

Signs of Frequencies and Phases in NMR: The Role of Radiofrequency Mixing

Malcolm H. Levitt and Ole G. Johannessen

Physical Chemistry Division, Stockholm University, S-10691 Stockholm, Sweden

Received July 20, 1999; accepted September 3, 1999

This article analyzes the influence of the radiofrequency mixing scheme on the sign of phase shifts experienced by the nuclear spins. It is an addendum to a previous article on the signs of phases and frequencies in NMR (M. H. Levitt, *J. Magn. Reson.* **126, 164 (1997)).** © 2000 Academic Press

Key Words: radiofrequency phases; signs of phases; phase cycling.

INTRODUCTION

In a previous paper (1), one of us discussed the signs of phases and frequencies involved in NMR experiments. It was argued that one must take into account the sense of the nuclear spin precession around the static field when predicting the effect of radiofrequency phase shifts. A set of recommendations was given for facilitating the correspondence between the spectrometer operation, the spectral presentation, and the microscopic dynamics of the nuclear spins. Several papers have appeared implementing all or some of these recommendations (2–16).

Since the publication of Ref. (1), it has become apparent that the *radiofrequency mixing scheme* in the spectrometer adds a further level of complexity. In some circumstances, the radiofrequency generation scheme in the spectrometer console introduces further sign changes of the radiofrequency phases. To make matters even more complicated, the spectrometer manufacturers have partially corrected these sign changes with software. This partial software correction must be disentangled in order to treat the problem in full.

DISCUSSION

The Carrier Wave and Radiofrequency (RF) Pulses

Consider an NMR experiment on a set of nuclear spins with Larmor frequency ω_0 defined by

$$\omega_0 = -\gamma B_0, \quad [1]$$

where γ is the magnetogyric ratio and B_0 is the static magnetic field. The nuclear spins are exposed to a radiofrequency field derived from a carrier wave of frequency ω_{carrier} . In order to influence the spins, the absolute frequency of the carrier wave must be close to the absolute nuclear Larmor frequency:

$$|\omega_{\text{carrier}}| \cong |\omega_0|. \quad [2]$$

As discussed in Ref. (1), the phase of the resonant component of the RF field depends on the relative signs of the frequencies ω_0 and ω_{carrier} . This potential sign change must be taken into account for a rigorous treatment of the nuclear spin dynamics.

On most spectrometers, the carrier wave is derived from a radiofrequency signal generated by a RF synthesizer, which is under software control. However, the synthesizer wave is usually subjected to one or more frequency conversion steps in order to obtain the carrier wave. These frequency conversion steps may introduce further sign changes in the RF phases.

Suppose that the radiofrequency synthesizer generates a wave described by the equation

$$s_{\text{synth}}(t) = \cos(|\omega_{\text{synth}}|t + \psi_{\text{synth}}), \quad [3]$$

where $|\omega_{\text{synth}}|$ is the (positive) angular frequency of the synthesizer, and ψ_{synth} is the phase of the synthesizer wave. Consider a single-stage mixing scenario, in which an idealized double-balanced mixer is used to multiply the synthesizer wave by a “local oscillator” signal s_{LO} with a frequency $|\omega_{\text{LO}}|$,

$$s_{\text{LO}}(t) = \cos(|\omega_{\text{LO}}|t). \quad [4]$$

The output of the idealized mixer contains two signal components, with frequencies $|\omega_{\text{LO}}| + |\omega_{\text{synth}}|$ and $|\omega_{\text{LO}}| - |\omega_{\text{synth}}|$, as is easily seen from the trigonometric identities

$$\begin{aligned} s_{\text{synth}}(t)s_{\text{LO}}(t) &= \cos(|\omega_{\text{synth}}|t + \psi_{\text{synth}})\cos(|\omega_{\text{LO}}|t) \\ &= \frac{1}{2} \cos(\omega_{\text{sum}}t + \psi_{\text{synth}}) \\ &\quad + \frac{1}{2} \cos(\omega_{\text{diff}}t - \psi_{\text{synth}}), \end{aligned} \quad [5]$$

where

$$\begin{aligned} \omega_{\text{sum}} &= |\omega_{\text{LO}}| + |\omega_{\text{synth}}| \\ \omega_{\text{diff}} &= |\omega_{\text{LO}}| - |\omega_{\text{synth}}|. \end{aligned} \quad [6]$$

The output of the mixer is filtered in order to obtain either the sum frequency ω_{sum} or the difference frequency ω_{diff} , depending on which of these is close in magnitude to the Larmor frequency:

$$\begin{aligned} \text{if } |\omega_0| &\cong |\omega_{\text{LO}}| + |\omega_{\text{synth}}| && \text{then } \omega_{\text{carrier}} = \omega_{\text{sum}} \\ \text{if } |\omega_0| &\cong |\omega_{\text{LO}}| - |\omega_{\text{synth}}| && \text{then } \omega_{\text{carrier}} = \omega_{\text{diff}} \\ \text{if } |\omega_0| &\cong |\omega_{\text{synth}}| - |\omega_{\text{LO}}| && \text{then } \omega_{\text{carrier}} = -\omega_{\text{diff}}. \end{aligned} \quad [7]$$

Clearly, the relationship between the synthesizer phase ψ_{synth} and the carrier phase ψ_{carrier} depends on which wave is selected and also on whether $|\omega_{\text{LO}}|$ is larger or smaller than $|\omega_{\text{synth}}|$:

$$\begin{aligned} \text{if } |\omega_0| &\cong |\omega_{\text{LO}}| + |\omega_{\text{synth}}| && \text{then } \psi_{\text{carrier}} = +\psi_{\text{synth}} \\ \text{if } |\omega_0| &\cong |\omega_{\text{LO}}| - |\omega_{\text{synth}}| && \text{then } \psi_{\text{carrier}} = -\psi_{\text{synth}} \\ \text{if } |\omega_0| &\cong |\omega_{\text{synth}}| - |\omega_{\text{LO}}| && \text{then } \psi_{\text{carrier}} = +\psi_{\text{synth}}. \end{aligned} \quad [8]$$

In this article, the cases with $\psi_{\text{carrier}} = +\psi_{\text{synth}}$ are referred to as “up-mixing,” while the cases with $\psi_{\text{carrier}} = -\psi_{\text{synth}}$ are referred to as “down-mixing” (these definitions differ slightly from usual electronic practice, which does not take into account the signs of the frequencies). In general, the mixing scheme, and hence the relationship between the synthesizer and carrier phases, differs from instrument to instrument and also differs from channel to channel in the same instrument.

A real mixer generates many other harmonics and combination frequencies. However, in practice these are suppressed by radiofrequency filtering and may be ignored for the purpose of this discussion.

In general, there may be several frequency conversion stages between the RF synthesizer and the RF carrier. Each of these stages may invert the RF phase.

In Ref. (1), the following statement was made: “On current spectrometers, the pulse program software allows direct control of the phase ψ_{carrier} .” In retrospect, this statement is misleading. In fact, the pulse program software allows control of the phase ψ_{synth} . The relationship of ψ_{synth} and ψ_{carrier} depends upon the radiofrequency mixing scheme.

As discussed in Ref. (1), the phase of the spin nutation axis during a RF pulse, which is of relevance to the spin dynamics, is related to the carrier phase according to

$$\phi_{\text{pulse}} = -(\text{sign } \gamma) \psi_{\text{carrier}}^{\text{pulse}}. \quad [9]$$

The effect of the RF mixing scheme may now be included as well:

$$\begin{aligned} \phi_{\text{pulse}} &= -(\text{sign } \gamma) \psi_{\text{synth}}^{\text{pulse}} && \text{for up-mixing} \\ \phi_{\text{pulse}} &= +(\text{sign } \gamma) \psi_{\text{synth}}^{\text{pulse}} && \text{for down-mixing.} \end{aligned} \quad [10]$$

There are therefore at least two potential sign changes intervening between the programmed synthesizer phases ψ_{synth} and the spin dynamical phases ϕ .

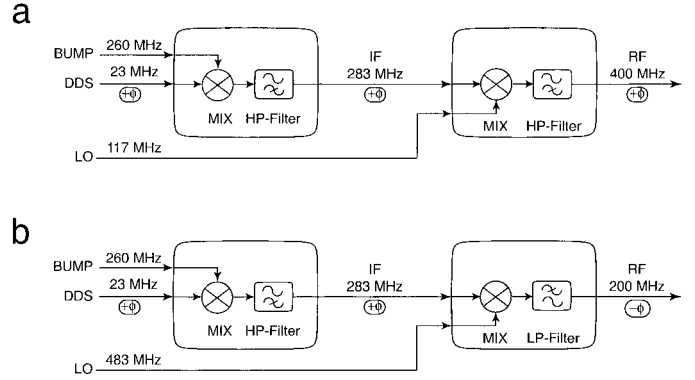


FIG. 1. Radiofrequency mixing schemes for RF pulse generation on the Chemagnetics Infinity-200 and Infinity-400 consoles. The boxes contain double-balanced mixers followed by radiofrequency filters. (a) A carrier frequency of 400 MHz is derived by first combining a 23-MHz DDS signal with a 260-MHz “BUMP” signal in order to obtain a 283-MHz intermediate-frequency signal, which is then combined with a 117-MHz local oscillator signal. The phase of the DDS signal is preserved. (b) A carrier frequency of 200 MHz is derived by combining the 283-MHz intermediate-frequency signal with a 483-MHz local oscillator signal. The phase of the DDS signal is inverted.

To make this clearer, consider the specific mixing schemes shown schematically in Fig. 1, which apply to the Chemagnetics CMX Infinity-200 and Infinity-400 consoles (produced by Varian Instruments, Palo Alto, CA). In both of these systems, a direct digital synthesizer (DDS) generates a 23-MHz wave whose phase is under control of the pulse programming device. This signal is mixed with a constant 260-MHz “BUMP” frequency signal and filtered, in order to obtain a 283-MHz intermediate-frequency (IF) signal. This up-mixing process conserves the phase of the DDS signal. The phase of the 283-MHz IF signal is therefore the same as that written in the pulse program.

The IF signal is subjected to a second mixing stage in order to obtain the carrier signal. Fig. 1a shows the case of a 400-MHz carrier frequency. A local oscillator signal with frequency 117 MHz is combined with the 283-MHz IF signal and passed through a high-pass filter in order to obtain the 400-MHz carrier wave. This second up-mixing scenario also preserves the phase of the IF signal. The phase of the carrier is therefore the same as the phase of the RF synthesizer: $\psi_{\text{carrier}} = +\psi_{\text{synth}}$.

Figure 1b shows the situation when the carrier frequency is equal to 200 MHz. This time, a local oscillator frequency of 483 MHz is chosen. The local oscillator signal is mixed with the 283-MHz IF signal and passed through a low-pass filter in order to obtain the 200-MHz carrier signal. This a down-mixing scenario so the phase of the carrier is opposite to the phase of the RF synthesizer: $\psi_{\text{carrier}} = -\psi_{\text{synth}}$.

In general, on the Chemagnetics CMX Infinity-200 and Infinity-400 consoles, all carrier frequencies above 283 MHz employ up-mixing and preserve the phase of the RF synthesizer, while all carrier frequencies below 283 MHz employ down-mixing and invert the phase of the RF synthesizer.

The consequences for the specific spectrometers are as follows. On the Chemagnetics CMX Infinity-200 console (magnetic field 4.7 T), the radiofrequency carrier waves for all nuclei are derived by down-mixing. This implies that the carrier phase is always opposite in sign to the synthesizer phase, as controlled by the pulse programmer. For positive- γ nuclei, such as ^1H and ^{13}C , this sign change is cancelled out by a second sign change associated with the negative sense of the Larmor precession (Eq. [9]). As a result, for positive- γ nuclei, on the CMX-200 console, the nutation axis phases are identical to the phases written in the pulse program. If an “ x -pulse” corresponds to a synthesizer phase of $\psi_{\text{synth}}^{\text{pulse}} = 0$, then a “ y -pulse” corresponds to a synthesizer phase of $\psi_{\text{synth}}^{\text{pulse}} = +\pi/2$. For negative- γ nuclei, on the other hand, the pulse program phases are opposite in sign to the nutation axis phases used in spin dynamical calculations. For these nuclei, if an x -pulse corresponds to a synthesizer phase of $\psi_{\text{synth}}^{\text{pulse}} = 0$, then a y -pulse corresponds to a synthesizer phase of $\psi_{\text{synth}}^{\text{pulse}} = -\pi/2$.

The situation is identical for the Chemagnetics CMX Infinity-400 console (magnetic field 9.4 T), except for the two nuclei ^1H and ^{19}F , whose Larmor frequencies are greater in magnitude than 283 MHz. In these cases, the carrier waves are generated by up-mixing. Since γ is positive for both of these nuclei, the pulse program phases are opposite in sign to the nutation axis phases of relevance for spin dynamical calculations.

Similar reasoning may be followed for any spectrometer console, if a detailed examination of the radiofrequency mixing path is used to unravel the relationship between the spin nutation phases and the pulse program phases.

It is also possible to determine empirically the sense of the RF phases by performing simple NMR experiments, as described in Ref. (1).

Signal Detection and Digitization

In the simplest quadrature detection scheme (described in (1)), the NMR signal (FID) emerging from the signal preamplifier enters the quadrature receiver. The quadrature receiver compares the NMR signal with a carrier wave signal, which is derived from the RF synthesizer wave by the same signal mixing process as used for the RF pulses. The phase of the RF synthesizer $\psi_{\text{synth}}^{\text{rec}}$ during signal detection is under software control (17). The quadrature receiver has two outputs, which are digitized using parallel analog–digital converters (ADCs). The complex NMR signal emerging from the quadrature digitizers is multiplied by the factor $\exp\{i\psi_{\text{postdig}}\}$, where ψ_{postdig} is called the postdigitization phase shift (17). (As described in Ref. (1), this complex multiplication is usually implemented by a combination of channel swapping and sign inversion operations). The product of the digitized complex NMR signal and the postdigitization phase factor is transmitted to the computer for signal accumulation and subsequent processing.

Radiofrequency receiver phase. In the simplest quadrature detection scenario, the RF receiver phase and the pulse phases

are derived from the same radiofrequency carrier wave. As a result, the RF mixing scheme has the same effect on both. The relationship between the RF synthesizer phase $\psi_{\text{synth}}^{\text{rec}}$ and the carrier phase $\psi_{\text{carrier}}^{\text{rec}}$ during signal reception is

$$\begin{aligned}\psi_{\text{carrier}}^{\text{rec}} &= +\psi_{\text{synth}}^{\text{rec}} && \text{for up-mixing} \\ \psi_{\text{carrier}}^{\text{rec}} &= -\psi_{\text{synth}}^{\text{rec}} && \text{for down-mixing.}\end{aligned}\quad [11]$$

In Ref. (1), it was recommended that spin dynamical calculations employ a “ γ -sensitive” receiver phase ϕ_{rec} , defined as

$$\phi_{\text{rec}} = -(\text{sign}\gamma)\psi_{\text{carrier}}^{\text{rec}}. \quad [12]$$

This recommendation allows the receiver phase and the pulse phase to be treated in the same way, independent of the sign of γ .

The RF mixing scheme must now be taken into account. From Eq. [11], the receiver phase ϕ_{rec} , as used in spin dynamical calculations, is linked to the RF synthesizer phase during signal acquisition, as specified in standard pulse programs, through

$$\begin{aligned}\phi_{\text{rec}} &= -(\text{sign}\gamma)\psi_{\text{synth}}^{\text{rec}} && \text{for up-mixing} \\ \phi_{\text{rec}} &= +(\text{sign}\gamma)\psi_{\text{synth}}^{\text{rec}} && \text{for down-mixing,}\end{aligned}\quad [13]$$

which is exactly analogous to Eq. [10]. Not surprisingly, the pulse phase and the receiver phase behave in exactly the same way.

For technical reasons, most NMR spectrometers use a detection RF mixing scheme which is more complicated than this. For example, on the Chemagnetics Infinity-200 and Infinity-400 consoles, the NMR signal is mixed down to a complex audio signal in two stages. First, the NMR signal, which oscillates at the Larmor frequency, is mixed with the local oscillator frequency and filtered in order to obtain a 283-MHz intermediate-frequency signal. This requires up-mixing for NMR signals with frequencies greater than 283 MHz and down-mixing for NMR signals with frequencies lower than 283 MHz. The 283-MHz frequency-converted NMR signal is passed into the quadrature receiver which is also supplied with a 283-MHz intermediate-frequency reference signal. The IF reference signal is in turn derived from the 23-MHz DDS signal, whose phase may be controlled from the pulse program, as described before.

The technical arguments will not be given here, but it may be shown that this two-stage mixing scheme leads to the same dependence of the detected signal phase on the synthesizer phase as for the single-stage detection scenario, Eq. [13].

Other spectrometer consoles use different mixing schemes for the detection of RF signals. However, the conclusions are unchanged.

Postdigitization phase. At first sight, the postdigitization phase appears to behave differently, since it is not a radiofrequency phase and should be independent of the radiofrequency mixing scheme. However, in practice, there is an additional complication. The spectrometer manufacturers have introduced a hidden software switch which changes the sign of ψ_{postdig} , depending on the sense of the RF mixing scheme! The implementation on current commercial spectrometers is

$$\begin{aligned}\psi_{\text{postdig}} &= +\psi_{\text{postdig}}^{\text{soft}} \quad \text{for up-mixing} \\ \psi_{\text{postdig}} &= -\psi_{\text{postdig}}^{\text{soft}} \quad \text{for down-mixing.} \quad [14]\end{aligned}$$

Here $\psi_{\text{postdig}}^{\text{soft}}$ is the value written in the pulse program, while ψ_{postdig} is the value actually used for the factor $\exp\{i\psi_{\text{postdig}}\}$ applied to the outputs of the ADCs.

For example, on the Chemagnetics CMX Infinity-200 and Infinity-400 consoles, the down-mixing switch is activated whenever the requested carrier frequency is greater than 283 MHz.

The manufacturers have implemented this switch for a very simple reason: without it, the NMR signals cancel out under phase cycling for the case of down-mixing. Nevertheless, the implementation chosen muddies the issue further. It would be more logical to correct the phase of the RF signals “at source,” rather than when the NMR signals are digitized.

Because of this “fix,” it is necessary to take into account the RF mixing scheme when implementing a postdigitization phase shift, as well as when implementing a radiofrequency phase shift. In Ref. (1), it was recommended that spin dynamical calculations use a γ -sensitive postdigitization phase ϕ_{postdig} , defined as

$$\phi_{\text{postdig}} = -(\text{sign}\gamma)\psi_{\text{postdig}}. \quad [15]$$

The relationship between the programmed postdigitization phase $\psi_{\text{postdig}}^{\text{soft}}$ and the γ -sensitive postdigitization phase is therefore

$$\begin{aligned}\phi_{\text{postdig}} &= -(\text{sign}\gamma)\psi_{\text{postdig}}^{\text{soft}} \quad \text{for up-mixing} \\ \phi_{\text{postdig}} &= +(\text{sign}\gamma)\psi_{\text{postdig}}^{\text{soft}} \quad \text{for down-mixing,} \quad [16]\end{aligned}$$

which is again analogous to Eqs. [10] and [13].

With these definitions, all phases ϕ may be treated in exactly the same way, independent of the sign of γ and the RF mixing scheme. If an x -pulse is generated by a pulse of phase $\phi_{\text{pulse}} = 0$, then a y -pulse is always generated by a pulse of phase $\phi_{\text{pulse}} = \pi/2$. Phase cycles may be implemented without explicit regard for the sign of γ or the details of the console. For example, in a simple one-pulse experiment, quadrature artifacts generated by imbalance of the receiver channels may be suppressed by incrementing the pulse phase ϕ_{pulse} and the postdigitization phase ϕ_{postdig} synchronously, in steps of $\pi/2$, while the RF receiver phase ϕ_{rec} is kept fixed.

CONCLUSIONS

Recommended Practice on Current Instruments

Current instruments (as of 1999) take no account of the sign of the Larmor precession, but have partially corrected for the sense of the radiofrequency mixing scheme by manipulating the postdigitization phase shift of the signals as they emerge from the analog–digital converters.

The spectrometer user must therefore take into account the sense of both the Larmor precession and the RF mixing scheme in order to rotate the nuclear spins around the desired axes in the rotating frame.

In current instruments, the relationship between the meaningful “spin dynamic phases” and the “pulse program phases” is

$$\begin{aligned}\gamma > 0 \text{ and up-mixing} &\Rightarrow \text{reverse all phases} \\ \gamma > 0 \text{ and down-mixing} &\Rightarrow \text{no phase reversal} \\ \gamma < 0 \text{ and up-mixing} &\Rightarrow \text{no phase reversal} \\ \gamma < 0 \text{ and down-mixing} &\Rightarrow \text{reverse all phases.} \quad [17]\end{aligned}$$

The term “all phases” refers to all radiofrequency phases as written in the pulse program, as well as the postdigitization phase as written in the pulse program (i.e., before this phase is manipulated by the internal spectrometer software).

To the best of our knowledge, these relationships apply to all current commercial NMR instruments (as of 1999).

Recommendations for Future Instruments

These tedious (and essential trivial) issues could be avoided by simple software modification. Recommendations 1 to 3 of Ref. (1) are now revised to read

Recommendation 1: A software flag for the sign of the magnetogyric ratio. The software should require that the spectrometer operator sets a flag for the sign of γ of the spins under observation.

Recommendation 2: Radiofrequency phases should take into account the radiofrequency mixing scheme as well as the sign of γ . The spin dynamical phases ϕ are written in pulse programs. The software translates these instructions into code for the RF synthesizer, taking into account the sign of γ and the radiofrequency mixing scheme used to generate the carrier wave. The sign of the phases is inverted if (i) γ is positive and up-mixing is employed, or if (ii) γ is negative and down-mixing is employed.

The radiofrequency receiver reference phase ϕ_{rec} is handled in identical fashion.

Recommendation 3: The postdigitization phase shift should take into account the sign of γ . The postdigitization phase shift implemented at the output of the ADCs should take into account the sign of γ . The sign of the postdigitization phase shift is inverted if γ is positive.

The postdigitization phase shift should *not* depend on the sense of the radiofrequency mixing scheme.

The other recommendations in Ref. (1) still stand.

These recommendations allow all phases to be programmed on the instrument exactly as they appear in spin dynamical calculations, avoiding the need for implementing Eq. [17] manually. We hope that future spectrometer generations will render this article and the previous one obsolete by implementing these recommendations "invisible" in the software.

ACKNOWLEDGMENTS

This research has been supported by the Swedish Natural Science Research Foundation and the Göran Gustafsson Foundation for Research in the Natural Sciences and Medicine. We would like to thank Chuck Bronnimann for information on the Chemagnetics consoles.

REFERENCES

1. M. H. Levitt, The signs of frequencies and phases in NMR, *J. Magn. Reson.* **126**, 164–182 (1997).
2. T. Karlsson and M. H. Levitt, Longitudinal rotational resonance echoes in solid state NMR: Investigation of zero quantum spin dynamics, *J. Chem. Phys.* **109**, 5493–5507 (1998).
3. T. Karlsson, A. Brinkmann, P. J. E. Verdegem, J. Lugtenburg, and M. H. Levitt, Multiple-quantum relaxation in the magic-angle-spinning NMR of $^{13}\text{C}_2$ spin pairs, *Sol. State Nucl. Magn. Reson.* **14**, 43–58 (1999).
4. M. Edén and M. H. Levitt, Pulse sequence symmetries in the NMR of spinning solids. Application to heteronuclear decoupling, *J. Chem. Phys.* **111**, 1511–1519 (1999).
5. O. N. Antzutkin, Y. K. Lee, and M. H. Levitt, ^{13}C and ^{15}N chemical shift anisotropy of ampicillin and penicillin-V studied by 2D-PASS and CP-MAS NMR, *J. Magn. Reson.* **135**, 144–155 (1998).
6. P. Andersson, A. Annala, and G. Otting, An α/β -HSQC- α/β experiment for spin-state selective editing of IS cross peaks, *J. Magn. Reson.* **133**, 364–367 (1998).
7. G. Otting, L. P. Soler, and B. A. Messerle, Measurement of magnitude and sign of heteronuclear coupling constants in transition metal complexes, *J. Magn. Reson.* **137**, 413–429 (1999).
8. K. V. Pervushin, R. Riek, G. Wider, and K. Wüthrich, Attenuated T-2 relaxation by mutual cancellation of dipole-dipole coupling and chemical shift anisotropy indicates an avenue to NMR structures of very large biological macromolecules in solution, *Proc. Natl. Acad. Sci. USA* **94**, 12366–12371 (1997).
9. K. V. Pervushin, G. Wider, and K. Wüthrich, Single transition-to-single transition polarization transfer (ST2-PT) in [N-15, H-1]-TROSY, *J. Biomol. NMR* **12**, 345–348 (1998).
10. C. Marichal and A. Sebald, Anisotropy of $^2J(^{119}\text{Sn}-^{117}\text{Sn})$ determined by off-magic-angle spinning ^{119}Sn NMR, *Chem. Phys. Lett.* **286**, 298–304 (1998).
11. S. Dusold, W. Milius, and A. Sebald, Iterative lineshape fitting of MAS NMR spectra: A tool to investigate homonuclear J coupling in isolated spin pairs, *J. Magn. Reson.* **135**, 500–513 (1998).
12. S. Dusold and A. Sebald, Magnitudes and orientations of NMR interaction tensors in isolated three-spin systems ABX, *Mol. Phys.* **95**, 1237–1245 (1998).
13. J. Briand and O. W. Sørensen, Simultaneous and independent rotations with arbitrary flip angles and phases for I, IS $^\alpha$, and IS $^\beta$ spin systems, *J. Magn. Reson.* **135**, 44–49 (1998).
14. R. E. D. McClung, Coherence transfer pathways and phase cycles: The decoding of a pulse sequence, *Concepts Magn. Reson.* **11**, 1–28 (1999).
15. M. T. Chenon, R. Dunkel, D. M. Grant, and L. G. Werbelow, NMR relaxation studies of the CH_3 - ^{13}C spin grouping in the vicinity of the T_1 minimum, *J. Phys. Chem. A* **103**, 1447–1456 (1999).
16. B. Wrackmeyer and P. Bernatowicz, Tetrakis(trimethylstannyl)germanium, the first observation of indirect nuclear ^{119}Sn - ^{73}Ge spin-spin coupling, *Magn. Reson. Chem.* **37**, 418–420 (1999).
17. Unfortunately, the nomenclature of the signal detection phases is often confused in the spectrometer descriptions and varies from instrument to instrument. On some instruments, there is no facility for changing the radiofrequency carrier phase $\psi_{\text{carrier}}^{\text{rec}}$ during signal detection, and the postdigitization phase ψ_{postdig} is instead termed "receiver phase." In other cases, the radiofrequency carrier phase and postdigitization phase are both loosely referred to as the "receiver phase."