

Why should one do solid-state NMR?

Given the high sensitivity and excellent resolution typically available from solution-state NMR, why should one consider solid-state NMR? There may be several reasons for doing so.

- a) Solvent may alter the coordination sphere
- b) Freezing and boiling points of solvents may limit the temperature range over which a material may be studied
- c) Low solubility/insolubility of sample
- d) Some samples may decompose before melting
- e) Monitor chemical reactions in the solid state
(i.e., baking of enamels
curing resins
thermal decompositions)
- e) Perhaps interest in the physics of the solid state
(i.e., chemical structure in comparison with solution
conformation
crystal modification
molecular dynamics
molecular adjacency, such miscible polymers versus domains)

Why are spectral lines broad in solid-state NMR?

Spectral resonances in solid-state NMR are usually broad and frequently quite featureless, especially for polycrystalline samples. These broad resonances typically result from overlapping strong interactions that are dependent upon orientation of the nuclei in the magnetic field. Such interactions commonly encountered in the solid state are the following:

- a) dipolar coupling, resulting from direct dipole-dipole interactions between like nuclei (homonuclear) and different nuclei (heteronuclear)
- b) magnetic shielding (also known as chemical shift anisotropy or Knight shift anisotropy), resulting from the electron distribution surrounding the nucleus
- c) electric quadrupolar coupling, resulting from the interaction of the non-spherical charge distribution in nuclei with a spin $I > \frac{1}{2}$ with the electric field gradient.

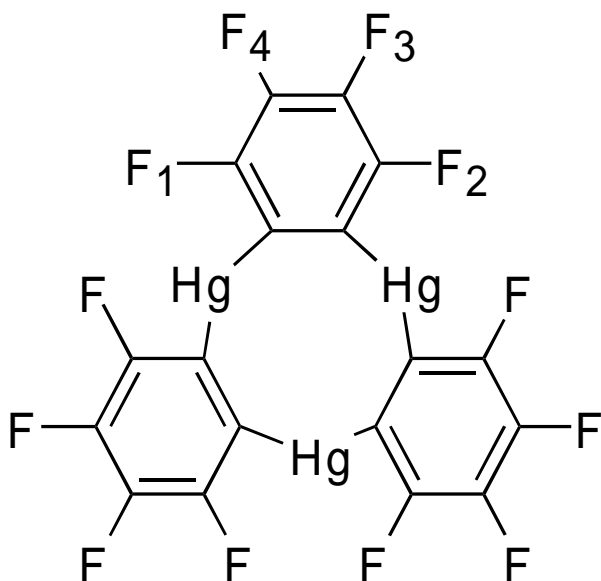
The rapid molecular motions and reorientations typical of a solution or of a melt do not usually occur in the more rigid solid state. As a result, those nuclear interactions that depend upon the orientations of the nuclei are not averaged. Broad spectral lines result.

In addition to the above interactions, the following also may exist:

d) scalar J-coupling, resulting from indirect spin-spin interactions

Dipolar couplings, being proportional to $\frac{\gamma_a \gamma_b}{r^3}$, are usually tens of kHz and are independent of the applied magnetic field. The anisotropy of the magnetic shielding, on the other hand, is directly proportional to applied magnetic field. For example, the chemical shift anisotropy of a doubly-bonded aromatic carbon of 200 ppm yields a line width of 15 kHz at a field strength of 7 T. While the electric quadrupolar coupling of ^2H may be around 170 kHz, that of other quadrupolar nuclei may be in the MHz range. Although scalar couplings are usually much smaller than the cited interactions, they can still be quite large, especially in comparison with those typically found for ^1H or ^{13}C . Large scalar couplings are quite common for metal nuclei.

For example, consider trimeric perfluoro-*ortho*-phenylene mercury. This compound can be isolated in the solid state as single crystals either of the pure compound or of supramolecular complexes consisting of alternating layers of the pure compound and benzene or other such aromatic molecules.

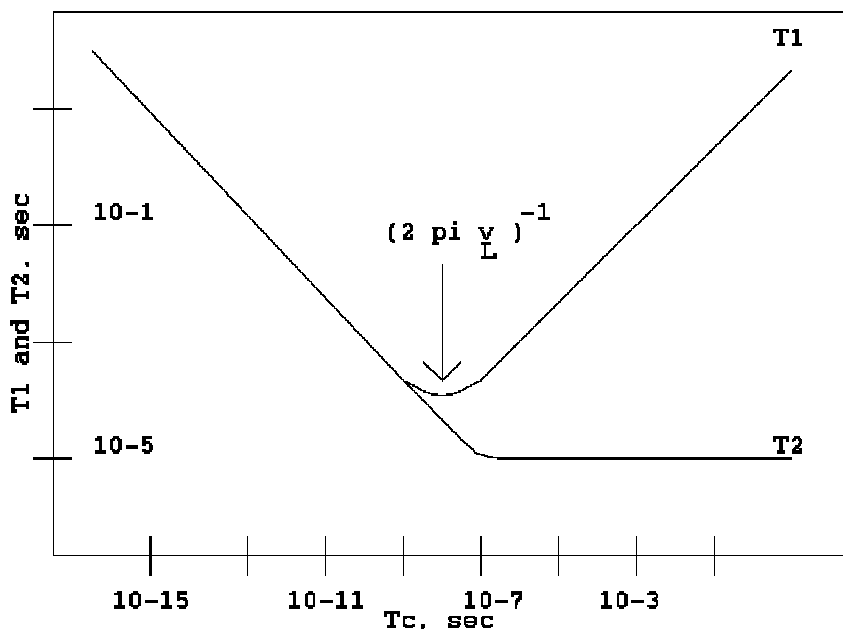


In the solid state the compound has both strong homonuclear dipolar interactions between the ^{19}F nuclei and strong heteronuclear dipolar interactions between the ^{19}F and ^{13}C nuclei. The chemical shift anisotropy of the spin- $1/2$ ^{199}Hg nuclei is around -3,300 ppm. The quadrupolar ^{201}Hg nuclei have not yet been observed in either the solid state or in solution. The one-bond $^1\text{J}(^{199}\text{Hg}-^{13}\text{C})$ scalar in organomercury compounds may range from 500 to 1,800 Hz. Even the long-range scalar coupling $^3\text{J}(^{199}\text{Hg}-^{19}\text{F})$ and $^5\text{J}(^{199}\text{Hg}-^{19}\text{F})$ are still on the order of hundreds of Hz.

Relaxation

In the early days of NMR, Bloembergen, Pound, and Purcell developed a theory to describe nuclear relaxation in liquids by magnetic dipole interactions. Typically, solution NMR is performed in the correlation time regime of "extreme narrowing," i.e., the correlation time $\tau_c \ll \nu_L^{-1}$, the inverse of the Larmor frequency. In this regime, the transverse and longitudinal relaxation times are equal. Generally, in solution, the viscosity increases and the relaxation time decreases as the temperature is lowered. When the correlation time becomes long enough to be comparable with the Larmor precession period (i.e., the inverse of Larmor frequency, ν_L^{-1}), the spin-lattice relaxation time passes through a minimum before increasing with the increasing viscosity.

However, the spin-spin relaxation time T_2 continues to decrease and eventually approaches a limiting value, which is a measure of the dipolar broadening in a rigid solid. In other words, solid-state NMR has a different correlation time regime than that of "extreme narrowing" generally associated with solution NMR.



Nuclear relaxation is basically the flipping of a nuclear spin caused by its coupling with the thermal motion of a lattice, i.e., the other degrees of freedom in the system. Any theory of nuclear relaxation in essence simply provides a calculation of the probability of such a spin flip. The spin flip results from a fluctuating magnetic field. This fluctuating magnetic field may arise from a magnetic dipole interaction (between like or unlike spins), paramagnetic substances, or even anisotropic magnetic shielding. For nuclei with spin $I > 1/2$, i.e., those with a quadrupole moment, a fluctuating electrical field gradient may also provide a means of relaxation. In short, some randomly time-dependent interaction affects the populations of the Zeeman energy levels and drives them to thermal equilibrium with the other degrees of freedom.

In this sense, many of the interactions which lead to relaxation in liquids and gases also lead to relaxation in solids. That is, relaxation from internal motions, such as

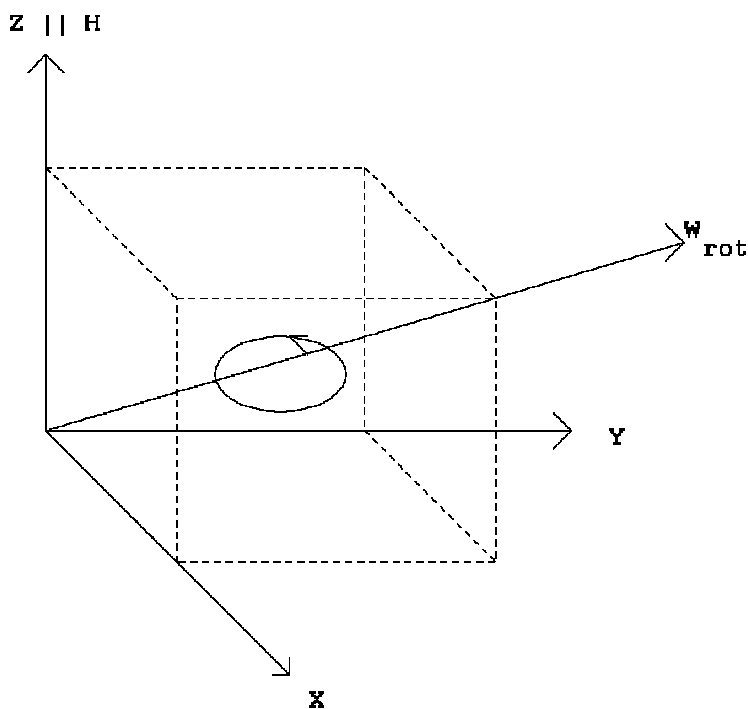
translational diffusion or hindered rotation that take place in solids, can be described by a similar theoretical formalism to that used for liquids. Even indirect scalar coupling between two nuclei can provide a relaxation mechanism if the coupling of the two spins is time dependent by virtue of movement of the two spins relative to each other or if one spin is efficiently relaxed and couples to the second spin.

As an example of a relaxation mechanism in the solid state, consider zwitterionic glycine. Rotation about the C-N bond creates fluctuating magnetic fields due to the protons in the rotating -NH_3 group. The difference in the solid as compared with a liquid is that the short spin-spin relaxation time from the strong homonuclear dipolar interaction allows this to be an efficient relaxation mechanism for the other proton spins in the molecule. Although the motion may be more restricted in the solid state, these same types of mechanisms can lead to relaxation in solids. Other solid-state relaxation mechanisms include conduction electrons in metals and lattice vibrations for quadrupolar nuclei in environments with lower than cubic symmetry.

MAS

Magic angle spinning (MAS) is a technique often used, either alone or in combination with radiofrequency pulse methods, to obtain high-resolution NMR spectra from solid samples. It is implemented in the NMR experiment by rotating the sample about an axis oriented at an angle of $\cos^{-1}(1/\sqrt{3})$, or about 54.7° , with respect to the applied static magnetic field. Sample rotation rates up to 35 kHz are commonly available on commercial NMR systems.

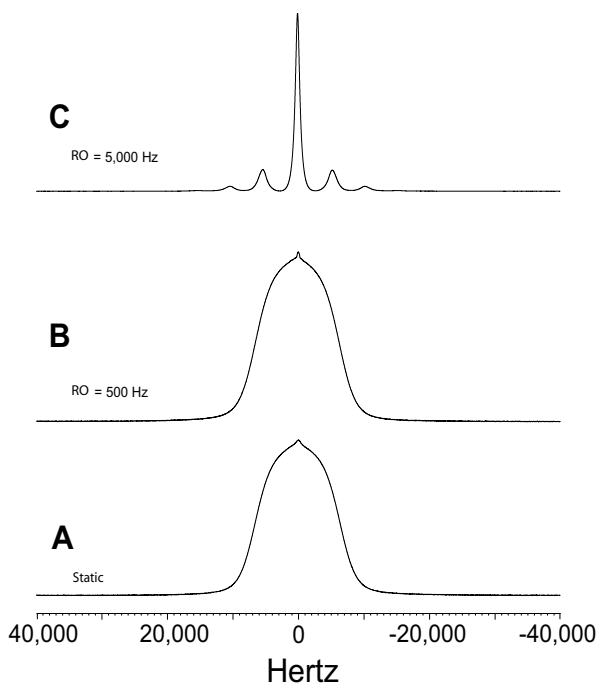
The method is an effective way to improve resolution in chemical systems with anisotropic interactions. A qualitative understanding of how MAS achieves this can be gained from the following often-repeated description of the averaging of the chemical shielding anisotropy from spinning the sample. The magic angle is simply the body diagonal of a cube. The X, Y, and Z coordinate axes are symmetric when viewed along the body diagonal. Over a single rotation period, each crystallite of the sample will experience the average of the effective chemical shift $\delta_{iso} = (\delta_{xx} + \delta_{yy} + \delta_{zz})/3$, which is the isotropic chemical shift.



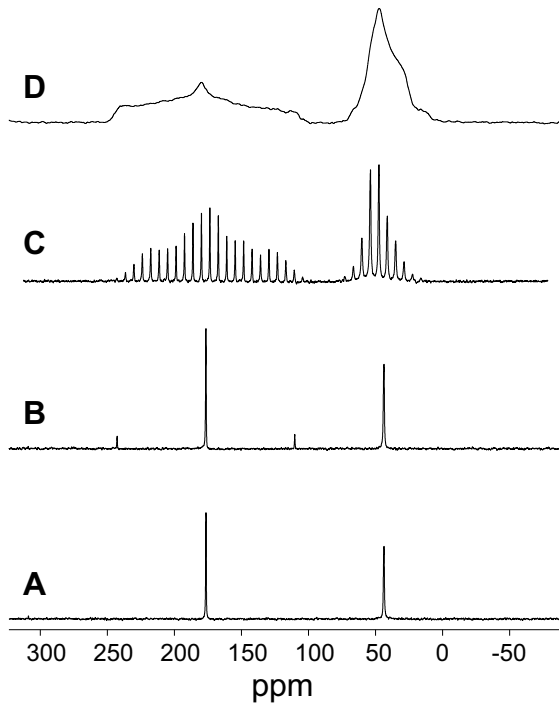
In the mathematical description of MAS, a factor containing the second-order Legendre polynomial $P_2(\cos \vartheta) = -\frac{1}{2}(3\cos^2 \vartheta - 1)$, where ϑ is the angle between the axis of rotation and the applied magnetic field, not only appears in dipolar and anisotropic shielding interactions but also in expressions for anisotropic electron-coupled spin-spin interactions and first-order quadrupolar interactions. As a historical note, the magic angle was so-named by Professor C. J. Gorter of Leiden when E. R. Andrew presented results at the Ampère Congress in Pisa in 1960. It is simply the value of ϑ where the second-order Legendre polynomial is equal to zero. Thus, all interactions scaled by this term are averaged out.

In applying MAS to obtain high-resolution solid-state spectra, the practical question of how fast to spin arises. The specific answer to this question depends upon which nuclear interactions are to be averaged, as these generally fall into one of two categories. Indeed the categories can be characterized by how the averaging of the interaction responds to MAS.

For the first category, homonuclear dipolar broadening serves as an example of a homogeneous interaction. This type of interaction is characterized by the requirement that the sample must be spun on the order of the static sample line width before an appreciable narrowing of the resonance is observed. If the sample is spun slowly, then no appreciable line narrowing is observed. This is usually the result of a many-body interaction in which the interaction is distributed over all the spins. Such a result is demonstrated by the ^1H MAS spectrum of adamantane. The line width of the static spectrum of adamantane is about 12.5 kHz. Spinning at 500 Hz produces no appreciable narrowing of the resonance. However, at higher spinning speeds such as 5 kHz, the resonance narrows to about 0.9 kHz and produces spinning sidebands.



For the second category, the chemical shift anisotropy serves as an example of an inhomogeneous interaction. This type of interaction is characterized by appreciable narrowing of the resonance even when the spin rate is very small compared to the static-sample line width. Slow spinning provides very narrow lines, although there may be a substantial number of spinning sidebands. It is interesting to note that the orientation-dependent information of the interaction remains, embedded in the amplitudes of the spinning sidebands. The spectra of glycine as a function of spin rate illustrate this.



There are limitations to the MAS technique. For example, second-order quadrupolar effects are not completely removed. Also dipolar coupling of the quadrupolar ^{14}N to ^{13}C is not removed at low magnetic fields when the quadrupolar coupling for ^{14}N is on the same order of magnitude as the Zeeman interaction. As a result, this interaction is no longer scaled by the simple second-order Legendre polynomial.

CP

Low(er) gamma nuclei present a challenge to NMR spectroscopy due to their small gyromagnetic ratio, often low natural abundance, and typically long spin-lattice relaxation times. All three conspire to yield low sensitivity. For example, the signal-to-noise ratio (S/N) of a NMR experiment is given by the following:

$$\frac{S}{N} \sim N \gamma (I+1) B_o^{3/2} T^{-3/2} f^{-1} \Phi (QV_s)^{1/2} b^{-1/2}$$

where f is the noise figure, Φ is the filling factor V_s/V_c , V_s is the sample volume, V_c is the NMR coil volume, and b is the receiver band width. A small number of nuclei, N , and a low gyromagnetic ratio, γ , lead to low sensitivities. Of course, the long spin-lattice

relaxation times require long data accumulation times when using multiple scans to improve S/N.

By using cross-polarization (CP), the sensitivity of each scan can be (theoretically) enhanced by the ratios of the gyromagnetic ratio of the two nuclei. For example, for CP from ^1H to ^{13}C , it is possible to enhance S/N up to a factor of ~ 4 . In addition, the repetition rate for multiple scans is determined by the (usually) very much shorter spin-lattice relaxation time of the protons. In combination, these may lead to an overall enhancement of ~ 20 for data acquisition in a given time.

Shielding Anisotropy

The origin of the magnetic shielding anisotropy arises from the electrons around a nucleus. Since electrons also have magnetic moments, the applied magnetic field induces an electronic current that produces small magnetic fields. These small fields may align with or oppose the applied magnetic field, creating an effective magnetic field for the nucleus slightly differing from the externally applied field. This shielding thus depends on the electronic environment around the nucleus and varies with molecular orientation to the applied magnetic field. In a liquid, the rapid molecular motion averages the various chemical environments and the diverse orientations to yield narrow spectral resonances.

The chemical shielding is a second-rank (3×3 matrix) tensor quantity. In the principal axis system, this shielding is described by the three principal values. With an aligned single crystal, these principal values can be measured relative to the molecular axes by making NMR measurements as the crystal is rotated about different axes. With a polycrystalline powder, only the three principal values can be determined from the NMR spectra, i.e., the powder patterns. With the vast number of randomly oriented crystallites, the orientation of the shielding tensor relative to the molecular axes is lost.

The simplest convention for reporting the three principal values of the shielding tensor is to list them individually as $\delta_{11} \geq \delta_{22} \geq \delta_{33}$. The data may also be reported as the isotropic chemical shift δ_{iso} , the anisotropy δ , and the asymmetry η . One definition for these values are the following:

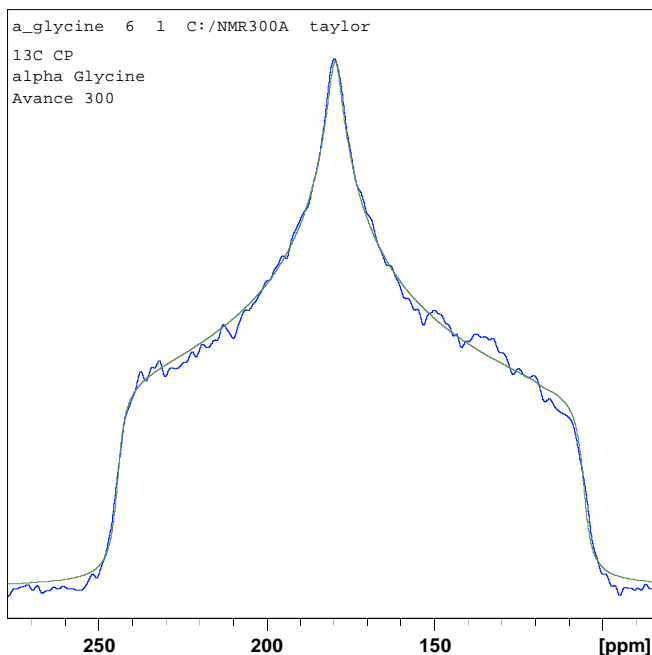
$$\delta_{iso} = (\delta_{11} + \delta_{22} + \delta_{33})/3$$

$$\delta = \delta_{33} - \delta_{iso}$$

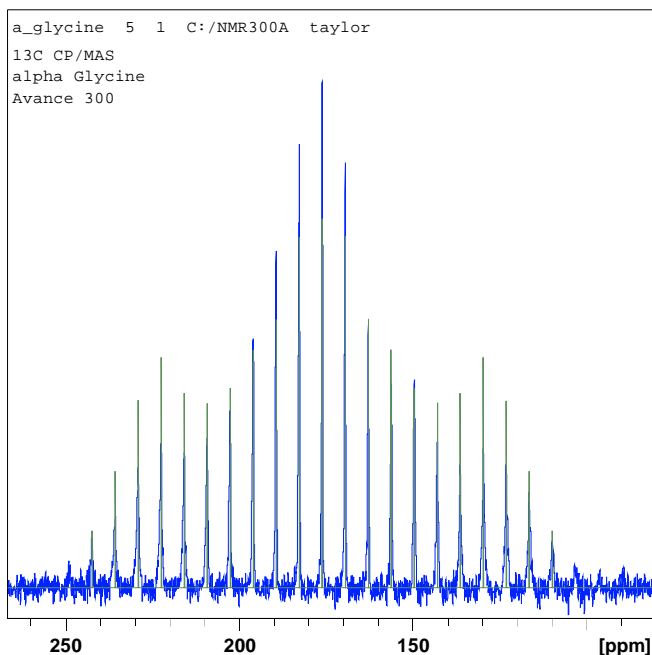
$$\eta = |\delta_{22} - \delta_{11}| / |\delta_{33} - \delta_{iso}|$$

However one should be aware that there are alternative definitions for both the anisotropy δ and asymmetry η .

Consider the ^{13}C carbonyl resonance of a static sample of alpha glycine as an example of chemical shielding anisotropy. Proton decoupling is applied to remove the strong heteronuclear coupling to the carbon. The fit of a theoretical non-axially symmetric chemical shielding powder pattern to the experimental data is shown. The three principal values of the chemical shift tensor are $\delta_{11} = 243.5$ ppm, $\delta_{22} = 178.9$ ppm, and $\delta_{33} = 108.7$ ppm, which yield an isotropic shielding value of 177.0 ppm.



Magic angle spinning can average the chemical shift anisotropy, as shown below for the carbonyl resonance in alpha glycine. Usually one spins fast compared to the line width of the anisotropy in order to remove the spinning sidebands from observation in order for easier spectral interpretation. However, even slow spinning provides very narrow lines, although there may be a substantial number of spinning sidebands. It is interesting to note that the orientation-dependent information of the interaction remains, embedded in the amplitudes of the spinning sidebands. Indeed, a simulation can extract the principal values of the chemical shift anisotropy from slow speed MAS spectra.



Quadrupolar Effects

The magnitude of the quadrupolar interaction has a large effect on the observed NMR spectrum. Unraveling the information contained within the spectrum can be quite a challenge. Before looking at some results, it may be helpful to first consider some of the usual nomenclature encountered in describing the quadrupolar interaction.

Electric quadrupolar coupling results from the interaction of the non-spherical charge distribution in nuclei with a spin $I > 1/2$ with the electric field gradient. The presence of such an asymmetric charge distribution in the nucleus depends on the number of protons and neutrons bound within in the nucleus. That such an asymmetric charge distribution within the nucleus is possible can be visualized, naively, simply by considering the difference between a hydrogen nucleus, a single proton with a nuclear spin $I = 1/2$, and the deuterium nucleus, consisting of a proton and a neutron with a nuclear spin $I = 1$. The subject of the structure and constitution of the nucleus is usually given by the Standard Model and left to the field of nuclear physics. However, simple electrostatic interaction can cause the nucleus with a quadrupole moment to orient itself within an asymmetric electronic density.

To better understand the conventional nomenclature and its origin, the rather formidable Hamiltonian for this interaction is given, using Abragam's notation, by

$$H_Q = \frac{e^2 q Q}{4I(2I-1)} \left[3I_z^2 - I(I+1) + \frac{1}{2} \eta (I_+^2 + I_-^2) \right]$$

where e is the charge of an electron, eq is the Z -component of the electric field gradient, η is the asymmetry in the electric field gradient, and Q is the nuclear electric quadrupole moment. All the nuclear properties enter the interaction only through eQ . The electrostatic field due to the environment enters only through eq and η .

For NMR, this problem is usually solved in the limit of high magnetic field using perturbation theory. In perturbation theory, the basis functions ψ_n are eigenfunctions of the main part of the Hamiltonian H_0 . In this limit of high magnetic field, the main part of the Hamiltonian H_0 is the Zeeman interaction. This simply assumes that the Zeeman interaction is much larger than the quadrupolar interaction and that the wavefunctions are simply the usual eigenstates of the Zeeman interaction. The corrected wave functions and energies resulting from the perturbation H_1 are given by

$$\Psi_n = \psi_n - \sum_{m \neq n} \frac{\langle m | H_1 | n \rangle}{\epsilon_m - \epsilon_n} \psi_m$$

and

$$E_n = \epsilon_n + \langle n | H_1 | n \rangle - \sum_{m \neq n} \frac{\langle m | H_1 | n \rangle \langle n | H_1 | m \rangle}{\epsilon_m - \epsilon_n}.$$

The zeroth-order energy and wave functions arise from the Zeeman interaction. As a specific example, the Zeeman eigenstates of deuterium are still described by -1, 0, and 1. The quadrupolar hamiltonian provides the perturbation H_1 . Using Abragam's notation for brevity

$$v_Q = \frac{3e^2qQ}{2I(2I-1)h}, \quad a = I(I+1), \quad \mu = \cos \vartheta, \quad \text{and} \quad v_L = \frac{\gamma H}{2\pi},$$

second-order perturbation theory gives the following results:

$$E_0 = -\gamma H m = -h v_L m$$

which is the Zeeman interaction at the Larmor frequency,

$$E_1 = \frac{1}{4} h v_Q (3\mu^2 - 1) (m^2 - \frac{1}{3} a)$$

which is the first-order correction, and

$$E_2 = -h \left(\frac{v_Q^2}{12v_L} \right) m \left[\frac{3}{2} \mu^2 (1 - \mu^2) (8m^2 - 4a + 1) + \frac{3}{8} (1 - \mu^2)^2 (-2m^2 + 2a - 1) \right]$$

which is the second-order correction.

These perturbations to the Larmor frequency allow some general observations regarding quadrupolar spectra. Powder patterns for quadrupolar nuclei in polycrystalline samples are symmetric about the Larmor frequency to first-order. For half-integer spins the frequency of the central transition, $-1/2 \rightarrow 1/2$, is not shifted in first-order by the quadrupole transition. Frequencies of the satellite lines are shifted relative to the Larmor frequency. Magic angle spinning can average the first-order quadrupolar interaction.

For half-integer spins the frequency of the central transition, $-1/2 \rightarrow 1/2$, the second-order quadrupolar coupling gives rise to an asymmetrical resonance with its center of gravity shifted below the unperturbed frequency v_L . The magnitude of this shift depends inversely upon the magnetic field strength. Using higher magnetic field strengths will reduce the shift. By rapidly spinning the sample, the orientation dependence of the second-order quadrupolar broadening becomes more complicated than that of the first-order and corresponds mathematically to the zeroth-, second-, and fourth-order Legendre polynomials:

$$P_0(\cos \vartheta) = 1$$

$$P_2(\cos \vartheta) = -\frac{1}{2} (3 \cos^2 \vartheta - 1)$$

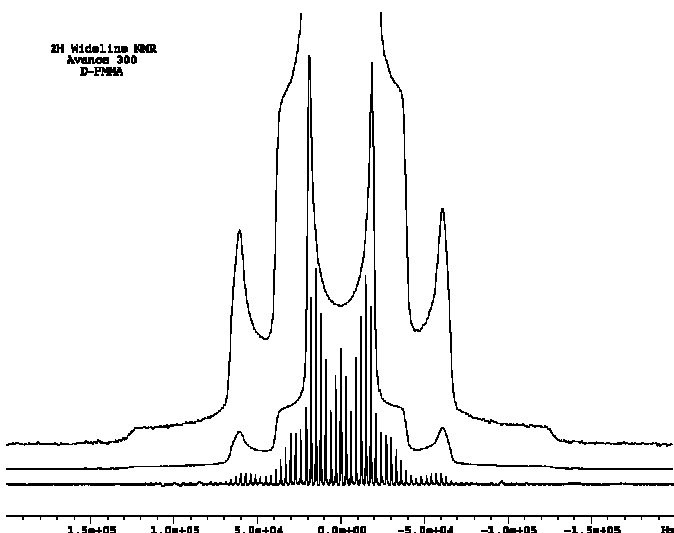
and

$$P_4(\cos \vartheta) = \frac{1}{8}(3 - 30 \cos^2 \vartheta + 35 \cos^4 \vartheta)$$

As a result, magic angle spinning alone cannot average the second-order quadrupolar broadening.

In reading the literature concerning quadrupolar coupling, it should be noted that the definition of ν_Q differs from the quadrupolar coupling constant (QCC = e^2qQ) by a factor of $\frac{3}{2I(I+1)}$. Both terms are frequently encountered. Additionally, two sets of frequency units, related by $\omega_Q \text{ rad/sec} = 2\pi\nu_Q \text{ Hz}$, are used.

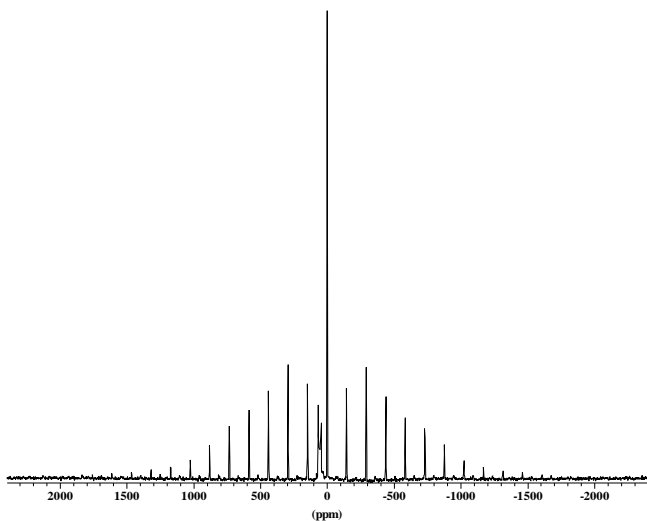
Consider the case of deuterium as an example of the quadrupolar interaction for a spin $I = 1$ nucleus. The wide-line ^2H spectrum of deuterated polymethylmethacrylate is shown. The first-order quadrupolar coupling produces a distinctive spectrum. The powder pattern for the deuterated methyl groups as well as the much broader powder pattern for the deuterated methylene groups can be seen in the spectrum from the static sample. Magic angle spinning, even at slow spinning speeds, can average this first-order quadrupolar coupling (since the orientational dependence is the same as the chemical shift anisotropy) to a relatively narrow resonance, albeit with a lot of spinning sidebands. The MAS spectrum with a rotation rate of 3 kHz, small compared to the first-order quadrupolar coupling, shows very narrow lines. The second-order quadrupolar coupling is proportional to $\frac{\nu_Q^2}{\nu_L}$. A typical first-order quadrupole coupling constant of 170 kHz has a second-order quadrupolar coupling on the magnitude on the order of 600 Hz. Of course, this contribution can be further reduced simply by going to higher fields.



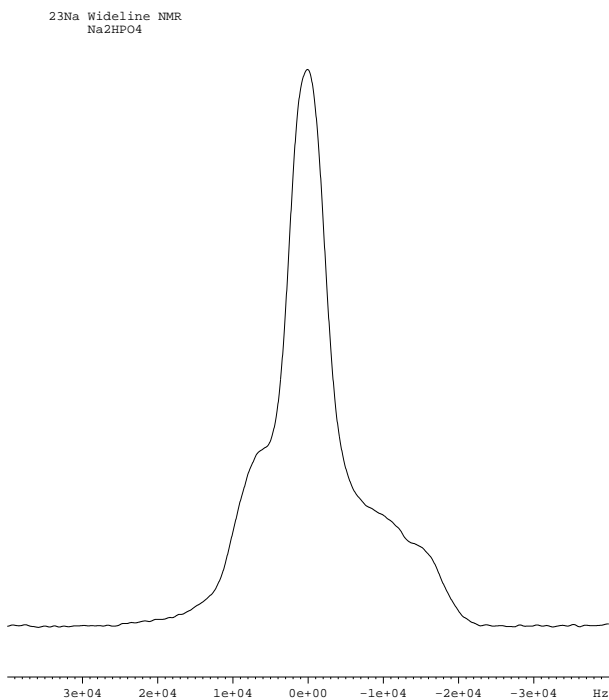
One of the practical difficulties of solid-state NMR of quadrupolar nuclei is the acquisition of quantitative data. The response of quadrupolar nuclei to a radiofrequency pulse depends upon the magnitude of the quadrupolar coupling constant. This can be

particularly noticeable in a multi-site chemical system in which the nuclear sites have sizeable differences in the magnitudes of the quadrupolar coupling constants. As a general rule for quadrupolar nuclei, the solid-state ninety degree pulse width is equal to the solution-state ninety degree pulse width divided by the quantity $(I + 1/2)$. For example, the solid-state ninety of spin $I = 5/2$ ^{27}Al is one-third of the solution-state ninety. For materials with multiple nuclear sites with varying quadrupolar coupling constants, quantitative data can usually be acquired by excitation with small flip angle radiofrequency pulses. In this limit of small flip angles, the responses of sites with large and small coupling constants relative to the radiofrequency field strength are approximately the same.

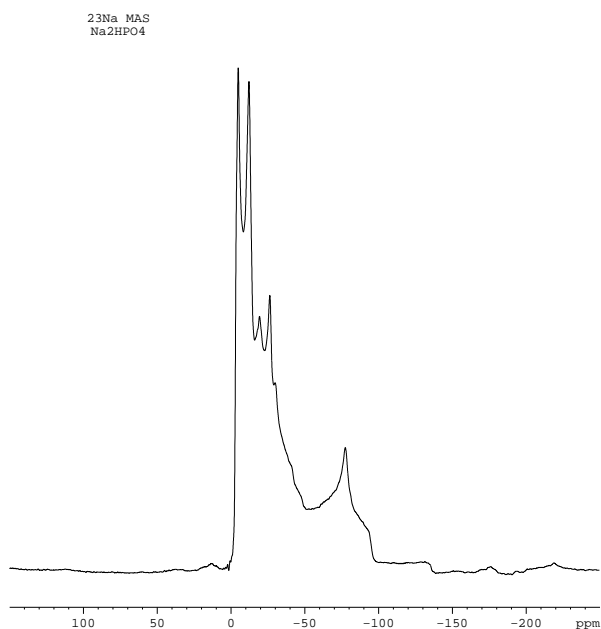
Consider the case of ^{27}Al in YAG as an example of the quadrupolar interaction for a half-integer nuclear spin. Using MAS to average out the first-order quadrupolar broadening, the resonances of two sites are visible in the spectrum, including one showing a substantial second-order quadrupolar broadening.



As an example of unraveling the overlapping contributions to the spectrum, consider the ^{23}Na spectra of Na_2HPO_4 . The first figure shows the single-pulse one-dimensional wideline spectrum on a static sample of this compound. One sees spectral features, though the spectrum is not symmetric.



MAS averages the first-order quadrupolar interactions to show in the figure below the resonances of the second-order quadrupolar interactions.



Finally a two-dimensional triple-quantum MAS spectrum unravels the three overlapping sites. All three sites have differing quadrupolar coupling constants.

²³Na Triple quantum MAS
Na₂HPO₄

