Supplementary Material (ESI) for Chemical Science

High-Resolution and Sensitivity Through-Bond Correlations in Ultra-Fast Magic Angle Spinning (MAS) Solid-State NMR

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1. Solid-state NMR Spectroscopy

Alanine spectra:

The spectra of fully ^{13}C-labeled L-Alanine (Figure 1c and d) were recorded on a 500 MHz Bruker Avance III spectrometer, equipped with a double resonance 1.3 mm MAS probe spinning at 60 kHz MAS. Swept low-power (slpTPPM)[1] decoupling was applied during the echo periods and during acquisition ($\omega_1/2\pi \sim \nu_R/4$ = 13.6 kHz according to flip pulse calibration (optimized on echo sequence), 40% pulse duration ramp with reference τ_p = 33.33 μs, phase difference 41°).
The INADEQUATE spectra correspond to 1D experiments recorded, for the CO resonance, after a non-selective CP, and for the Cα resonance after a selective CP on the carbonyls. In all cases the Δ delay was set to 4.5 ms. Gaussian Pulse Cascades[2] (5000 points) of a length of 800 μs for CO and Cα were used.

SOD spectra:

The 2D refocused INADEQUATE and INADEQUATE-S^{3}E spectra were performed on a 850 MHz Bruker Avance III spectrometer using a triple resonance (1H/13C/15N) 1.3 mm MAS probe on a microcrystalline, uniformly labeled [^{15}N, ^{13}C] sample of stabilized human dimeric oxidized Cu(II), Zn(II) superoxide dismutase (Protera srl, Sesto Fiorentino, Italy).[3] The spinning frequency was 60 kHz and the temperature was set to 245 K (corresponding to a sample temperature of about 5 °C as estimated by the shift of the water resonance).[4] For the INADEQUATE-S^{3}E experiment, a total of 320 points were acquired in t_1 (two FIDs corresponding to experiments A and B were recorded for each real t_1 increment), with 256 scans each. The conventional refocused INADEQUATE spectrum was acquired with twice as many scans (512 scans) and 160 t_1 points. In both cases, the maximum acquisition times were 6.8 ms in t_1 and 21 ms in t_2 (interscan delay of 2.4 s). Quadrature detection was obtained with States.[5] Swept low-power slpTPPM[1] decoupling was applied ($\omega_1/2\pi \sim \nu_R/4$ = 13.6 kHz according to flip pulse calibration (optimized on echo sequence), 40% pulse duration ramp with reference τ_p = 33.33 μs, phase difference 41°). A selective cross-polarization on the CO resonances was used with a linear ramp (100% to 90% of r.f. field strength) on the ^{1}H channel, with a 1.5 ms contact time and an rf field strength of 72 kHz for ^{1}H and 64 kHz for ^{13}C. For the conventional refocused INADEQUATE spectrum, the $\Delta/2$ delays of the first and second echo periods were set to respectively 4.5 and 3.5 ms, and a Z-filter delay of 5 ms was appended before acquisition. Refocused coherence lifetimes $T_{2'}$ of 60 ms were measured for the CO resonances. For the INADEQUATE-S^{3}E experiment, Gaussian Pulse Cascades[2] (2000 points) of a length of 450 μs for CO and Cα were used. The delay $\Delta/2$ was set to 4 ms for the first echo period, and $\Delta/4$ was set to $1/8J_{COC_\alpha}$ = 2.25 ms in the refocusing block.

GB1 spectra:

CP and CP-INADEQUATE spectra of Figure 1 were recorded on a 800 MHz Bruker Avance III spectrometer using a triple resonance (^{1}H/^{13}C/^{15}N) 1.3 mm MAS probe on microcrystalline, uniformly labeled [^{15}N, ^{13}C] sample of the protein domain GB1,{Franks, 2005 #742} (form A prepared as described in reference {Schmidt, 2007 #1524}).
For the experiments recorded at 10 kHz MAS, SPINAL-64 heteronuclear decoupling was applied at a RF field strength $\omega_1/2\pi$ = 80 kHz. At ultra-fast MAS (60 kHz MAS), low-power slpTPPM[1] decoupling was applied ($\omega_{1H}/2\pi \sim \nu_R/4$=13.6 kHz according to flip pulse calibration (optimized on echo sequence), 40% pulse duration ramp with reference τ_p = 33.33 μs, phase difference 41°).

The 2D refocused INADEQUATE-S^{3}E spectrum of Figure 3 was performed on the 1000 MHz Bruker Avance III spectrometer using a triple resonance (1H/13C/15N) 1.3 mm MAS probe. The spinning frequency was 60 kHz and the temperature was set to 245 K (corresponding to a sample temperature of about 20 °C as estimated by the shift of the water resonance). A total of 2048 points were acquired in t_1 (two FIDs for each real t_1 increment), with 8 scans each. The maximum acquisition times were 37 ms in t_1 and 50 ms in t_2 for a total experimental time of 9 hours (interscan delay of 2 s). Quadrature detection was obtained with States.[5] Low-power slpTPPM[1] decoupling was applied ($\omega_{1H}/2\pi \sim \nu_R/4$=13.6 kHz according to flip pulse calibration (optimized on echo sequence), 40% pulse duration ramp with reference τ_p = 33.33 μs, phase difference 41°). A selective cross-polarization[6] on the CO resonances was used with a linear ramp (100% to 90% of RF field strength) on the ^{1}H channel, with a 1.5 ms contact time and an RF field strength of

47 kHz for ^{1}H and 19 kHz for ^{13}C. Gaussian Pulse Cascades[2] (4000 points) of a length of 500 μs for CO and Cα were used. The delay $\Delta/2$ was set to 4 ms for the first echo period and $\Delta/4$ was set to $1/8J_{COC\alpha}$ = 2.25 ms for the S^{3}E block.

Spectra of N,N-bis(diphenylphosphino)-N-((S)-α-methylbenzyl)amine

The sample was provided by the Laboratoire d'Etudes Dynamiques et Structurales de la Sélectivité (Grenoble, France). All NMR spectra were recorded on a Bruker Avance III spectrometer operating at ^{1}H and ^{31}P resonance frequencies of 500.1 and 202.5 MHz, respectively.

The phosphorus-31 spectra of Figure S3(a) and (b) were recorded using a double resonance 2.5 mm probe as previously described in reference[7] (spinning frequency of 20 kHz and TPPM-15 1H decoupling at $\omega_{1H}/2\pi$ = 140 kHz). The 1D ^{31}P CPMAS spectrum displays five broad resonances, which actually correspond to eight chemically distinct phosphorus sites arising from four inequivalent molecules per unit cell in the crystal structure. In agreement with previous studies, the eight different sites were labeled x and x', with x ranging from1 to 4. The refocused ^{31}P INADEQUATE spectrum displays correlations between the four pairs of bonded phosphorous-31. Spectra of Figure S3(c) - (f) were recorded using a double resonance 1.3 mm probe at a spinning frequency of 60 kHz, under low-power slpTPPM[1] decoupling ($\omega_{1H}/2\pi \sim \nu_R/4$=13.6 kHz according to flip pulse calibration (optimized on echo sequence), 40% pulse duration ramp with reference τ_p = 33.33 μs, phase difference 41°). A ^{31}P refocused coherence lifetime of 110 ms (corresponding to a refocused linewidth of 2.9 Hz) was measured for the 3a resonance. Cross polarization was achieved using a linear ramp on the ^{1}H channel, with a 2 ms contact time and a RF field strength of 100 kHz for ^{1}H and 54 kHz for ^{31}P.

For the INADEQUATE-S^{3}E experiment, selective refocusing of sites 3a and 3b was achieved using Gaussian Cascades[2] Q3 pulses (5000 points) of 2200 μs. A total of 56 t_1 points (two FIDs for each t_1 increment) were recorded with 5120 scans each. For the conventional refocused INADEQUATE spectrum, a Z-filter delay of 5 ms was appended before acquisition. A total of 28 t_1 points with 2560 scans were recorded. In both cases, the maximum acquisition times were 11.6 ms in t_1 and 30 ms in t_2 (interscan delay of 1 s) and the delay Δ was set to $1/2J_{PP}$ = 19.2 ms (corresponding to a J coupling constant of 25.9 Hz as measured in reference).[8] Quadrature detection was obtained with States.[5]

2. NMR data treatment

For the INADEQUATE-S^{3}E experiments, two FIDs (corresponding to the blocks A and B depicted in Figure 2(a)) were recorded for each t_1 increment, stored separately and used to reconstruct two distinct sets of two-dimensional maps. The resulting 2D spectra were subsequently summed and subtracted to separate for each peak the two multiplet components α and β. After applying a 90° phase correction on one of them, the resulting two spectra were shifted to the center of the original doublet (by $\pm J_{COCA}/2$ = ±26.5 Hz in the case of the CO-Cα coupling) and summed to obtain J-decoupled correlations. For a fair comparison in terms of signal to noise ratio between the two types of INADEQUATE experiments, the INADEQUATE-S^{3}E spectra were divided by $\sqrt{2}$ (to account for the fact that the spectra are summed twice) when compared with conventional INADEQUATE spectra.

3. SOD INADEQUATE-S^{3}E spectra

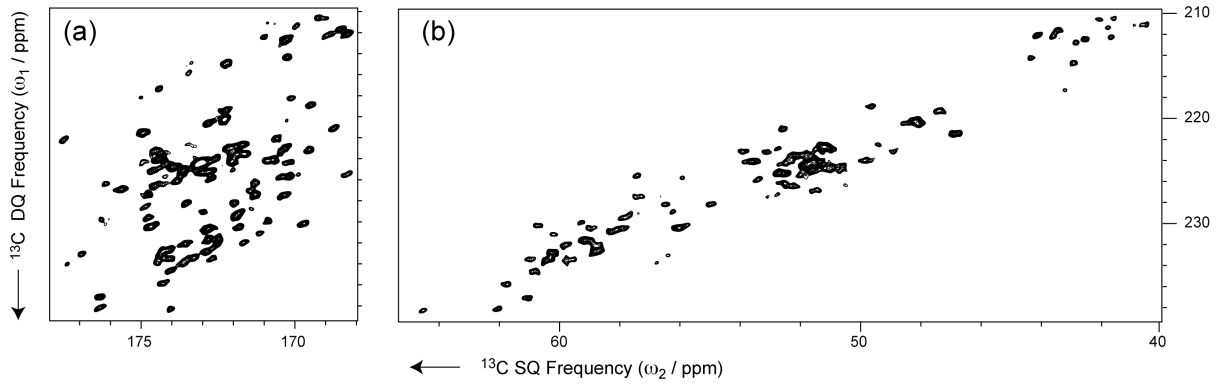

Figure S1: Two-dimensional INADEQUATE-S^{3}E spectrum recoded on a microcrystalline, uniformly labeled [^{15}N, ^{13}C] sample of SOD. (a) and (b) correspond respectively to the carbonyl and aliphatic regions of the spectrum.

4. Scalar versus dipolar correlation spectra

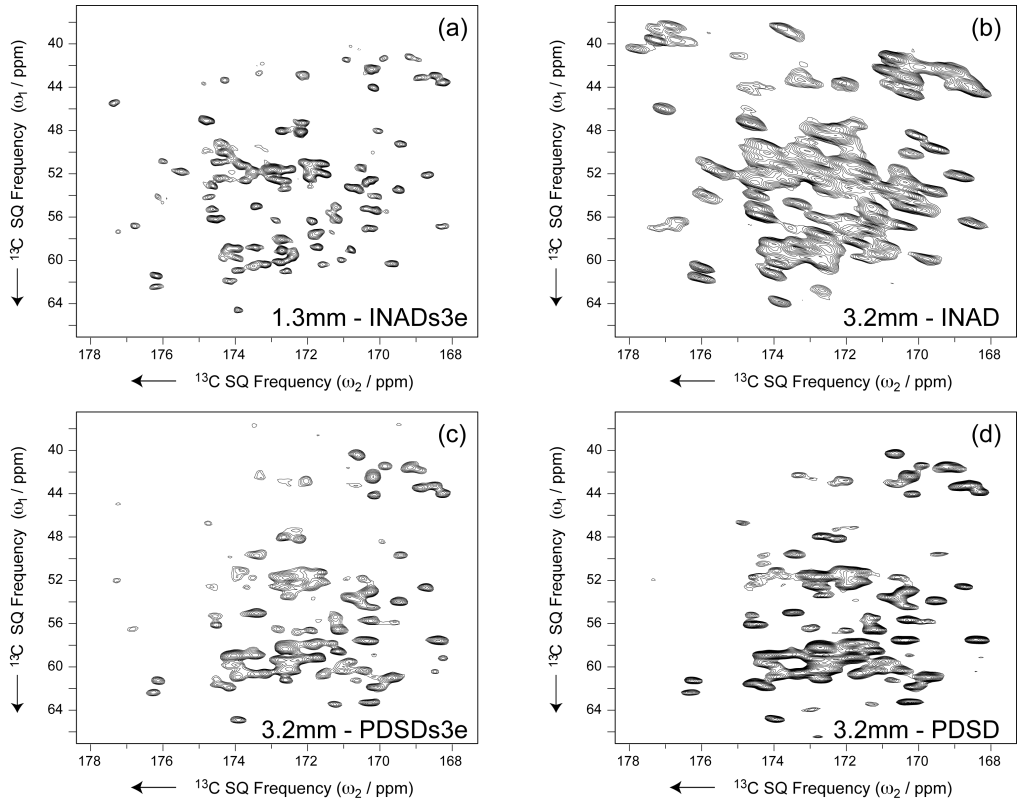

Figure S2: CO-Cα regions of two-dimensional carbon-carbon correlation spectra on microcrystalline, oxidized fully-^{13}C,^{15}N-Cu^{II},Zn^{II} SOD at 850 MHz. Sheared INADEQUATE spectra obtained with S^{3}E (a) and conventional (b) refocusing period, recorded respectively on a 1.3 mm rotor at 60 kHz MAS, and on a 3.2 mm rotor at 20 kHz MAS. PDSD spectra (20 ms mixing time) obtained with (c) and without (d) S^{3}E virtual decoupling. The spinning frequency was 10 kHz.

5. INADEQUATE-S^{3}E spectra of N,N-bis(diphenylphosphino)-N-((S)-α-methylbenzyl)amine

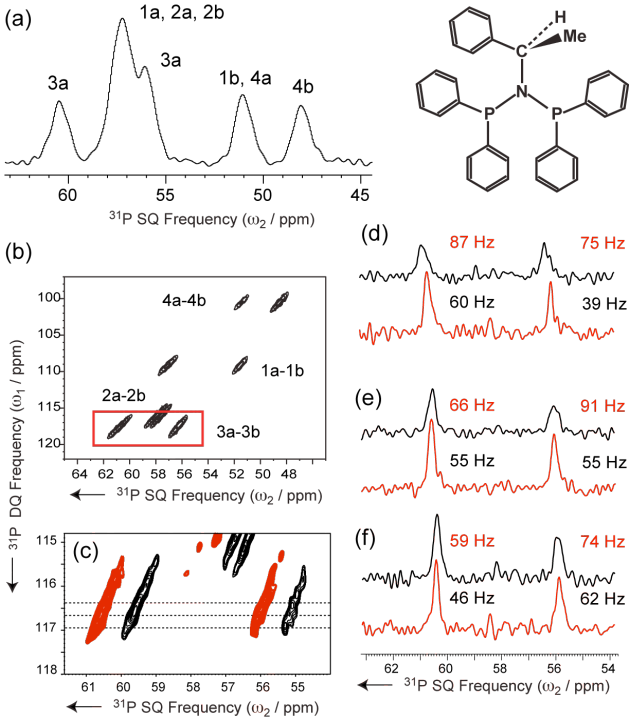

Figure S3: (a) ^{31}P-^{1}H CPMAS and (b) DQ refocused INADEQUATE spectra of N,N-bis(diphenylphosphino)-N-((S)-α-methylbenzyl)amine recorded at 11.7 T and at a MAS frequency of 20 kHz, under TPPM-15 ^{1}H decoupling at 140 kHz. (c) / (f) Comparisons between INADEQUATE spectra acquired using the conventional refocusing period (red) and the S^{3}E block (black) and a MAS frequency of 60 kHz.

6. INADEQUATE-S^{3}E and refocused INADEQUATE pulse schemes and phase cycles

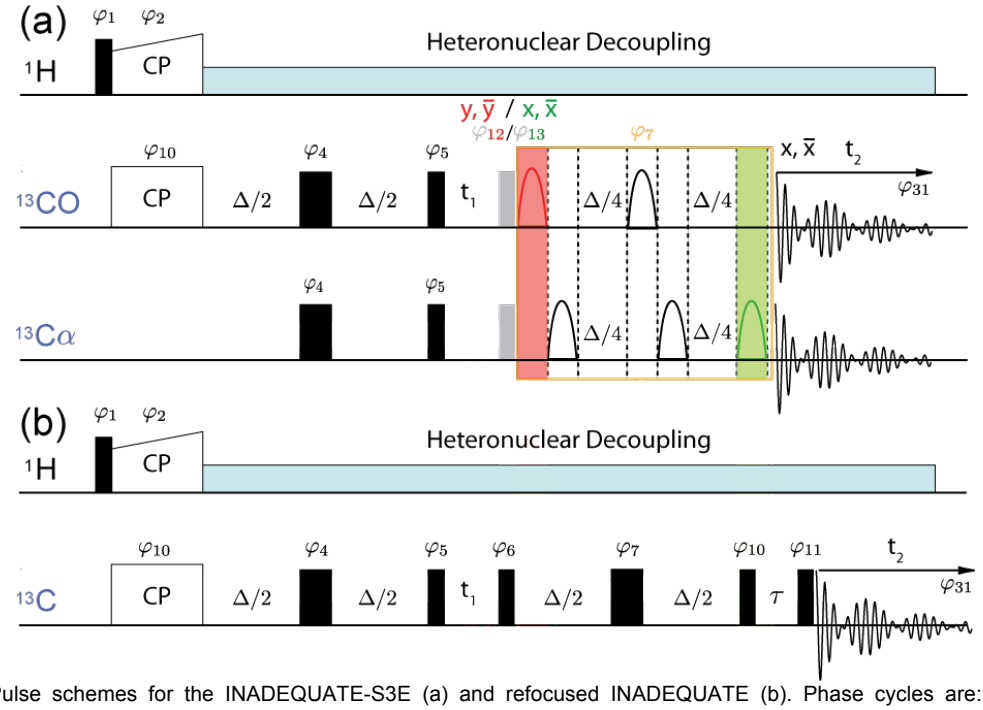

Figure S4: Pulse schemes for the INADEQUATE-S3E (a) and refocused INADEQUATE (b). Phase cycles are: (a) ϕ1={y,-y}; ϕ2={y,y,-x,-x,-y,-y,x,x}; ϕ4={x,x,y,y,-x,-x,-y,-y,-x,-x,-y,-y,x,x,y,y}; ϕ5={x,x,y,y,-x,-x,-y,-y}; ϕ7={x}; ϕ10={x}; ϕ12={y}*16, {-y}*16; ϕ13={x}*16, {-x}*16; ϕ31={x,-x,-x,x}*4, {-x,x,x,-x}*4; (b) ϕ1={y,-y}; ϕ2={y,y,-x,-x,-y,-y,x,x}; ϕ4={x,x,y,y,-x,-x,-y,-y,-x,-x,-y,-y,x,x,y,y}; ϕ5={x,x,y,y,-x,-x,-y,-y}; ϕ6={x}; ϕ7={y}*16,={-y}*16; ϕ10={x}; ϕ11={x}*32,={y}*32,={-x}*32,={-y}*32; ϕ31={x,-x,-x,x,x,-x,-x,x}*4,={y,-y,-y,y,y,-y,-y,y}*4,={-x,x,x,-x,-x,x,x,-x}*4,={-y,y,y,-y,-y,y,y,-y}*4.

7. References

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