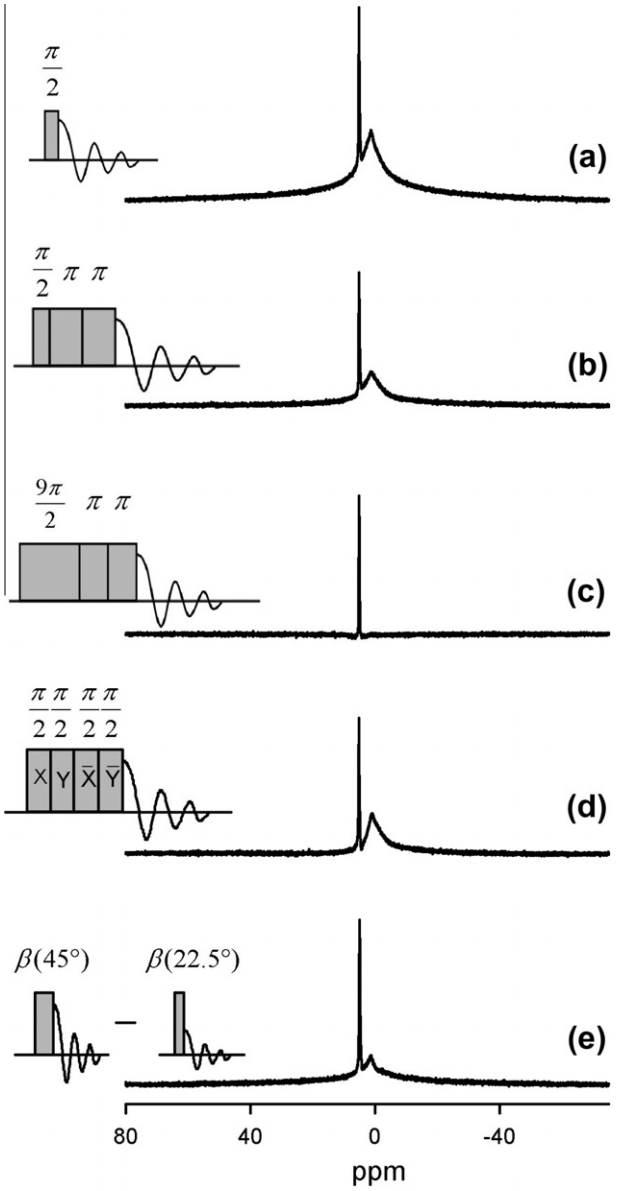

Fig. 5. ^{1}H spectra of D_2O (Aldrich, 99.9 atom% D) acquired with: (a) $\pi/2$ single pulse excitation; (b) $\pi/2$-DEPTH sequence; (c) $9\pi/2$-DEPTH sequence; (d) XY-4 composite pulse [2]; (e) the scheme in Ref. [3], i.e. subtracting the spectrum excited with 22.5° pulse (with respective to spins inside the coil) from that excited with 45° pulse. Insets show the corresponding pulse sequence for each spectrum. Spectra (a–d) were collected with 2 s repetition delay and 128 scans. Each of the two single pulse spectra used to yield Figure (e) was obtained with 2 s repetition time and 800 scans.

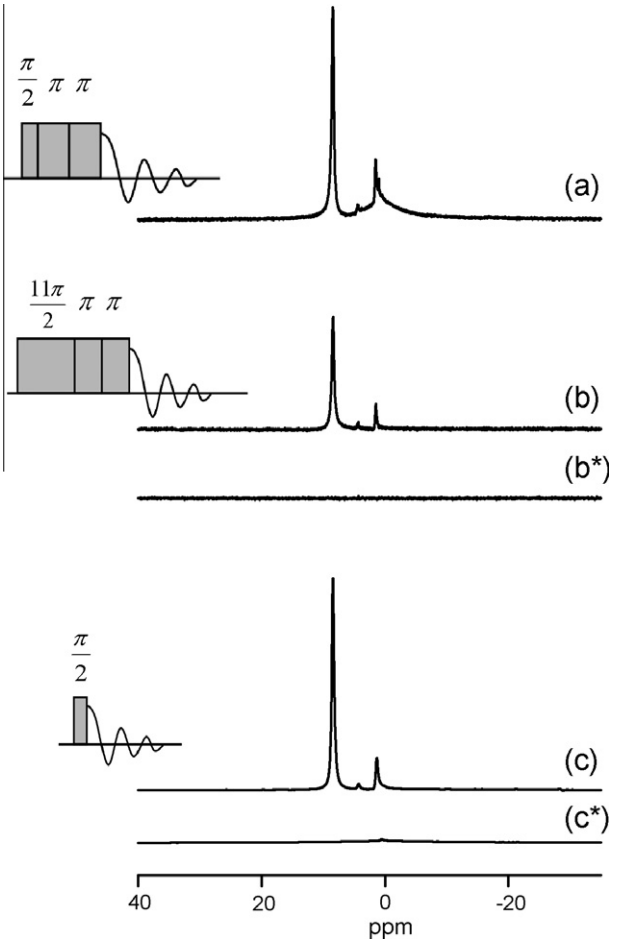

Fig. 6. ^{1}H MAS spectra obtained for a Ba-doped (5 Mol%) lanthanum metaphosphate glass sample. (a) and (b) were acquired on the 5 mm Doty XC triple channel probe (default one through the paper) with: (a) $\pi/2$ DEPTH sequence, 128 scans; (b) $11\pi/2$ DEPTH sequence, 128 scans. (c) is the single pulse spectrum (64 scans) obtained with a 4 mm Doty CRAMPS probe, which contains low ^{1}H background signals. As a comparison, (b*) and (c*) show the ^{1}H spectra for empty rotors obtained under identical conditions as for (b) and (c) respectively. Spinning rate is 10 kHz for all the spectra. Insets show the corresponding pulse sequence for each spectrum.

A Ba-doped (5 Mol%) lanthanum metaphosphate glass [6], which is potentially a membrane material for proton conducting fuel cell, is used to demonstrate the application of this new approach to solid samples undergoing magic angle spinning. The ^{1}H MAS spectrum acquired with the $\pi/2$-DEPTH sequence (Fig. 6a) contains a sharp peak around 8.4 ppm, which is assigned to the P–O–H group, and some minor peaks between 5 and 0 ppm obscured by the intense, broad hump of probe background signals in this range. In comparison, the $11\pi/2$-DEPTH sequence exhibits the ability to completely remove the residual probe background in terms of the present spectral noise (Fig. 6b*), and unambiguously resolve the resonances at 4.3 ppm and 1.5 ppm, which likely arise from mobile water and isolated OH group respectively, as shown in Fig. 6b. The result is verified by the ^{1}H single pulse MAS spectrum obtained with a 4 mm DOTY CRAMPS probe that contains low ^{1}H background (Fig. 6c and c*).

Higher efficiency in probehead background suppression can help to reduce the amount of sample required for NMR experiments. A derivative of MOF-5 [7], namely Zn_4(1,4-benzenedicarboxylate)$_3$ Metal–Organic Framework, is used to demonstrate this merit. We packed a few pellets of sample with total size no larger than 1 mm^3 into a 5 mm (o.d., 200 μL) Doty Zirconia rotor and stuffed it with KBr (Fisher, CAS # 7758-02-3) as filler. The ^{1}H MAS spectrum acquired with the conventional $\pi/2$-DEPTH sequence for the as-packed sample (Fig. 7a) contains the peak from benzenedicarboxylate within the MOF structure (~8.3 ppm), and the broad residual background signals apparently centering at 1.2 ppm. The $11\pi/2$-DEPTH sequence further suppresses the probe background (Fig. 7b*) and reveals the weak shoulder (centering around 3 ppm) hidden in the background range otherwise (Fig. 7b), which is attributed to either the synthetic impurity or molecules captured in the pore. The spectral pattern in Fig. 7b is qualitatively identical to the ^{1}H single pulse MAS spectrum obtained for a full rotor of the MOF sample (Fig. 7c), in terms of the peak positions. The difference in spinning side band intensity between the benzenedicarboxylate

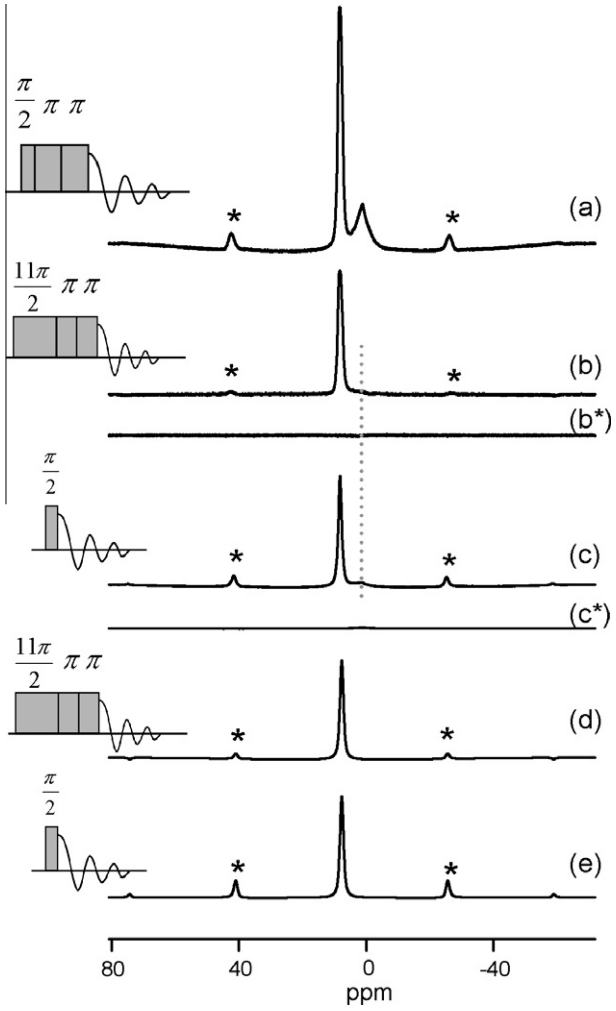

Fig. 7. (a–c) ^{1}H MAS spectra acquired for MOF-5 derivative, Zn_4(1,4-benzenedicarboxylate)$_3$ Metal–Organic Framework. (a) and (b) were obtained with $\pi/2$-DEPTH and $11\pi/2$-DEPTH sequence respectively, for which a few sample particles were packed with KBr, totally 1280 scans. (c) is the ^{1}H single pulse MAS spectrum acquired for a full rotor of samples (16 scans). (b*) and (c*) show the ^{1}H spectra for empty rotors under identical conditions as for (b) and (c) respectively. (d–e) ^{1}H MAS spectra simulated with SIMPSON package [9] on a ^{1}H–^{1}H spin pair with 10 kHz homonuclear dipolar coupling. Pulse sequences used for (d) and (e) are $11\pi/2$-DEPTH sequence and single pulse excitation respectively. Spinning rate is 10 kHz for all the spectra. Insets show the corresponding pulse sequence for each spectrum. Asterisks denote the major spinning sidebands, and the gray dotted line indicates the small shoulder peak observed in both (b) and (c).

signals in Fig. 7b and Fig. 7c is the effect of ^{1}H–^{1}H homonuclear dipolar coupling on the initial long pulse excitation, as is discussed in detail in next section. The high degree of background elimination provides more flexibility to use less amount of sample in NMR experiments, which can be especially important for the analysis of rare natural or expensive synthetic materials.

Potential limitations of the present method include the effects of strong internal spin interactions on the long pulse excitation in the DEPTH sequence. To attain uniform excitation for powder samples, the secular Hamiltonian for the period of the initial long pulse should solely contain the term corresponding to the *r.f.* pulse, i.e. $\hat{I}_x$ or $\hat{I}_y$. For a spin-½ nucleus, the chemical shift ($\hat{I}_z$) and heteronuclear dipolar coupling terms ($\hat{I}_z\hat{S}_z$) do not commute with the spin operator describing the external pulse, and thus can be non-secular upon sufficiently strong *r.f.* pulse. Magic angle sample spinning introduces an additional time-dependence to the chemical shift and heteronuclear dipolar coupling interactions, for which the Hamiltonian can be treated similarly to that describing Cross Polarization Magic Angle Spinning [8], except that only a single rotating frame is considered for this case. To ensure no time-independent term remains in the interaction frame of the *r.f.* field (i.e., the secondary rotating frame around $\hat{I}_x$ or $\hat{I}_y$), the smallest modulation frequency contained in the Hamiltonian, $\omega_{rf} - 2\omega_{spinning}$, should be much larger than the CSA and the heteronuclear dipolar coupling interactions. Experimentally, the size of the effective CSA and heteronuclear dipolar coupling can be roughly estimated as the spinning rate beyond which the spinning side band intensity in the single pulse MAS spectra can be suppressed to a negligible level compared with the center band. The homonuclear dipolar coupling interaction, on the other hand, constantly contains a time-independent part in the interaction frame ($\frac{1}{2}\hat{H}_{\mathrm{hom}o}$), regardless of the strength of the external pulse, in the absence of sample spinning [8]. This term is non-secular only when the spinning rate is sufficiently high compared with the homonuclear dipolar coupling. For the presence of homonuclear dipolar coupling during a long pulse excitation, therefore, the fast magic angle spinning is required, in addition to a strong *r.f.* pulse, to attain a completely uniform excitation. The spinning side band difference between Fig. 7b and c in fact arises from the perturbation of the ^{1}H–^{1}H homonuclear dipolar couplings of benzenedicarboxylate protons in the MOF. Using the SIMPSON package [9], the simulation of the $11\pi/2$-DEPTH spectrum (Fig. 7d) and the $\pi/2$ single pulse spectrum (Fig. 7e) on a ^{1}H–^{1}H spin pair with 10 kHz homonuclear dipolar coupling, which is close to the dipolar coupling strength between the adjacent H in the benzene ring, exhibits consistent variations in spinning side band intensity similar to those observed experimentally (Fig. 7b and c). To conclude, the applicability of this DEPTH-based approach varies with individual probe designs, and the excitation uniformity can be determined according to the principles described here. As the probe can afford larger B_1 field strength inside the coil and faster spinning rate, the method can be applied to spin systems with stronger internal spin interactions.

4. Conclusion

Applying a long initial excitation pulse in DEPTH sequence to remove background signals provides a new option for NMR spectroscopists to suppress background signals arising when strong B_1 fields outside the coil are present. This method is constrained to the spin systems with weak internal spin interactions, relative to the *r.f.* pulse and to spinning rate for the presence of homonuclear dipolar coupling, to attain efficient and uniform excitation. It is worth noting that this method is potentially useful for comparative double resonance NMR experiments, such as REDOR [10,11] and TRAPDOR [12–14], which require accurate measurements of peak intensities.

Acknowledgments

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, of the US Department of Energy under Contract No. DE-AC02-05CH11231.

Reference

[1] D.G. Cory, W.M. Ritchey, J. Magn. Reson. 80 (1988) 128–132.
[2] J.L. White, L.W. Beck, D.B. Ferguson, J.F. Haw, J. Magn. Reson. 100 (1992) 336–341.
[3] Q. Chen, S.S. Hou, K. Schmidt-Rohr, Solid State Nucl. Magn. Reson. 26 (2004) 11–15.
[4] M.R. Bendall, R.E. Gordon, J. Magn. Reson. 53 (1983) 365–385.
[5] G. Bodenhausen, R. Freeman, D.L. Turner, J. Magn. Reson. 27 (1977) 511–514.
[6] G. Harley, K.D. Kreuer, J. Maier, L.C. De Jonghe, J. Non-Cryst. Solids 355 (2009) 932–937.

[7] M. Eddaoudi, H.L. Li, O.M. Yaghi, J. Am. Chem. Soc. 122 (2000) 1391–1397.
[8] E.O. Stejskal, J. Schaefer, J.S. Waugh, J. Magn. Reson. 28 (1977) 105–112.
[9] M. Bak, J.T. Rasmussen, N.C. Nielsen, J. Magn. Reson. 147 (2000) 296–330.
[10] T. Gullion, J. Schaefer, J. Magn. Reson. 81 (1989) 196–200.
[11] T. Gullion, J. Schaefer, in: W.D. Warren (Ed.), Advances in Magnetic Resonance, vol. 13, Academic Press, New York, 1989.
[12] E.R.H. van Eck, R. Janssen, W.E.J.R. Maas, W.S. Veeman, Chem. Phys. Lett. 174 (1990) 428–432.
[13] C.P. Grey, W.S. Veeman, A.J. Vega, J. Chem. Phys. 98 (1993) 7711–7724.
[14] C.P. Grey, A.J. Vega, J. Am. Chem. Soc. 117 (1995) 8232–8242.