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Principios Básicos de RMN en sólidos destinado a usuarios

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Principios Básicos de RMN en sólidos destinado a usuarios

In general NMR is a good diagnostic technique that provide information about the chemical nature of solids, particularly on amorphous materials being not useful diffraction techniques. We will try in this discussion to present the NMR of solids as a complementary technique to diffraction techniques when the aim is the detemination of crystalline structure. This is what we call “NMR crystallography” and it is an emergent and evaluating topic nowadays.

Introduction

At the beginning, since about 50 years, NMR on solids materials, was limited to study relaxation effects and line shapes of nuclear spins (mainly protons) in wide lines. During the last 20 years, have had a considerable interest in the application of NMR high resolution techniques of solids, to get information of chemical nature of a wide variety of solids materials.

NMR of solids: **structural** and **molecular** packing determination
 molecular dynamic studies.

NMR of solids (SSNMR) can give useful information about the number of molecules in the asymmetric unit or on the symmetry of the molecular site in the lattice, to help in the powder X Ray refinement data when proper single crystals are no available. Alternatively it can be used to measure internuclear distances in a direct way, many times with high accuracy. For amorphous and disordered solids, NMR provides an invaluable structural information, that can not be obtained by any other method.

NMR can give information about molecular dynamic. Even the most simple molecules undergo conformational interchange at room temperature, these changes can not be ignored at the moment to determine the properties of solids materials.

NMR is an excellent method to determine chemical composition. The “chemical shifts” are different for each distinct chemical site, this able us to differentiate them, and, in principle NMR intensity signal is proportional to the number of sites in the sample. From this we get another ability of NMR that is to distinguish different polymorphs.

The Basics of Solid-State NMR

The vector model of pulsed NMR

The net magnetization arising from the nuclei in a sample is \mathbf{M} and is the vectorial sum of all the individual magnetic moments associated with all the nuclei

$$\vec{M} = \sum_i \vec{\mu}_i$$

$\vec{\mu}_i$ magnetic moment of the i th nucleus

\vec{I}_i nuclear spin

$$\vec{\mu}_i = \gamma \vec{I}_i$$

$$\vec{M} = \gamma \vec{J}$$

γ gyromagnetic ratio, a constant different for each type of nuclei

\vec{J} net spin angular moment of the sample

If the nuclei are placed in a uniform magnetic field

$$\vec{B}$$

as in the NMR experiment , a torque

$$\vec{T}$$

is exerted on the magnetization vector

$$\vec{T} = \frac{d}{d t} \vec{J}$$

where the torque is given by

$$\vec{T} = \vec{M} \times \vec{B}$$

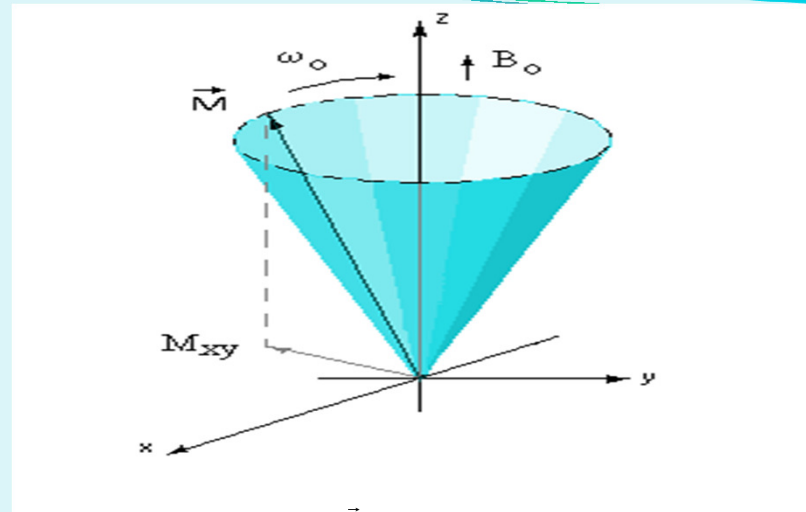
and combining the last two equations we obtain

$$\frac{d}{d t} \vec{M} = \gamma \vec{M} \times \vec{B}$$

This equation predicts that the magnetization precesses about a fixed magnetic field at a constant rate

$$\omega = \gamma B$$

The external magnetic field is oriented along the z axis of a laboratory frame



$$\vec{B}_0 = (0, 0, B_0)$$

ω_0 : Larmor frequency

Radio frequency pulses

To observe the properties of the nuclear spins in NMR is necessary to get the system out of equilibrium. We can do this applying oscillating magnetic fields, electromagnetic waves.

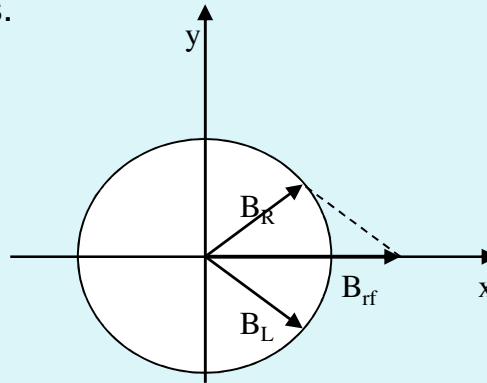
We use radio frequency waves (rf) with frequencies from tens of megahertz up to 1 GHz.

These fields interact with nuclei in addition to the interaction with the static magnetic field.

The rf wave is set up in a way that the oscillating field is perpendicular to the z axis, i.e. to the field

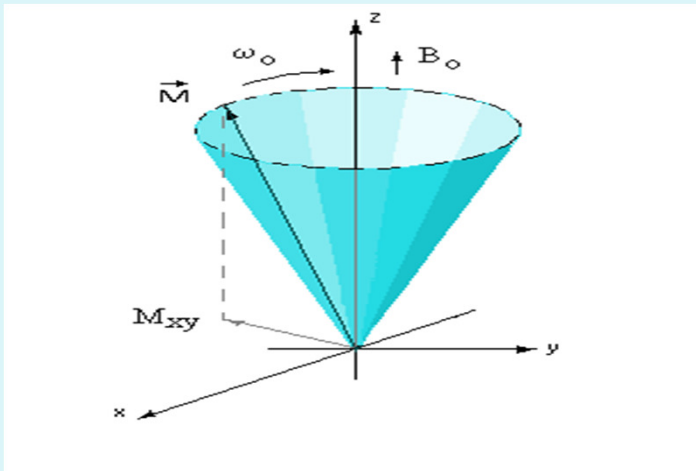
$$\vec{B}_0$$

The effect of the oscillating magnetic field can be analyzed by breaking it into two rotating components, each of amplitude B_1 , one rotating clockwise and the other counterclockwise. We will keep the component rotating in the same sense of the spins.

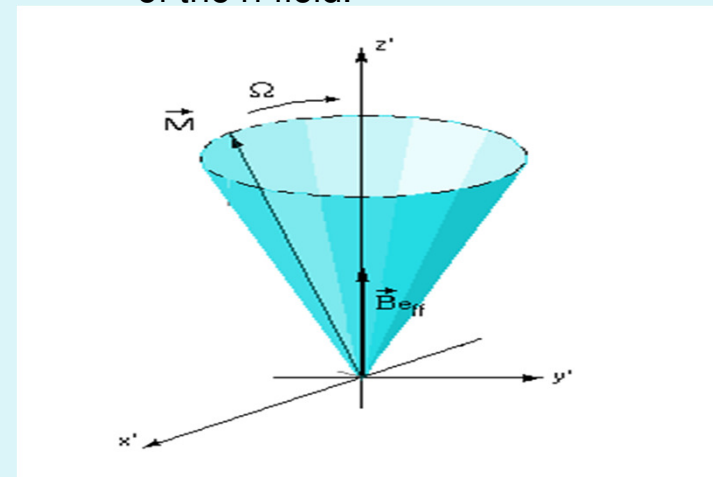


Rotating System

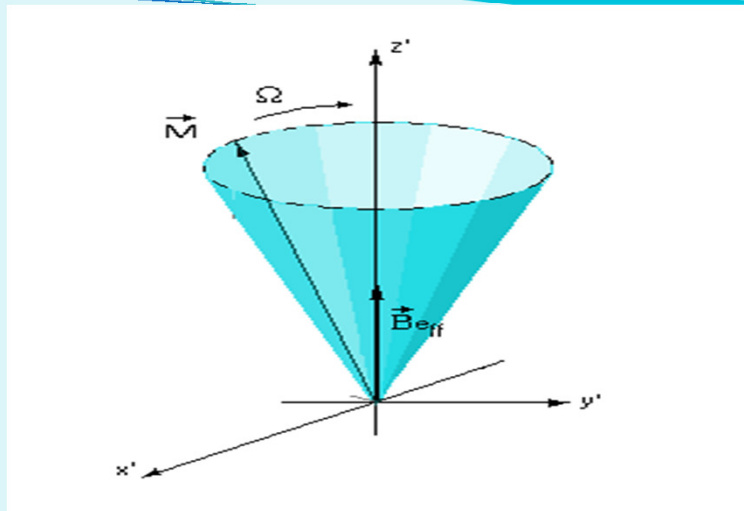
To describe more easily the effects of the rf fields is convenient to view the problem from a system rotating around the z axis of the laboratory frame, at the frequency of the rf field.



Laboratory frame



Rotating frame



where $\Omega = \omega_{rf} - \omega_0$

and $B_{eff} = B_0 (1 - \omega_{rf} / \omega_0)$

If the field \vec{B}_1 is applied out of resonance: $\omega_{rf} \sim \omega_0$

The magnetization precesses in the rotating frame around a remaining field (effective field) $B_{eff} \ll B_0$

In resonance $\omega_{rf} = \omega_0$ ($B_{eff} = 0$) the magnetization remains fixed in the rotating frame.

If we apply an on resonance rf pulse (pulse = rf field applied during certain time), the only field in the rotating frame will be \vec{B}_1 , the magnetization precesses around \vec{B}_1 at the frequency $\omega_1 = \gamma \cdot B_1$

If we keep the field “on” during time t_p so

$$\gamma B_1 t_p = \omega_1 t_p = \theta_p = \pi/2$$

the magnetization is turned without changing its magnitude, and the pulse produce the condition

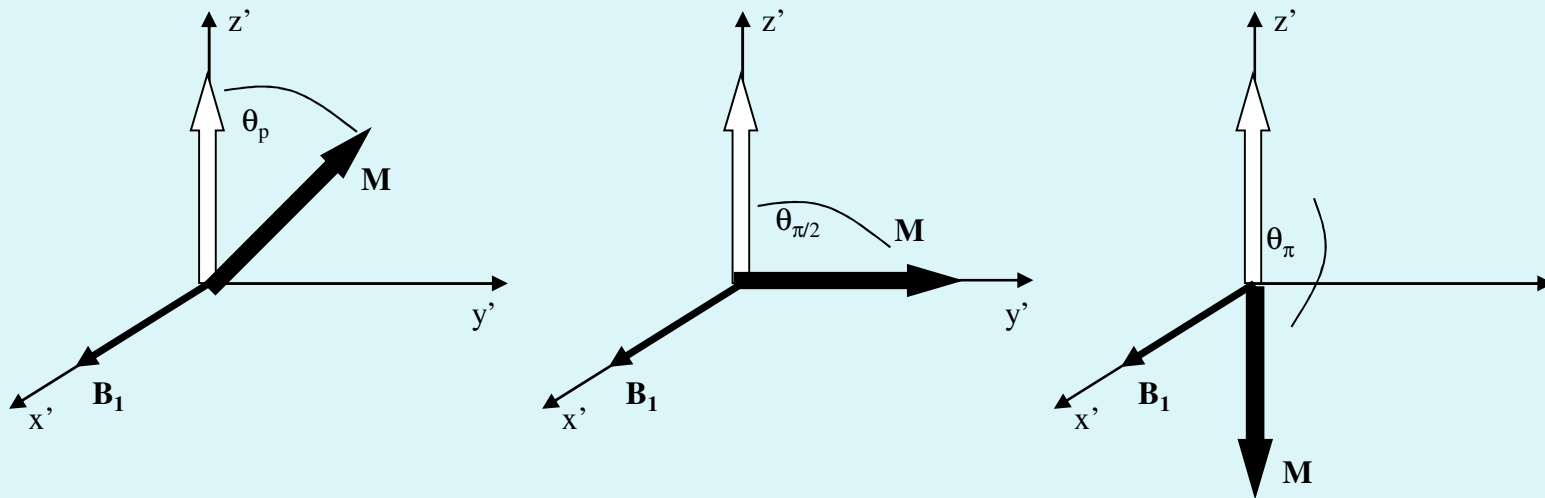
$$M_{z'} = 0; M_{x'} = 0; M_{y'} = M$$

A $(\pi/2)_x$ pulse was applied.

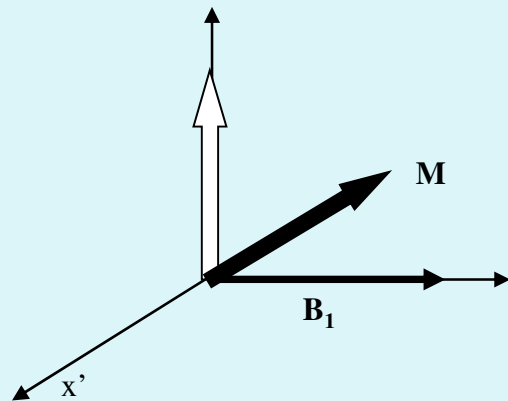
Similarly if the final situation is

$$M_{z'} = -M; M_{x'} = 0; M_{y'} = 0$$

a π_x pulse was applied



Phase of the pulse: is the angle between the rf field and the x axis of the rotating frame.



$\pi/2$ pulse with a 90° phase

Quantum mechanical picture

NMR of condensed matter involves a huge number of magnetic nuclei ($> 10^9$)

The quantum mechanical picture begins with isolated spins and from this we construct the description of the whole spin system. Is what we call "ensemble average".

Spin system is a group of spins that interact one with each other in a certain way and in the presence of a specific environment, for example a static magnetic field

The state of a spin system in equilibrium is one between a number of possible states or eigenstates.

The specific form of the state depends on the nature of the spin system.

The sample contains many of that spin systems .

The proportion of the spin systems in the sample in a certain eigenstate is given by the Boltzmann distribution for a sample in thermal equilibrium. We must describe the state of each spin system in the sample as a superposition of possible eigenstates of the spin system

The superposition of eigenstates is the same for spin systems that are identical and take into account the probability of occurrence of each eigenstate

Hamiltonian for a single isolated spin in the presence of a magnetic field

$$\hat{H} = - \hat{\mu} \cdot \vec{B}_0 \quad (1.2.1)$$

Hamiltonian: energy operator of the system.

$$\hat{H} = - \gamma \hbar \hat{I}_z B_0 \quad (1.2.2)$$

Static magnetic field in the z direction \hat{I}_z

The eigenstates of \hat{H} are the eigenstates of \hat{I}_z .

$$|I, m\rangle$$

Eigenfunctions: $\hat{H} |I, m\rangle = -(\gamma \hbar B_0) \hat{I}_z |I, m\rangle = -(\gamma \hbar B_0) m |I, m\rangle$

I : quantum number of nuclear spins

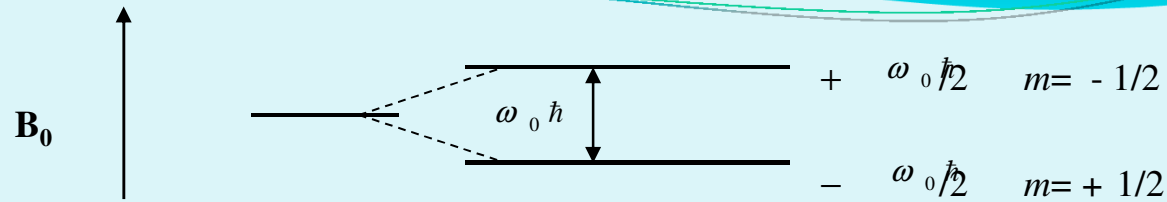
m : quantum magnetic number, eigenvalue of

m has $2I+1$ possible values: $I, I-1, I-2, \dots, -I$.

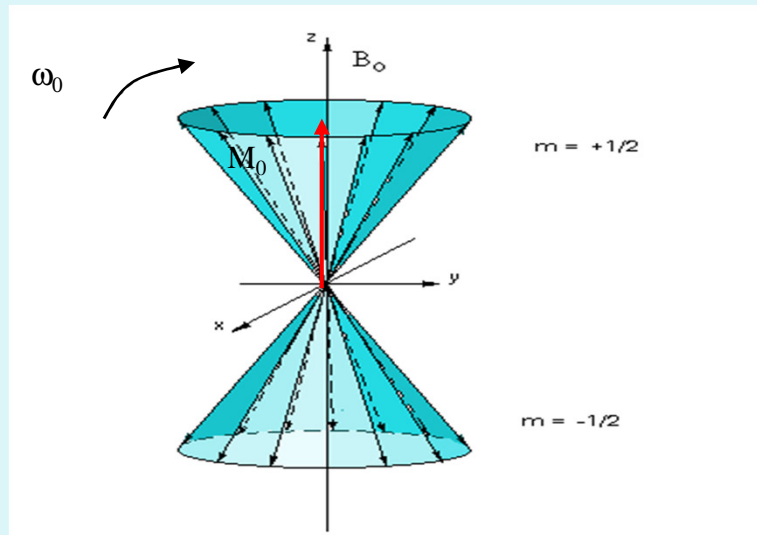
Energies of the eigenstates of \hat{H} : $E_{I,m} = -\gamma \hbar B_0 m$

For one $I = \frac{1}{2}$ spin there are two eigenstates $m = \pm \frac{1}{2}$, with energies

$$E_{\frac{1}{2}, \pm \frac{1}{2}} = \mp \frac{1}{2} \gamma \hbar B_0 = \mp \frac{1}{2} \hbar \omega_0$$



Energy levels for nuclei with spin $I=1/2$. Zeeman states



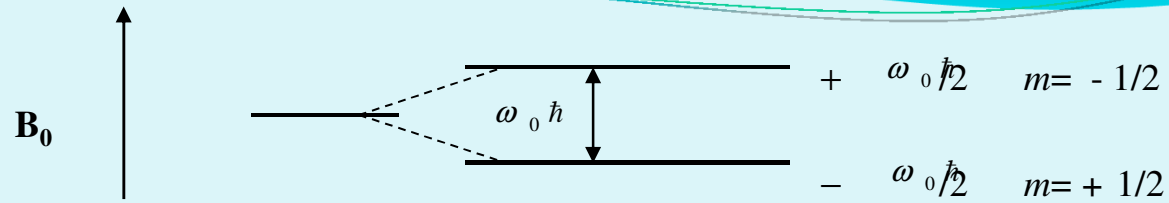
Energy difference between levels
in frequency units corresponds to

$$\Delta E = \omega_0 \hbar$$

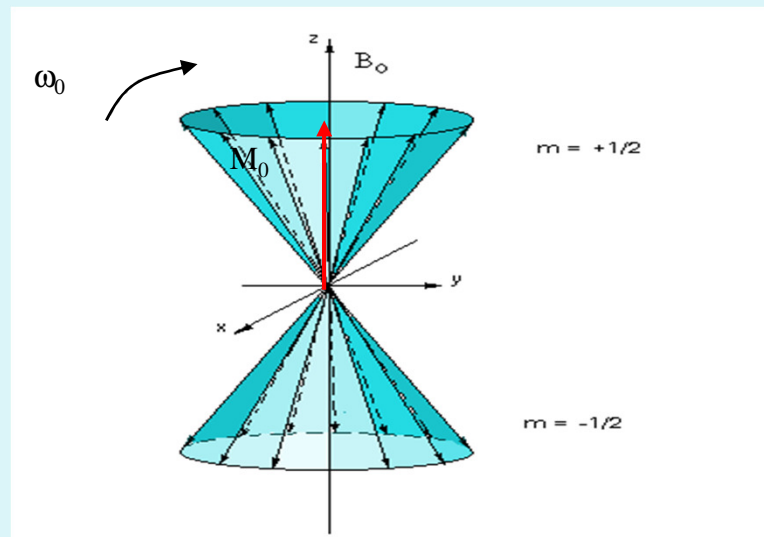
$$\omega_0$$

Classical picture: rotation frequency around static magnetic field

Quantum picture: frequency of the transition between the energy levels.



Energy levels for nuclei with spin $I=1/2$. Zeeman states



$\pi/2$ pulse means equal populations of the energy levels

For a system of no interacting spins, each spin can be in one of the two states. The equilibrium population of the eigenstate ψ (Boltzmann distribution), is

$$p_{\psi} = \frac{\exp(-E_{\psi} / k_B T)}{\sum_{\psi} \exp(-E_{\psi} / k_B T)}$$

$I = 1/2$ results

$$\sum_{m = \pm 1/2} \exp(-E_m / k_B T) \approx 2$$

Each spin system belongs to a superposition state

$$\Psi = \sum_{\psi} \frac{\sqrt{p_{\psi}}}{p_{\psi}} |\psi\rangle$$

Probability for the spin system to be in the eigenstate ψ .

NMR measure only properties of the ensemble average, for example z magnetization will be

$$\langle \hat{\mu}_z \rangle = \gamma \hbar \langle \Psi | \hat{I}_z | \Psi \rangle = \gamma \hbar \sum_{\psi} p_{\psi} \langle \psi | \hat{I}_z | \psi \rangle = \frac{1}{2} \gamma \hbar (p_{\frac{1}{2}} - p_{-\frac{1}{2}}) \quad (1.2.4)$$

where $\gamma \hbar \langle \psi | \hat{I}_z | \psi \rangle$

is the expectation value of the z magnetization for a spin in the state ψ .

Z magnetization correspond to the population difference between the two spin states.

Radio frequency pulses

An alternating magnetic field mix the Zeeman levels

$B_1(t)$ oscillating in the x direction. The total magnetic field acting on the spin is

$$\vec{B} = B_1 \cos(\omega_{rf} t) \hat{i} + B_0 \hat{k}$$

The Hamiltonian becomes

$$\hat{H} = -\gamma \hbar (\hat{I}_z B_0 + \hat{I}_x B_1 \cos(\omega_{rf} t))$$

Transforming to the rotating system. Time dependence of the hamiltonian is eliminated

$$\hat{H}' = -\hbar ((\gamma B_0 - \omega_{rf}) \hat{I}_z + \gamma B_1 \hat{I}_x) \quad (1.2.7)$$

Applying a 90° pulse, i.e.

$$\omega_1 t = \pi / 2, \quad t = \pi / (2 \omega_1) = t_p$$

We obtain

$$p_{\frac{1}{2}}(t_p) = \frac{1}{2} (p_{\frac{1}{2}}(0) + p_{-\frac{1}{2}}(0))$$
$$p_{-\frac{1}{2}}(t_p) = \frac{1}{2} (p_{-\frac{1}{2}}(0) + p_{\frac{1}{2}}(0))$$

A 90° pulse makes equal the populations of the energy levels of the 1/2 spin system. In the same way we can see that a 180° pulso inverts the populations,

$$p_{\frac{1}{2}}(t_p) = p_{-\frac{1}{2}}(0) \quad p_{-\frac{1}{2}}(t_p) = p_{\frac{1}{2}}(0)$$

From the classical vectorial picture we know that a pulse on the x axis generates a magnetization on the y axis, if we calculate the expectation value of the magnetization on the y axis we obtain

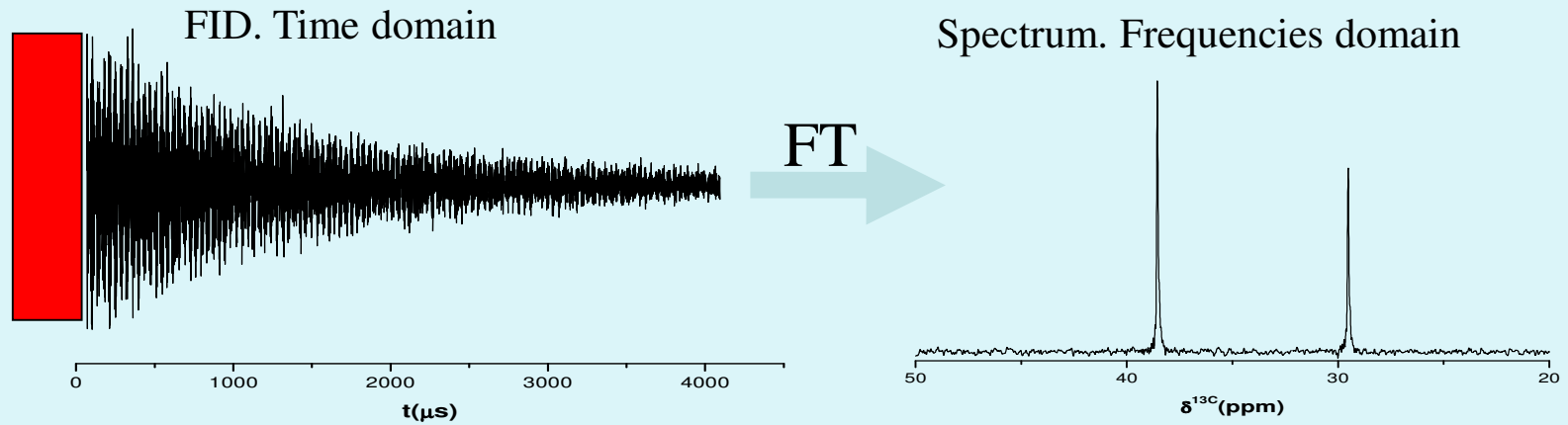
$$\langle \hat{\mu}_y(t) \rangle = \gamma \hbar \langle \hat{I}_y(t) \rangle = \gamma \hbar \langle \Psi' | \hat{I}_y | \Psi' \rangle = -\frac{1}{2} \gamma \hbar \left(p_{\frac{1}{2}}(0) - p_{-\frac{1}{2}}(0) \right) \sin(\omega_1 t)$$

The same result from the vectorial picture, if

$$\omega_1 t = \pi / 2$$

How we do spectroscopy ?

RF Pulse



Nuclear spin interactions

Spectra of liquids are much more simple than the solids

Molecular motions average out many orientationally dependent interactions

Advantages: high resolution

Disadvantages: lack of information

Solid state spectra may have comparable resolution to liquids

We need to understand the nature of the interactions in NMR

External and internal interactions to the molecular system.

External: Zeeman interaction (\mathbf{B}_0)

RF interaction (\mathbf{B}_1)

Internal interactions involve nuclear and magnetic quantities of interest

Nuclear: chemical shift and chemical shift anisotropy

dipole-dipole coupling

Indirect scalar coupling

Quadrupole coupling

In NMR experiments the magnitude of the interactions with the external magnetic field are order of magnitude stronger than the internal interactions with local magnetic fields or than the internal nuclear interactions

The effect of the internal interactions are considered as perturbations to the total system Hamiltonian.

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Chemical shift and chemical shift anisotropy

Electrons shield the nucleus from the effect of the external magnetic field. Usually decrease the field on the nucleus so the resonance frequency decreases also.

The magnitude of the shielding depends on the electronic environment of the observed nuclei. Environments are linked to the chemical behaviour, the effect is known as “chemical shift”

Two electronic contributions:

Diamagnetic and paramagnetic

Diamagnetic is the most important (electrons rounding around the magnetic field applied to the sample) $1/r^3$ dependence with the distance between electrons and nucleus. Diminish the magnetic field on the nuclear site

Paramagnetic: arise because external magnetic fields can mix excited electron state (paramagnetic states) with the fundamental electron state. This contribution unshields the nuclear spin

Solution NMR: each chemical distinct nucleus has its own chemical shift value.

Solids NMR: the shielding change with the molecular orientation so we will get a very broad dispersion of frequencies, i.e. a very broad line

Chemical shift interaction

$$\hat{H}_{cs} = -\gamma \hbar \hat{I}_z \sigma_{zz}^{lab} B_0$$

σ is a second rank tensor called chemical shielding tensor

The diagonal part of σ affect the NMR spectrum

We can chose and reference system fixed to the molecule where σ is diagonal : principal axis system (PAS)

Three quantities represent this tensor

Isotropic value σ_{iso} ,

anisotropy Δ

symmetry η .

In the pas system

$$\begin{aligned}\sigma_{iso} &= \frac{1}{3}(\sigma_{xx}^{pas} + \sigma_{yy}^{pas} + \sigma_{zz}^{pas}) \\ \Delta &= \sigma_{zz}^{pas} - \sigma_{iso} \\ \eta &= (\sigma_{xx}^{pas} - \sigma_{yy}^{pas}) / \sigma_{zz}^{pas}\end{aligned}$$

The first order contribution to the energy of the spin system coming from the chemical shielding is

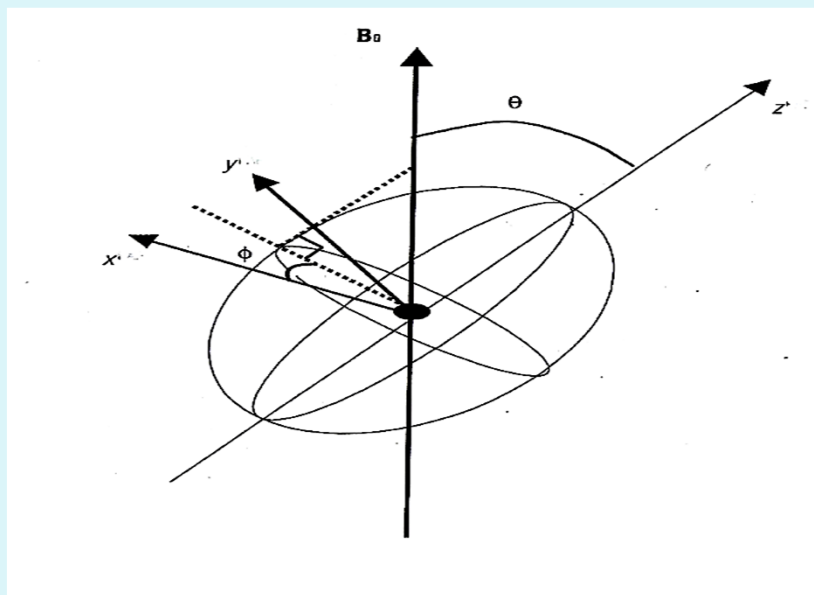
$$E_{cs} = -\gamma \hbar \sigma_{zz}^{lab} B_0 \langle I, m | \hat{I}_z | I, m \rangle = -\gamma \hbar \sigma_{zz}^{lab} B_0 m$$

For $1/2$ spins the contribution to the resonance frequency is

$$\omega_{cs} = -\gamma \sigma_{zz}^{lab} B_0 = -\omega_0 \sigma_{zz}^{lab}$$

It can be shown that in the pas system

$$\omega_{cs}(\theta, \phi) = \omega_0 \sigma_{iso} - \frac{1}{2} \omega_0 \Delta (3 \cos^2 \theta - 1 + \eta \sin^2 \theta \cos 2\phi)$$



PAS system

Chemical shift value in ppm independent on the strength of B_0

$$\delta = \frac{\nu - \nu_{ref}}{\nu_{ref}}$$

$$(\nu = \omega/2\pi)$$

Glycine

static with ^1H decoupling

CSA remains, heteronuclear dipole coupling averaged

MAS at 700 Hz

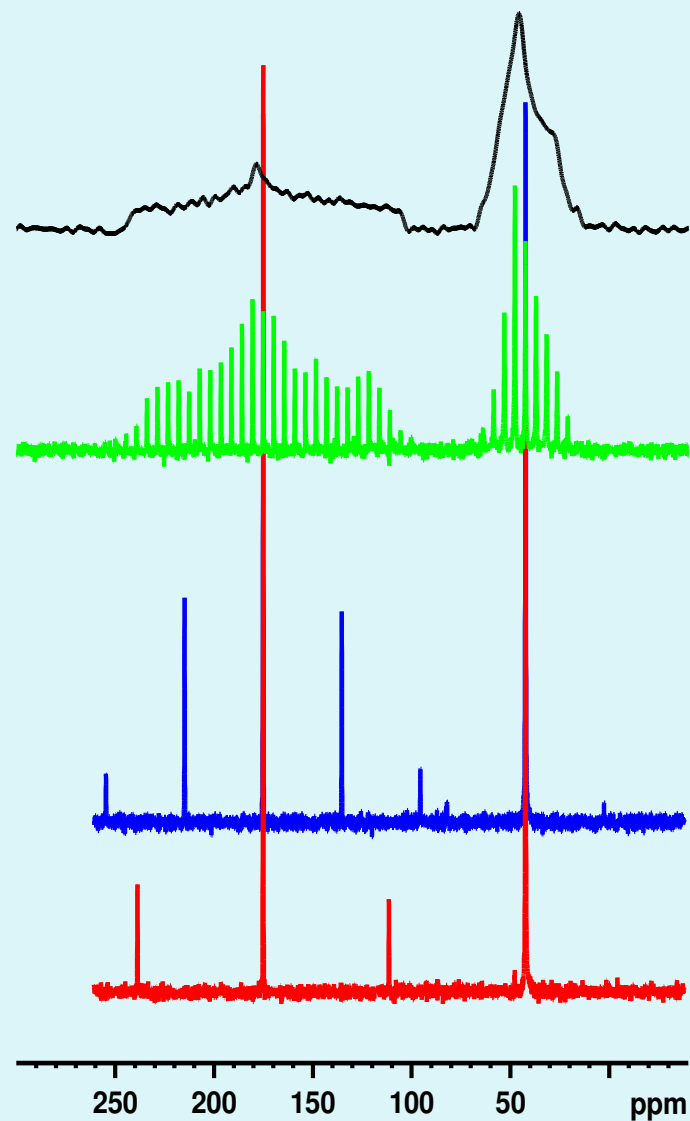
≈ 50 Hz line width

MAS at 5 kHz

≈ 50 Hz line width

MAS at 8 kHz

≈ 50 Hz line width



Dipole dipole coupling

From a classical point of view this term is equivalent to the interaction between two macroscopic magnets. For a couple of spins I and S separated by a distance r , this interaction is represented by the following Hamiltonian (in units of angular frequency, rad / s)

$$\hat{H}_{IS} = - \frac{\mu_0}{4\pi} \gamma_I \gamma_S \hbar \left(\frac{\hat{I} \cdot \hat{S}}{r^3} - 3 \frac{(\hat{I} \cdot \vec{r})(\hat{S} \cdot \vec{r})}{r^5} \right)$$

The isotropic average of the dipolar interaction is zero, so that the dipolar couplings do not influence the resonance frequencies in solution NMR. However in solids the dipolar effects are considerable. The values of the dipolar coupling constant

$$d_{IS} = \left(\frac{\mu_0}{4\pi} \right) \gamma_I \gamma_S \left(\frac{\hbar}{2\pi} \right) r^{-3}$$

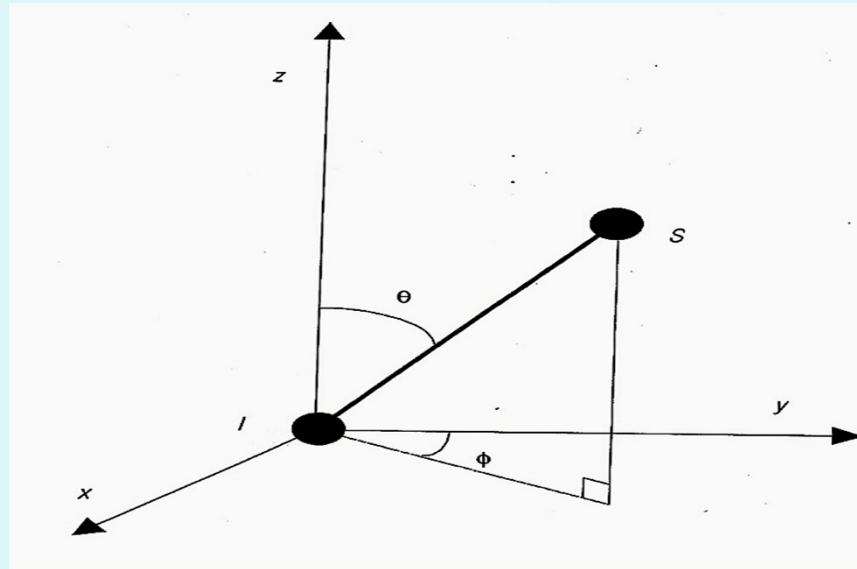
Because its dependence $1 / r^3$, range from zero up to 80 kHz approximately.

The alphabetic expansion of the dipolar Hamiltonian is

$$\hat{H}_{IS} = - \frac{\mu_0}{4\pi} \gamma_I \gamma_S \hbar \frac{1}{r^3} (A + B + C + D + E + F)$$

$$\begin{aligned}
 A &= \hat{I}_z \hat{S}_z (3 \cos^2 \theta - 1) && \text{secular} \\
 B &= -\frac{1}{4} [\hat{I}_+ \hat{S}_- + \hat{I}_- \hat{S}_+] (3 \cos^2 \theta - 1) && \text{flip-flop} \\
 C &= -\frac{3}{2} [\hat{I}_z \hat{S}_+ + \hat{I}_+ \hat{S}_z] \sin \theta \cos \theta e^{-i\phi} \\
 D &= -\frac{3}{2} [\hat{I}_z \hat{S}_- + \hat{I}_- \hat{S}_z] \sin \theta \cos \theta e^{+i\phi} \\
 E &= -\frac{3}{4} [\hat{I}_+ \hat{S}_+] \sin^2 \theta e^{-2i\phi} \\
 F &= -\frac{3}{4} [\hat{I}_- \hat{S}_-] \sin^2 \theta e^{+2i\phi}
 \end{aligned}
 \left. \begin{array}{l} \\ \\ \\ \\ \\ \end{array} \right\} \begin{array}{l} \\ \\ \text{single quantum} \\ \\ \text{double quantum} \end{array}$$

$$\hat{I}_{\pm} = \hat{I}_x \pm i \hat{I}_y, \quad \hat{S}_{\pm} = \hat{S}_x \pm i \hat{S}_y$$



Note: If we consider a system of N uncoupled spins in the presence of a static magnetic field, the total energy operator of the system is the sum of the energy operators for each spin of the system:

$$\hat{H}_0 = -\gamma \sum_j \hat{I}_z^j \vec{B}_0$$

\hat{I}_z^j works on the spin coordinates of the spin j .

The eigenfunctions of \hat{I}_z^j are $|I_j m_j\rangle$

$$\Psi = |I_1 m_1; I_2 m_2; \dots; I_N m_N\rangle$$

The eigenfunctions of the Hamiltonian operator are the products of

$$|I_j m_j\rangle$$

Is a complete set for a system of N spins. Is a good choice to describe a spin system with dipolar interaction.

The interactions that can produce a significant effect on the spin system at equilibrium have the form

$$-\gamma \hbar (\hat{I}_x B_x^{loc}(t) + \hat{I}_y B_y^{loc}(t) + \hat{I}_z B_z^{loc}(t)) \quad (1.4.1)$$

$$B_z^{loc}$$

May represent a static field parallel to \vec{B}_0 that affect the energy levels of the spins.

The other terms are magnetic fields perpendicular to \vec{B}_0 , that affect the system only if their frequencies are near to the Larmor frequencies of the nuclear spins

Terms A and B have the form (1.4.1).

Term A $B_z^{loc} = \hat{S}_z (3 \cos^2 \theta - 1)$

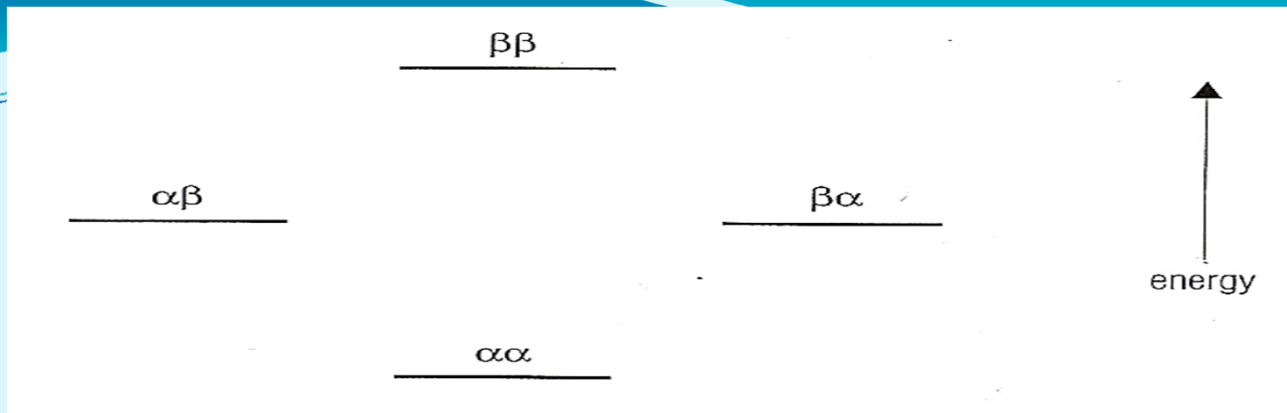
Term B $B_x^{loc}(t) = -\frac{1}{2} \hat{S}_x (3 \cos^2 \theta - 1)$ and $B_y^{loc}(t) = -\frac{1}{2} \hat{S}_y (3 \cos^2 \theta - 1)$

The cross terms are only effective if the local field produced by the spin S at the site of spin I precesses around \vec{B}_0 about the Larmor frequency of spin I.

More formally stated the terms that commute with the Zeeman Hamiltonian are those that have a significant effect on energy levels of a spin system IS.

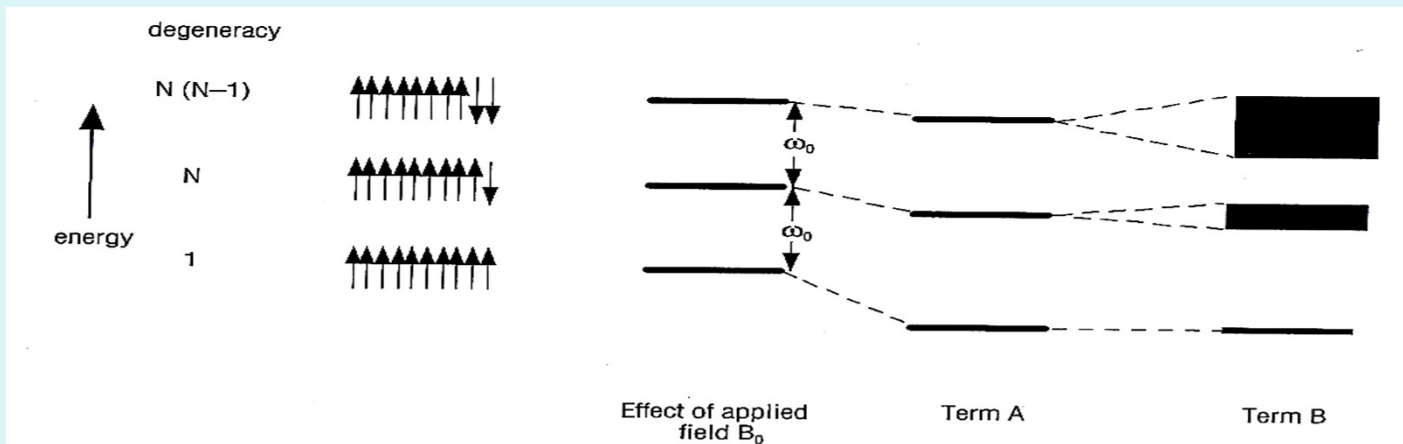
In the case of homonuclear dipolar coupling (like spins) the Hamiltonian can be reduced to (main contributions)

$$\hat{H}_{IS} = -\frac{\mu_0}{4\pi} \gamma_I \gamma_S \hbar \frac{1}{r^3} (3 \cos^2 \theta - 1) \left[\hat{I}_z \hat{S}_z - \frac{1}{2} \left[\hat{I}_x \hat{S}_x + \hat{I}_y \hat{S}_y \right] \right]$$



The energy levels and wavefunctions in a homonuclear two-spin system, before dipolar coupling is considered, i.e. the Zeeman states. The $\alpha\beta$ and $\beta\alpha$ levels are degenerate in a homonuclear spin system and are mixed by dipolar coupling.

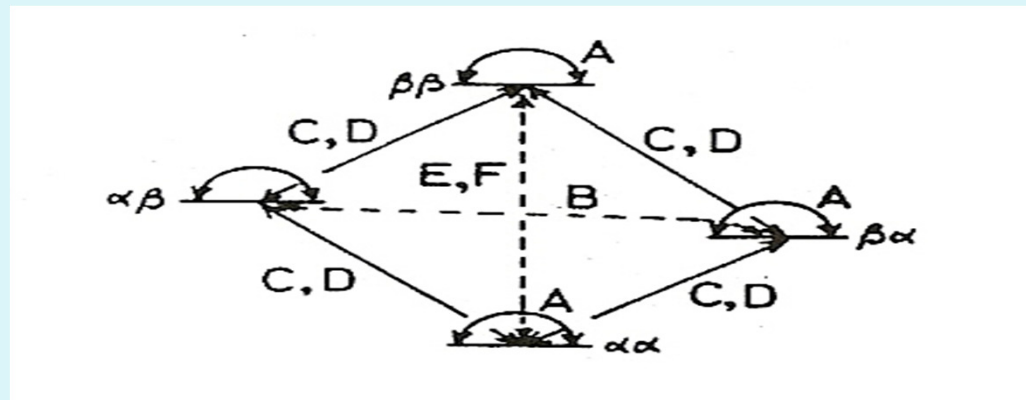
A term: change at first order all the energy levels. *B* term: mix the degenerated states and split their energies producing very wide lines in proton resonances for example.



In an N -spin, homonuclear, system, there may be many Zeeman levels with the same M quantum number ($M = m_1 + m_2 + \dots + m_N$); these are degenerate in the absence of dipolar coupling. Dipolar coupling has the effect of mixing these degenerate states and splitting their energy.

Heteronuclear case. The B term can be neglected, because S spin resonance is far away from I spin resonance. The reduced Hamiltonian is

$$\hat{H}_{IS}^{hetero} = -\frac{\mu_0}{4\pi} \gamma_I \gamma_S \hbar \frac{1}{r^3} (3 \cos^2 \theta - 1) \hat{I}_z \hat{S}_z$$



Energy levels and allowed transitions for a system with heteronuclear coupling

In this case there are no mixing of the spin states, the product

$$|I, m_I\rangle |S, m_S\rangle = |I, m_I; S, m_S\rangle$$

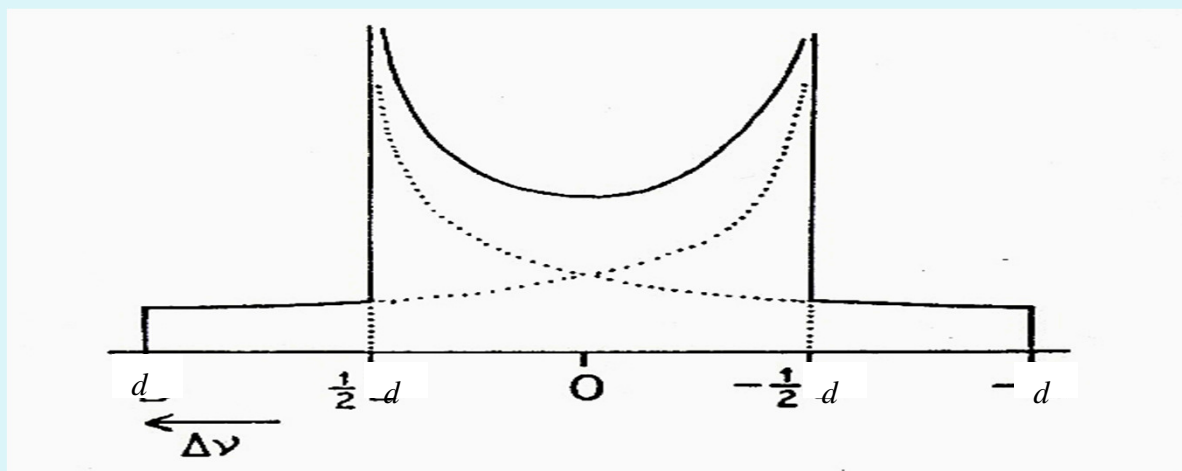
are eigenfunctions of the Heteronuclear dipolar Hamiltonian

$$E_{IS}^{hetero} = -d \hbar (3 \cos^2 \theta - 1) m_I m_S, \quad d = \frac{\mu_0}{4\pi} \gamma_I \gamma_S \frac{1}{r^3}$$

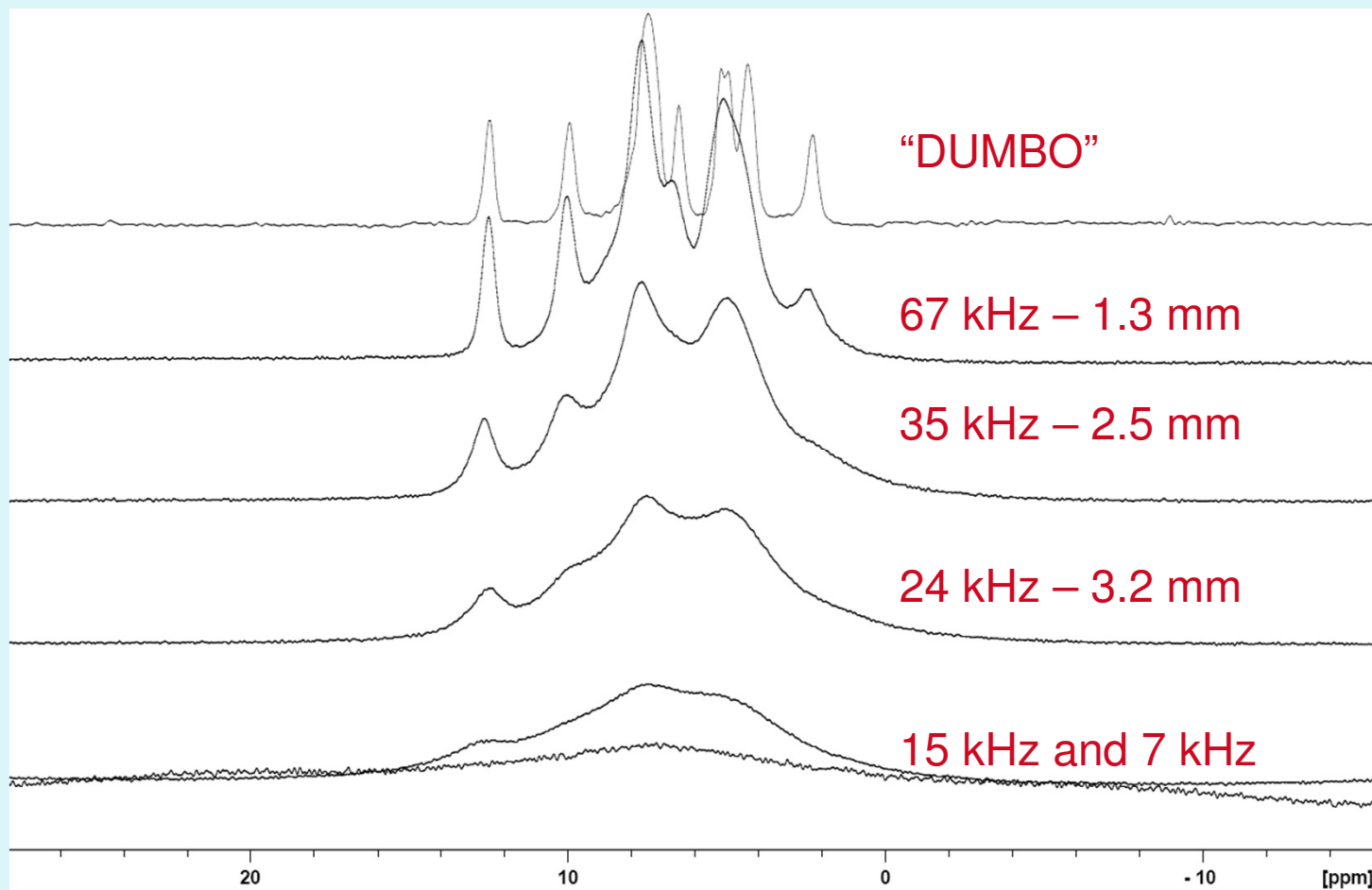
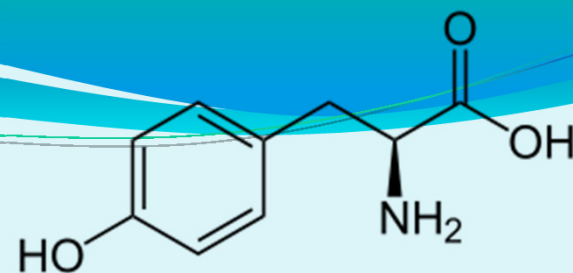
Transitions frequencies for spin I are

$$\omega^I = \omega_0^I \pm \frac{1}{2}d (3 \cos^2 \theta - 1)$$

The powder lineshape for the I spin in a heteronuclear two-spin system. The shape is due to the θ dependence of the frequency. The splitting of the 'horns' is equal to the dipolar coupling constant d . The horns are created by crystallites in which the I - S internuclear vector is perpendicular to the applied field

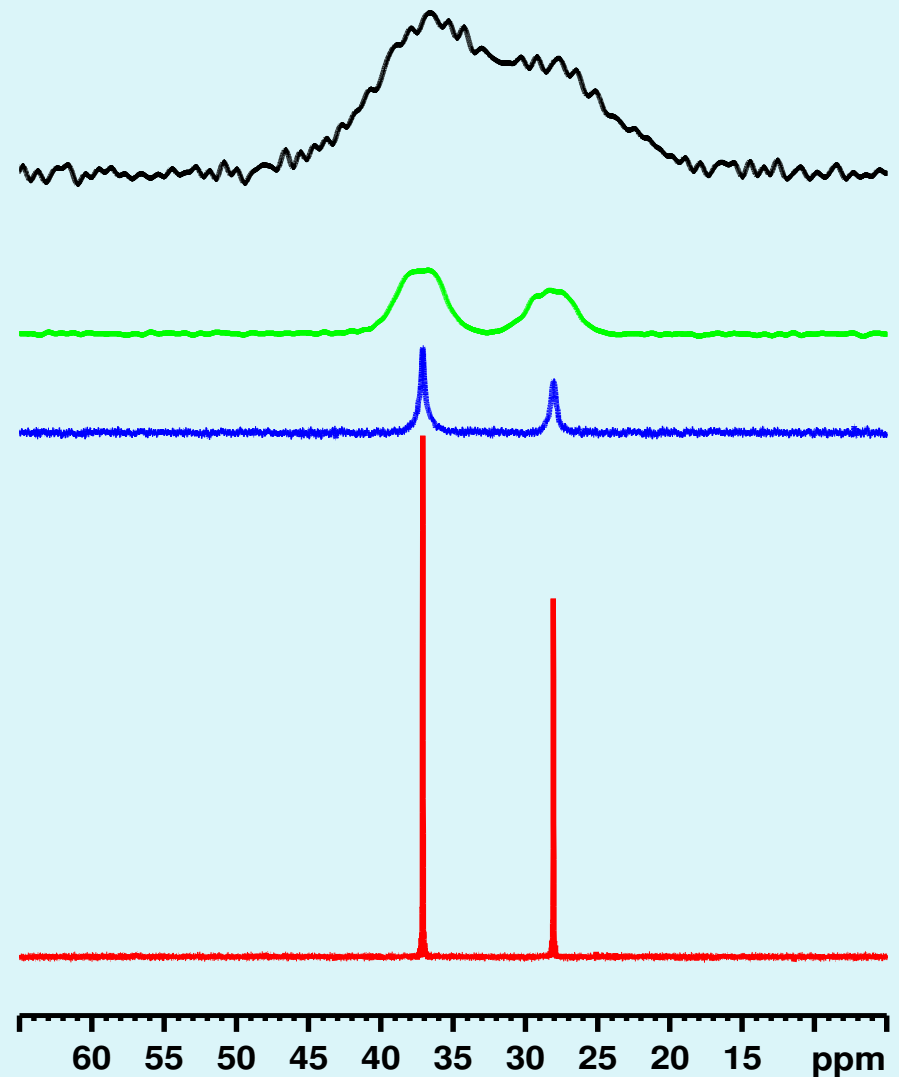


Tyrosine
Homonuclear dipolar coupling



Adamantane Heteronuclear ^{13}C - ^1H dipolar coupling

- static, not ^1H decoupled
 - CSA and hetero dipole
 - 1000 Hz line width
- static, ^1H decoupled
 - CSA, no hetero dipole
 - 500 Hz line width
- MAS, not ^1H decoupled
 - no CSA, hetero dipole
 - 50 Hz line width
- MAS, ^1H decoupled
 - no CSA, no hetero dipole
 - 5 Hz line width



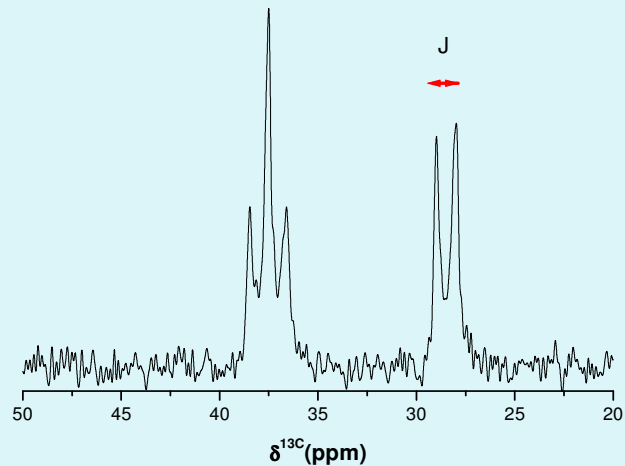
Indirect coupling or scalar coupling J

This occurs via the electronic path that connects the coupled nuclei. There is an isotropic value J_{KI} , which produces the known splittings in NMR of solutions. These isotropic values are between Hertz and less than a few hundred Hertz. Therefore this coupling is rarely observed in solids.

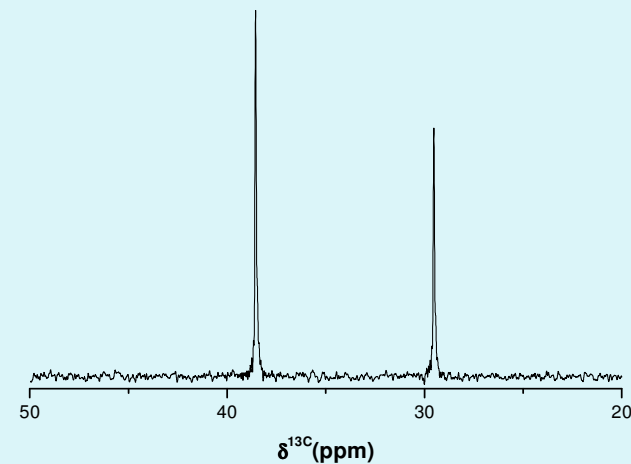
The scalar coupling Hamiltonian is of the form:

$$\hat{H}_J = 2\pi\hbar \hat{I} \cdot \mathbf{J} \cdot \hat{S}$$

$^{13}\text{C} \{^1\text{H}\}$ CP/MAS spectrum with homonuclear proton decoupling during acquisition. It can be observed the heteronuclear ^1H - ^{13}C coupling



$^{13}\text{C} \{^1\text{H}\}$ CP/MAS spectrum with heteronuclear proton-carbon decoupling during acquisition



Quadrupole Coupling

This coupling occurs only for nuclei with spin quantum number $I > 1/2$. Relates the electric quadrupole coupling of an electric field gradient produced by electrons in the vicinity of the nucleus. The isotropic value is zero, so that does not affect the spectra of solutions. However, for solids can be very important because the interaction may have values ranging from zero to hundreds of MHz. More than 79% of the nuclei have spin greater than $1/2$. Important, in what follows, we will assume that the quantization axis is defined by the direction of the external field, i.e. Zeeman interaction is still dominant and so I and m denote the total spin and total spin projection on the axis quantization. This is not true for all quadrupolar nuclei and all fields.

Quadrupole interaction Hamiltonian

$$\hat{H}_Q = \frac{e^2 Q}{6 I (2 I - 1)} \hat{I} \cdot \mathbf{e} \mathbf{q} \cdot \hat{I}$$

$\mathbf{e} \mathbf{q}$ is the electric field gradient tensor; i.e. $e q_{\alpha\beta}$ ($\alpha, \beta = x, y, z$) is the α gradient component of the electric field in the β direction. The $\mathbf{e} \mathbf{q}$ tensor has null trace, i.e. there is no isotropic contribution. In the PAS system of the molecule we define two parameters, the quadrupolar constant coupling χ and the asymmetry parameter η .

$$\chi = \frac{e^2 q_{zz}^{pas} Q}{\hbar} \quad \eta = \frac{q_{xx}^{pas} - q_{yy}^{pas}}{q_{zz}^{pas}}$$

At first order in \vec{B}_0

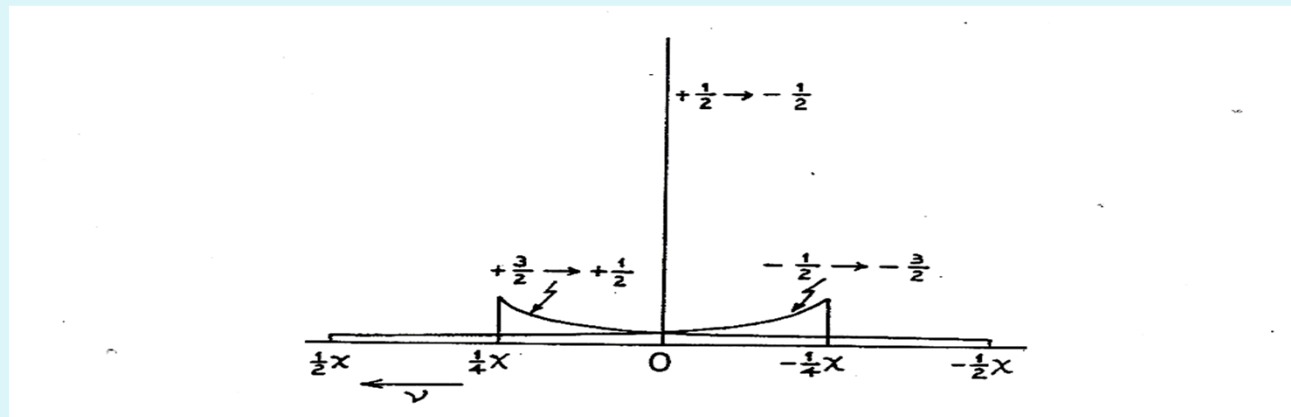
$$\hat{H}_Q = \frac{3\chi}{8I(2I-1)} (3\cos^2\theta - 1 + \frac{1}{2}\eta \sin^2\theta \cos 2\phi) (3\hat{I}_z^2 - \hat{I}^2)$$

θ and ϕ polar angles, define the orientation of the magnetic field \vec{B}_0 in the pas system of the EFG tensor.

For axial symmetry, $q_{xx}^{pas} = q_{yy}^{pas} \neq q_{zz}^{pas}$ we have

$$\omega_Q(\theta) = \omega_0 - \frac{3}{8} \left(\frac{2m-1}{I(2I-1)} \right) \chi (3\cos^2\theta - 1), \quad m = I, I-1, \dots, -I$$

For $I = 3/2$, $m = +1/2$ to $m = -1/2$ transition is not θ dependent, i.e. narrow line (see figure below)



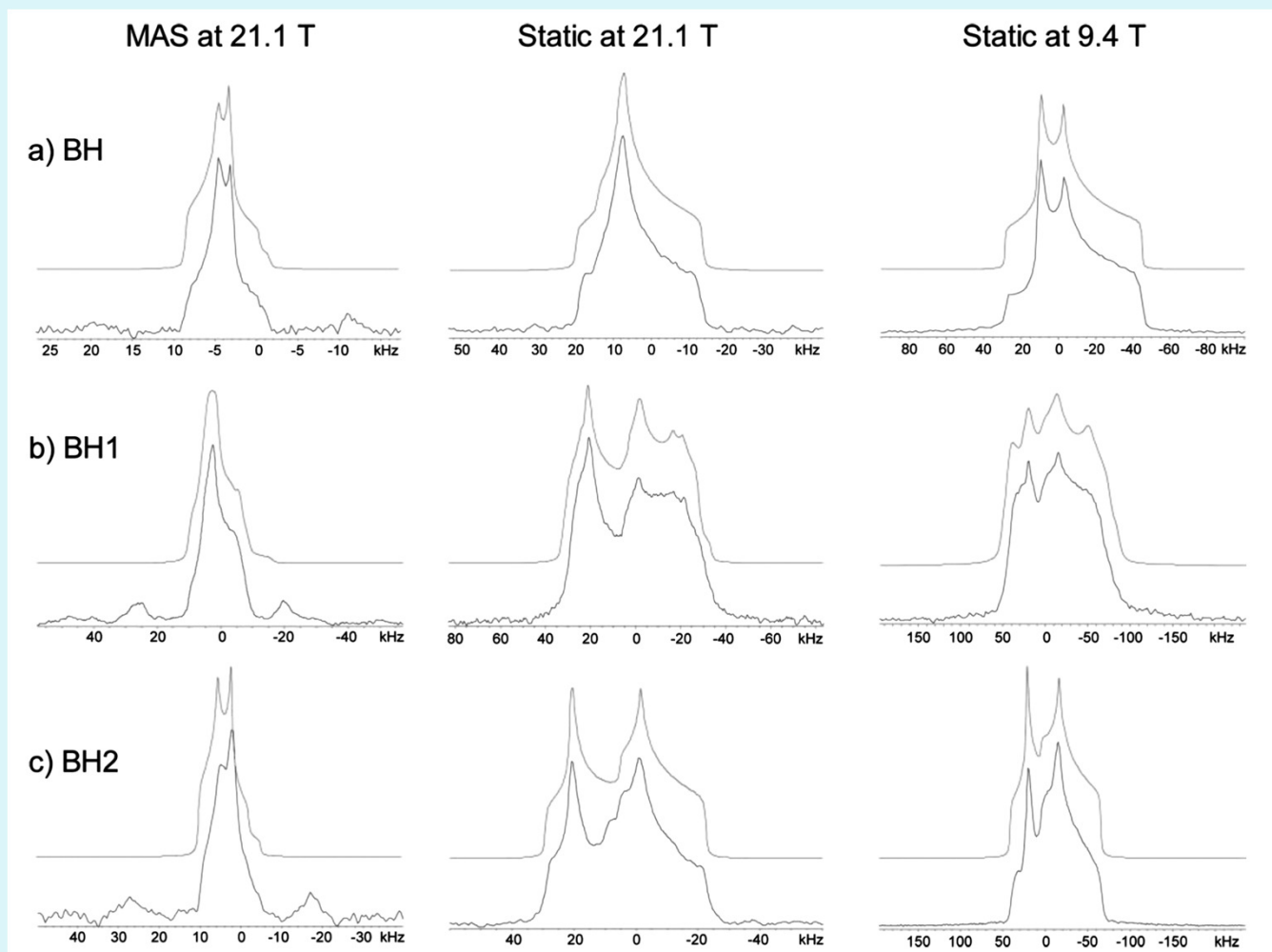


Figure 5: ^{35}Cl SSNMR spectra (bottom) and simulations (top) of monohydrated bupivacaine HCl (BH) and its polymorphs: (a) commercial BH; (b) BH1; (c) BH2. Hamaed, H., et al., *Journal of the American Chemical Society*, 2008. **130**(33): p. 11056-11065..

Common facts:.

- all interactions involve tensorial quantities (a tensor is a property that link two vectors).
- all depend on the orientation of the molecule relative to the external magnetic field.
- all have the same dependence with orientation, $(3\cos^2\theta-1)$, θ is the angle between \vec{B}_0 and the direction of the molecular axis.
- all terms can be written as

$$\hat{H} = C \cdot \hat{I} \cdot \mathbf{R} \cdot Y$$

C is a constant, \hat{I} is a nuclear spin operator, \mathbf{R} is a geometric quantity (tensor), Y can be an operator or other quantity.

In conclusion, the appearance of NMR spectra in solids depend on the molecular orientations range involved. For samples of microcrystalline powder or amorphous materials, there will be a full range of orientations and therefore very broad resonance lines will be observed.

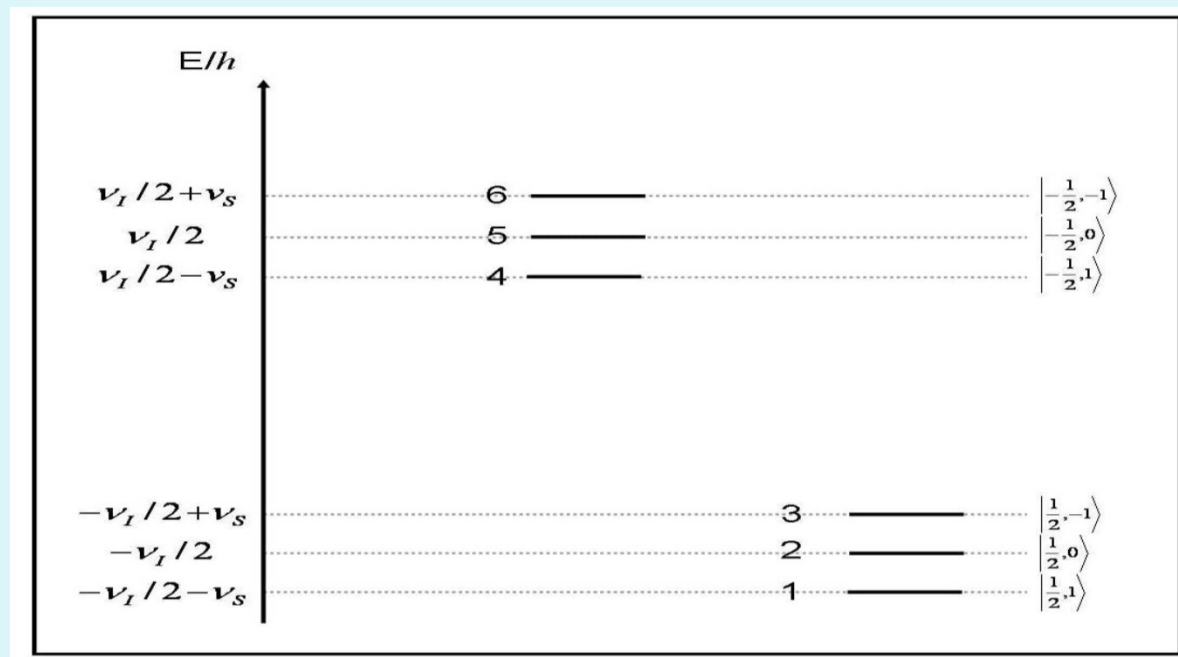


Residual dipolar interaction

NMR signals of ^{13}C nuclei or (in general $\frac{1}{2}$ spin nuclei) bond to quadrupolar nuclei present particular line shapes. This phenomenon involves the transference of the quadrupolar effects to the nucleus with $\frac{1}{2}$ spin being observed. This effects are transmitted via dipolar magnetic interaction between the nuclear species, and therefore depends on the internuclear distance.

The zeeman interaction for a pair of spins I and S (I has spin $\frac{1}{2}$, S has spin 1) is,

$$H_z = H_{Iz} + H_{Sz}$$



Zeeman energy levels for a system I = $\frac{1}{2}$, S = 1

If we consider now the dipolar interaction, the transition frequencies will be

$$\nu_{1 \rightarrow 4} = \nu_I - b_{IS} (1 - 3 \cos^2 \theta)$$

$$\nu_{2 \rightarrow 5} = \nu_I$$

$$\nu_{3 \rightarrow 6} = \nu_I - b_{IS} (1 - 3 \cos^2 \theta)$$

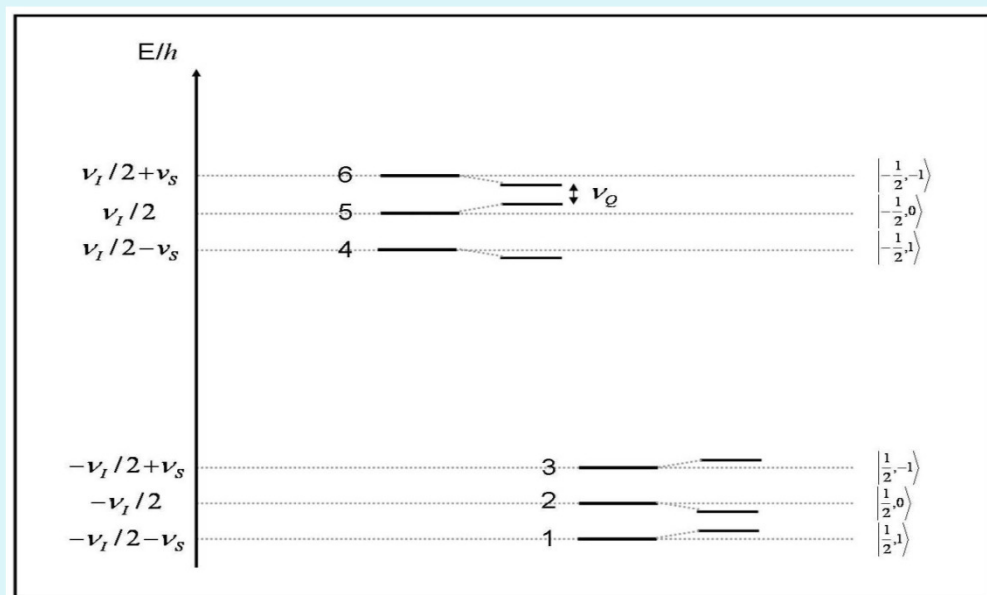
Where b_{IS} is the magnitude of the heteronuclear dipolar interaction and θ the angle between the internuclear vector and the external magnetic field

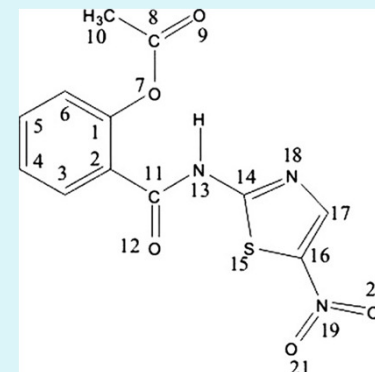
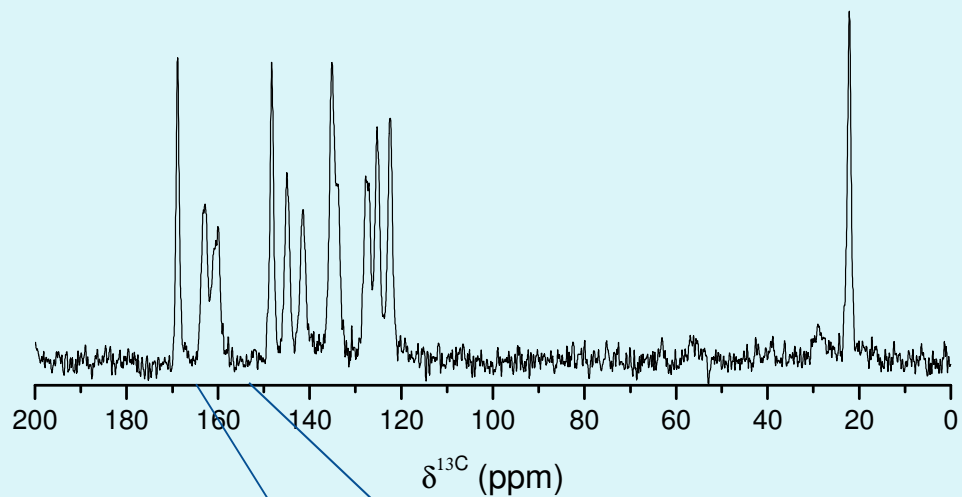
Finally taken into account also the quadrupolar interaction, we will have

$$\nu_{1 \rightarrow 4} = \nu_I - \frac{9}{4} \frac{b_{IS} \chi}{\nu_S}$$

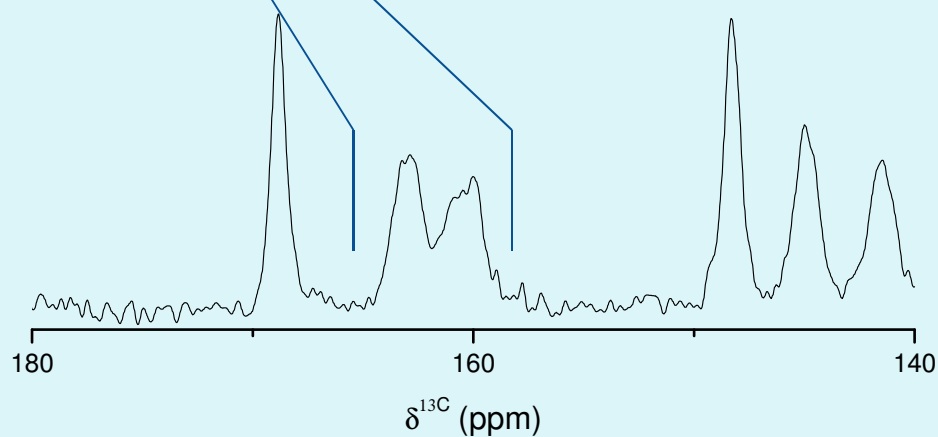
$$\nu_{2 \rightarrow 5} = \nu_I + \frac{9}{2} \frac{b_{IS} \chi}{\nu_S}$$

$$\nu_{3 \rightarrow 6} = \nu_I - \frac{9}{4} \frac{b_{IS} \chi}{\nu_S}$$





Nitazoxanida



the broadening of the peaks for the 11-carbonyl carbon (163.0 ppm) and C-14 (160.4 ppm) can be attributed to residual dipolar interaction with quadrupolar ^{14}N atoms.
Bruno et al. *Journal of Molecular Structure*, **984**, 51-57 (2010)