

# High-Resolution Heteronuclear Correlation between Quadrupolar and Spin- $\frac{1}{2}$ Nuclei Using Multiple-Quantum Magic-Angle Spinning

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Heteronuclear correlation (HETCOR) NMR spectroscopy has been used in both liquid and solid states to provide information on the proximity of different nuclei in a complex spin system (1–5). In the solid state, the experiment is generally carried out under magic-angle-spinning (MAS) conditions, which average away the line broadening due to chemical-shift anisotropy and heteronuclear dipolar coupling (3). Although HETCOR experiments involving half-integer quadrupolar nuclei have been performed on certain systems (6, 7), the resolution in the quadrupolar dimension of a HETCOR spectrum is often poor since the second-order quadrupolar interaction is only partially averaged by MAS. Recently, Jarvie *et al.* (8) demonstrated that a high-resolution HETCOR spectrum could be obtained from a quadrupolar nucleus and a spin- $\frac{1}{2}$  nucleus by applying the principles of dynamic-angle spinning (9–11) (DAS), which averages the second-order quadrupolar interaction, but requires sample spinning at two different angles. The purpose of the current Communication is to present an alternative method of performing a high-resolution HETCOR experiment that requires sample spinning at only one angle. Our approach is based on the method recently described by Frydman and Harwood (12, 13) who exploited multiple-quantum coherence in conjunction with magic-angle spinning to obtain high-resolution spectra of quadrupolar nuclei.

In a simple HETCOR experiment (1–3) between two spin- $\frac{1}{2}$  nuclei, I and S, a  $\pi/2$  pulse is first applied to the I spins to bring the I-spin magnetization into the  $x$ - $y$  plane. The magnetization evolves under the I-spin Hamiltonian for a time  $t_1$ , and then is transferred through cross polarization to the S spins and detected. After two-dimensional Fourier transformation of the time-domain signal, cross peaks will appear between the resonances of dipolar-coupled nuclei. These yield information about the proximity of different chemical sites.

To achieve high resolution for quadrupolar nuclei in a HETCOR experiment, it is necessary to construct an isotropic  $t_1$  dimension. Until recently, this construction was only achieved by dynamic-angle spinning (8). A high-resolution HETCOR spectrum of sodium trimetaphosphate ( $\text{Na}_3\text{P}_3\text{O}_9$ ) was measured by applying appropriate RF pulses to  $^{23}\text{Na}$  while spinning the sample sequentially around angles of  $79.19^\circ$  and  $37.38^\circ$  with respect to the  $B_0$  field during  $t_1$ . The evolution times at the first and second angles were chosen such that an isotropic echo was formed at the end of the  $t_1$  evolution period. This magnetization was stored along  $B_0$  using a  $z$  filter and was subsequently transferred via cross polarization to  $^{31}\text{P}$  with the sample spinning at an angle of  $0^\circ$ . The  $^{31}\text{P}$  signal was then detected at the magic angle. While this experiment gives high resolution in both the  $^{23}\text{Na}$  and  $^{31}\text{P}$  dimensions, it requires three rotor-axis reorientations during each scan and therefore cannot be used to study nuclei with short  $T_1$  values, such as  $^{27}\text{Al}$  or  $^{11}\text{B}$ .

Recently, Frydman *et al.* (12) proposed an alternative approach for the removal of the second-order quadrupolar interaction (13, 14). This method is analogous to DAS in that an isotropic echo is generated by sequential manipulation of the Hamiltonian. However, in contrast to DAS, the sample in the MQMAS experiment is spun only at the magic angle, and the magnetization evolves sequentially under the triple-quantum Hamiltonian in the first part of  $t_1$  and under the single-quantum Hamiltonian during the second part. Judicious selection of the length of these two evolution periods generates an isotropic echo. To date, MQMAS has been used to study a number of materials and its advantages over DAS have been discussed (15–18). This Communication demonstrates that the MQMAS experiment combined with Hartmann–Hahn cross polarization (19, 20) can give a high-resolution HETCOR spectrum in which one of the dimensions is from a half-integer quadrupolar nucleus.

The pulse sequence, coherence-transfer pathway, and phase cycle for the pure-absorption-mode MQMAS/HETCOR experiment is shown in Fig. 1. As written, this

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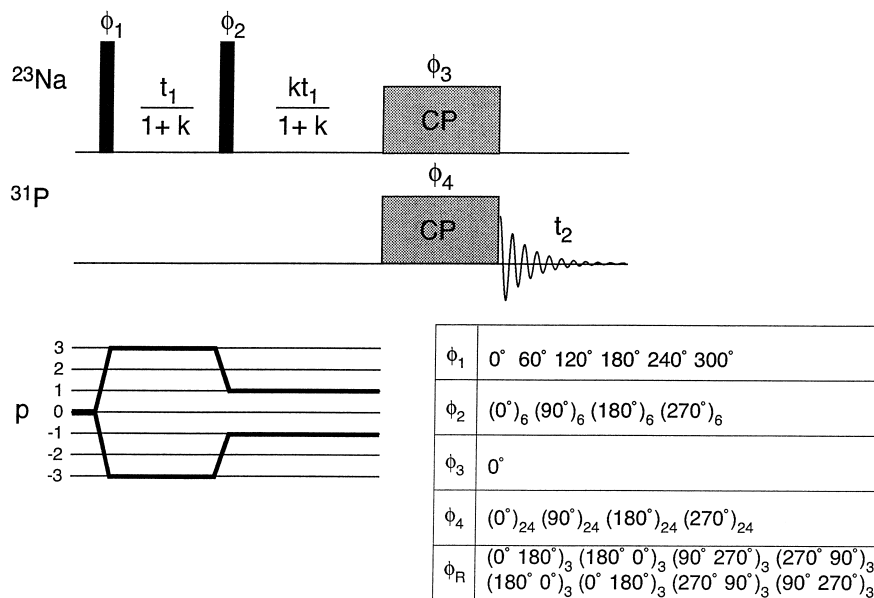


FIG. 1. Pulse sequence, coherence-transfer pathway, and phase cycle for MQMAS/HETCOR. “Mirror-image” coherence-transfer pathways are retained during the evolution-time period so that two-dimensional pure-absorption lineshapes can be obtained. The 96-step phase cycle incorporates CYCLOPS cycling and spin-temperature alternation. The second data set needed for States-type processing can be generated by shifting the phase of  $\phi_3$  by  $90^\circ$ .

sequence can be used for correlating a spin- $\frac{3}{2}$  nucleus to a spin- $\frac{1}{2}$  nucleus, although the same principles can be applied to construct analogous pulse sequences involving higher multiple-quantum coherences if other odd-half-integer quadrupolar nuclei are to be studied. The sequence in Fig. 1 shows that the evolution period,  $t_1$ , for the quadrupolar nucleus is divided into two parts: (i) evolution of the triple-quantum coherence for a time period  $t_1/(1+k)$ , and (ii) evolution of the single-quantum coherence for a time period  $kt_1/(1+k)$ . A single pulse is used for excitation of the triple-quantum coherence (14, 21) of the quadrupolar nucleus ( $^{23}\text{Na}$ ), and a second pulse converts the triple-quantum coherence into single-quantum coherence. The ratio,  $k$ , of the two portions of the evolution period is chosen in such a way that an isotropic echo is formed at the end of  $t_1$ ; for a spin- $\frac{3}{2}$  nucleus,  $k$  is equal to  $7/9$  (12). At the end of the evolution period, magnetization is transferred to the spin- $\frac{1}{2}$  nucleus ( $^{31}\text{P}$ ) by Hartmann–Hahn cross polarization, and then the  $^{31}\text{P}$  spectrum is recorded. The result is a heteronuclear correlation experiment acquired under MAS with high resolution in both dimensions.

The phase cycle shown in Fig. 1 enables the collection of pure-absorption-mode two-dimensional spectra by retaining a pair of “mirror-image” coherence-transfer pathways during the evolution period  $t_1$  (3). To obtain a pure-phase, two-dimensional spectrum with frequency discrimination in both dimensions, two amplitude-modulated data sets are collected and processed according to the method of States *et al.* (22). In our experiment, this second data set is generated by using

a phase cycle identical to that shown in Fig. 1 except with  $\phi_3 = 90^\circ$ . The 96-step phase cycle also incorporates CYCLOPS (23) and spin-temperature alternation (24).

The utility of the MQMAS/HETCOR experiment is demonstrated in Fig. 2 on a sample of  $\text{Na}_3\text{P}_3\text{O}_9$ , prepared ac-

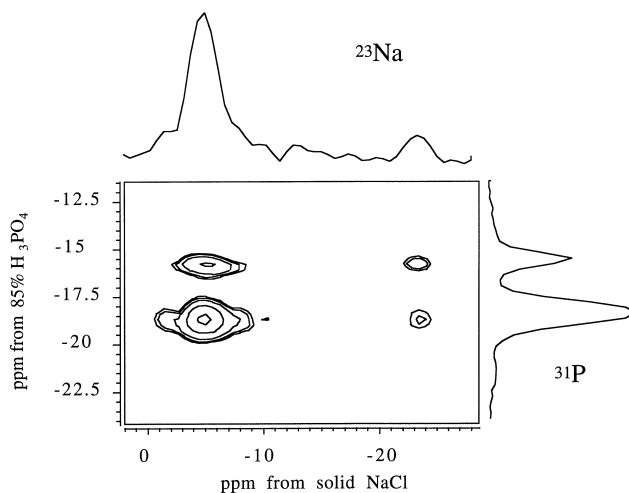


FIG. 2.  $^{23}\text{Na}/^{31}\text{P}$  MQMAS/HETCOR spectrum from  $\text{Na}_3\text{P}_3\text{O}_9$  recorded on a Chemagnetics CMX-500 spectrometer using a Chemagnetics probe that was double-tuned to 131.894 MHz for  $^{23}\text{Na}$  and 201.850 MHz for  $^{31}\text{P}$ . Each of the first two pulses was  $16 \mu\text{s}$ , corresponding to a  $3\pi$  rotation on the central transition of sodium (16). The cross-polarization contact time was 10 ms and the spinning speed was 5 kHz. Thirty-five complex  $t_1$  points consisting of 960 scans in each were collected with a recycle delay of 3 s.

ording to Jarvie *et al.* (8). The projections in each dimension show that two peaks are observed for each nucleus, corresponding to the crystallographically distinct sodium and phosphorus sites (25). The two phosphorus peaks are at  $-18.7$  and  $-15.5$  ppm with respect to 85%  $\text{H}_3\text{P}_3\text{O}_4$  at 0 ppm, and the two peaks in the  $^{23}\text{Na}$  spectrum are at  $-6.2$  and  $-22.1$  ppm with respect to solid  $\text{NaCl}$  at 0 ppm. The positions of these peaks agree, within experimental error, with the values of  $C_q$ ,  $\eta$ , and the isotropic chemical shifts given by Koller *et al.* (26). However, the isotropic chemical shifts are slightly different from those determined from DAS by Jarvie *et al.* (8). The 2-D MQMAS/HETCOR spectrum shows four distinct cross peaks between the two  $^{31}\text{P}$  and two  $^{23}\text{Na}$  resonances. Correlation between the two nuclei is principally through dipolar coupling, which results from both sodium sites being in close proximity to both phosphorus sites. As in the DAS experiment, the measured intensities of the cross peaks in this new experiment may not yet be considered quantitative. In our experiment, this discrepancy arises from a combination of two factors. First, as discussed by Vega (27), cross-polarization dynamics of quadrupolar nuclei are complicated under magic-angle-spinning conditions by the time dependence of the first-order quadrupolar interaction that interferes with the spin locking of the quadrupolar nucleus. De Paul *et al.* (28) have shown that, even for a known spinning speed and quadrupolar coupling constant, intensities in a 1D CPMAS experiment involving quadrupolar nuclei cannot always be predicted. However, this is not true for the DAS HETCOR experiment as polarization transfer occurs at  $0^\circ$  to  $B_0$ , and therefore the nonspinning CP intensity can be achieved. The second factor that complicates the quantification of the MQMAS HETCOR experiment is that both the excitation of the triple-quantum coherence and its conversion back to single-quantum coherence depend strongly upon the RF excitation power and the quadrupolar parameters (29). Simulations and measurements for the 3Q/1Q experiment, using the same conditions as for the MAS HETCOR experiment, show that the site with the greater  $C_q$  has one-quarter of the intensity of the other site, despite the fact that its population is one-half that of the other site. Modifications of the original MQMAS experiment to make the intensities more quantitative have been proposed by Griffin *et al.* (30). We are currently investigating these modifications, as well as trying to understand the cross-polarization dynamics of this sample.

The advantage of combining the MQMAS experiment with the HETCOR experiment is immediately obvious when Fig. 2 is compared with a regular HETCOR spectrum for the  $\text{Na}_3\text{P}_3\text{O}_9$  (Fig. 3). Although the second-order quadrupolar interaction has not been completely averaged, the  $^{23}\text{Na}$  dimension for this sample still exhibits relatively high resolution because of the significant difference in chemical-shift,  $C_q$ , and  $\eta$  parameters between the two sites. However, even for this ideal case, it is clear that the MQMAS/HETCOR

experiment gives superior resolution. For a more complex system where the  $^{23}\text{Na}$  dimension is not so well resolved, such as sodium phosphate glasses, our MQMAS/HETCOR experiment should be of significant utility.

In principle, our heteronuclear correlation experiment could be applied in reverse, transferring the magnetization from  $^{31}\text{P}$  to  $^{23}\text{Na}$ , and then performing the 3Q/1Q MQMAS experiment to obtain high resolution in the  $^{23}\text{Na}$  dimension. However, performing the experiment in this way has two major drawbacks. The first is that the experiment would become a three-dimensional experiment, increasing the time required to collect the data. The second disadvantage is that the  $T_1$  of sodium is typically much shorter than that of phosphorus. For example, in  $\text{Na}_3\text{P}_3\text{O}_9$ , the delay between scans necessary to prevent significant saturation of the signal is 3 s for  $^{23}\text{Na}$  and 600 s for  $^{31}\text{P}$ ; thus, performing cross polarization from  $^{31}\text{P}$  to  $^{23}\text{Na}$  would increase the experimental time prohibitively.

Although cross polarization is less efficient for samples spun at the magic angle than for samples spun at an angle of  $0^\circ$  with respect to the static field (31), the MQMAS/HETCOR experiment has several advantages compared to the DAS version. The main advantage is that high-resolution HETCOR spectra may be obtained from quadrupolar nuclei using a conventional MAS NMR probe. Our experiments were performed using an unmodified Chemagnetics probe with a 7.5 mm rotor and an RF field strength of only 42 kHz for the multiple-quantum coherence excitation. As double-resonance MAS probes are available in most solid-state NMR laboratories, this simplification will enable this experiment to be widely applied. In contrast, the DAS/HETCOR experiment (8) requires a static coil dynamic-angle spinning probe that is capable of cross polarization at  $0^\circ$  with respect to  $B_0$  (32, 33); such probes are currently not commercially available.

A second advantage of the MQMAS/HETCOR experiment is that, potentially, the resolution of the  $^{23}\text{Na}$  dimension will be greater than that observed in the DAS/HETCOR experiment, hence increasing the possibility of separating signals from sites with similar chemical environments (18). This arises from scaling of the chemical and quadrupolar shifts in the MQMAS experiment by  $17/8$  and  $-5/4$ , respectively, which occurs due to the creation of triple-quantum coherence in a spin- $\frac{3}{2}$  nucleus. It has been demonstrated (34) that the peak positions may be calculated from the values of  $C_q$ ,  $\eta$ , the Larmor frequency, and the isotropic chemical shift. For example,  $^{23}\text{Na}$  shifts in a DAS/HETCOR spectrum of  $\text{Na}_3\text{P}_3\text{O}_9$  at 11.7 T would be expected to occur at  $-9.1$  and  $-23.0$  ppm, whereas the corresponding shifts in the 3Q/1Q MQMAS experiment are at  $-6.2$  and  $-22.1$  ppm, thus increasing the dispersion by 2.0 ppm.

A third advantage of the MQMAS/HETCOR experiment, and the most important for its application to a wide variety of materials, is that samples with short  $T_1$  values may be

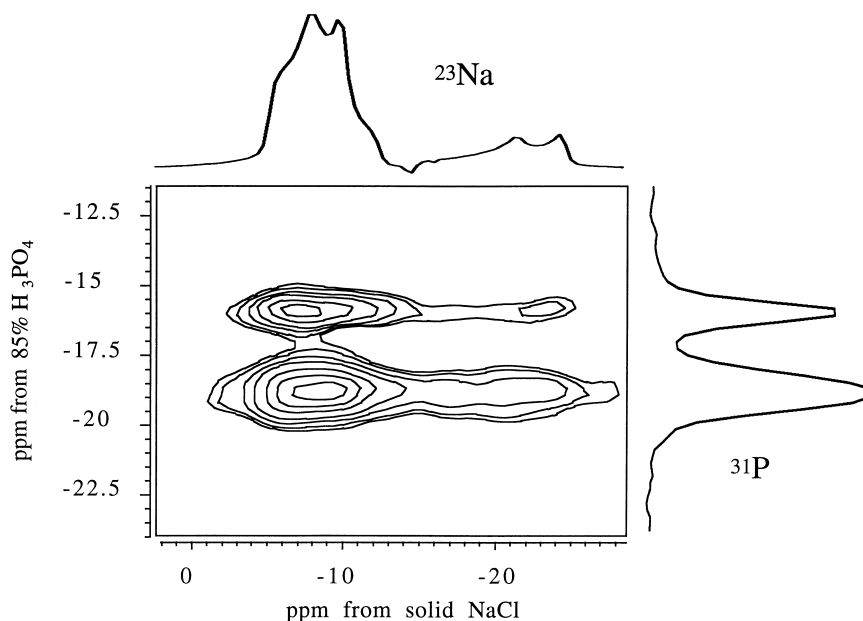


FIG. 3. A conventional two-dimensional  $^{23}\text{Na}/^{31}\text{P}$  HETCOR spectrum of  $\text{Na}_3\text{P}_3\text{O}_9$  collected using the same probe and spectrometer as described in the legend to Fig. 2. Experimental conditions that closely mimicked the MQMAS/HETCOR experiment were used so that the two methods could be compared directly. A  $90^\circ$  pulse length of  $27 \mu\text{s}$  for  $^{23}\text{Na}$  was used for optimal signal-to-noise, the cross-polarization contact time was 10 ms, and the spinning speed was 5 kHz. Thirty-two complex  $t_1$  points consisting of 256 scans were collected with a recycle delay of 3 s. Both resonances are broadened by the anisotropic second-order quadrupolar interaction, which cannot be removed purely by MAS.

investigated. DAS/HETCOR is limited to samples where  $T_1$  is greater than about 150 ms, as the time required to flip the spinning axis is about 40 ms, and the experiment requires three sample reorientations. This has previously excluded the study of many  $^{27}\text{Al}$  and  $^{11}\text{B}$  systems. We are currently investigating the feasibility of using the MQMAS/HETCOR experiment to study such systems, for example, the connectivity between Al and P in aluminophosphates. Also, the viability of performing a MQMAS/HETCOR experiment based on  $J$  couplings is under investigation.

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