NMR of Paramagnetic Molecules

Kara L. Bren
University of Rochester
Outline

• Resources
• Examples of effects on spectra
• What we can learn (why bother?)
• NMR fundamentals (review)
• Relaxation mechanisms in NMR
• Effects of unpaired electrons on relaxation
• Effects of unpaired electrons on chemical shifts
Resources


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Effects of Unpaired Electrons

Horse ferricytochrome c

$S = \frac{1}{2}$
Effects of Unpaired Electrons

Horse ferricytochrome c

S = 1/2

Heme methyls
Effects of Unpaired Electrons

CN-Fe(III) cytochrome c, D$_2$O

* = heme methyls

S = $1/2$

CN-Fe(III) M80A cytochrome c, D$_2$O

H$_2$O

JACS 1995, 8067

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Effects of Unpaired Electrons

*H. thermophilus* Fe(III)M61A cyt c

S = 1/2, 5/2

a, b, c, d = heme methyls

Bren group
Effects of Unpaired Electrons

*P. aeruginosa Cu(II) azurin*

\( S = \frac{1}{2} \)

\[ \delta, \text{ ppm} \]

![Graph showing peaks labeled A to J and a chemical structure with a Cu atom bonded to Cys and His residues.](image)
Effects of Unpaired Electrons

Ni(II) azurin

$S = 1$
Effects of Unpaired Electrons

*T. thermophilus* Cu$_A$ domain

Cu(I)Cu(II) $S = 1/2$

pH 8.0, H$_2$O

pH 4.5, H$_2$O

JACS 1996, 11658

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What Can We Learn?

- Metal oxidation state and spin state
- Electron spin relaxation time (estimate)
  - Presence of low-lying excited states
- Pattern and amount of electron spin delocalization onto ligands; hyperfine coupling constants
- Presence of hydrogen bonds
- Magnetic anisotropy, magnetic axes
- Structural refinement is possible
- (In addition, 3D structure, exchange phenomena, dynamics, etc.)
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Some nuclei have spin angular momentum and an associated magnetic moment, $\mu_I$.

$$\mu_I = g_N \left(\frac{e}{2m_p}\right) I$$

$$g_N \left(^1H\right) = 5.5856947$$

$$|\mu_I| = \left(\frac{h}{2\pi}\right) I[I(I+1)]^{1/2}$$

Need nucleus with non-zero spin ($I \neq 0$)

Examples: $^1H, ^{13}C, ^{15}N, ^{19}F, ^{31}P$ ($I = 1/2$)

$^2H, ^{14}N, (I = 1)$

Herein we will base examples in nuclei with $I = 1/2$
NMR Fundamentals

A nucleus with spin \( I \) has states with associated \( M_I \) values where \( M_I = -I, =I+1, \ldots I \).

When \( I = 1/2 \), \( M_I = \pm 1/2 \).

In the absence of a magnetic field, states with different \( M_I \) are degenerate and their magnetic moments \( \mu \) orient randomly.
NMR Fundamentals

Applying a magnetic field lifts this degeneracy. $^1\text{H}$ with $M_I = -1/2$ have a higher energy and $^1\text{H}$ with $M_I = +1/2$ have a lower energy.

The nuclear spins align with ($M_I = +1/2$) or opposed to ($M_I = -1/2$) the applied magnetic field:

The $z$ component of the magnetic moment is shown and is $M_I \hbar /2\pi$
NMR Fundamentals

The energies of the nuclei in the magnetic field are:

\[ E = -M_I \mu B_0 / I \]

Transitions may be induced between \( M_I \) states.

The selection rule is \( \Delta M_I = \pm 1 \)

\[ \Delta E = \mu B_0 / I = h \nu \]

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NMR Fundamentals

The energies of the nuclei in the magnetic field are:

\[ E = -M_I \mu B_0 / I \]

\[ \Delta E = \mu B_0 / I = h \nu \]

Traditionally, the magnetogyric ratio \( \gamma (T^{-1} \text{ s}^{-1}) \) is used in NMR:

\[ \gamma = \mu 2\pi / h I, \text{ so} \]

\[ \Delta E = \gamma B_0 / 2\pi = h \nu \]
A transition between $M_I$ states corresponds to a “spin flip.”

At equilibrium there is a small excess of spins aligned with the field:

$$\frac{N(-1/2)}{N(+1/2)} = \exp\left[-(E_{-1/2} - E_{+1/2})/k_B T\right]$$

$$\Delta E = \gamma B_0/2\pi$$
We can consider a net magnetization vector for the sample. Exciting the sample decreases the difference in up and down spins, tipping this vector, after which it returns to equilibrium:

Pulse width is time of pulse; adjust time to change tip angle (i.e. 90° pulse)
NMR Fundamentals

$M_z$ is undergoing precession throughout this process – think of a cone rather than just the $M_z$ vector tipping – precession frequency is the Larmor frequency:

$$\omega_0 = \gamma B_0 \text{ (rad)} \quad \text{or} \quad \nu_0 = \frac{\gamma B_0}{2\pi} \text{ (Hz)} \quad \text{(Larmor equation)}$$
NMR Fundamentals

The observable signal is recorded in the $xy$ plane during relaxation. $T_1 =$ relaxation along $z$ axis; $T_2 =$ relaxation in $xy$ plane. Precession frequency is observed.
NMR Fundamentals

The observable signal is recorded in the xy plane during relaxation. $T_1 = \text{relaxation along } z \text{ axis}; T_2 = \text{relaxation in xy plane.}$ Precession frequency is observed.

FID: time-domain signal in xy plane

Line width
$\Delta \nu = \frac{1}{\pi T_2}$

Fourier Transform
$\nu_0$

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NMR Fundamentals

The chemical shift results from small deviations from $\nu_0$

Chemical shift:
$$\delta \text{ (ppm)} = 10^6 \frac{\nu(\text{obs}) - \nu(\text{ref})}{\nu(\text{ref})}$$

The chemical environment of nuclei (especially circulation of electrons) leads to deviations of $\nu(\text{obs})$ giving different chemical shifts.

Unpaired electrons can have very large effects on chemical shifts through different mechanisms.
# Electrons vs. Nuclei

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Electron</th>
<th>$^1$H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>$S = 1/2$</td>
<td>$I = 1/2$</td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>$\mu_e$</td>
<td>$\mu_I$</td>
</tr>
<tr>
<td>Gyromagnetic ratio</td>
<td>$\gamma_e = \mu_B \frac{g_e}{h}$</td>
<td>$\gamma_I = \mu_I \frac{g_I}{h}$</td>
</tr>
<tr>
<td>Transition energy in field $B_0$</td>
<td>$h\nu = g_e \mu_B B_0$</td>
<td>$h\nu = h \gamma_I B_0/2\pi$</td>
</tr>
<tr>
<td>Transition between states</td>
<td>$M_S = \pm 1/2$</td>
<td>$M_I = \pm 1/2$</td>
</tr>
</tbody>
</table>
Electrons vs. Nuclei

Two major differences:

• Electrons have a larger magnetic moment
  • $|\mu_B| = 658 \; |\mu_1(1H)|$
  • Larger resonance frequency
  • More efficient relaxation

• Electrons are in orbitals
  • Delocalization
  • Spin-orbit coupling
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Relaxation in NMR

The observable signal is recorded in the $xy$ plane during relaxation. $T_1 = \text{relaxation along } z \text{ axis}; \ T_2 = \text{relaxation in } xy \text{ plane.}$

FID: time-domain signal in $xy$ plane

Line width
$\Delta \nu = 1/(\pi T_2)$

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Relaxation in NMR

The observable signal is recorded in the xy plane during relaxation. $T_1 =$ relaxation along $z$ axis; $T_2 =$ relaxation in xy plane.

Assumption here: $T_1 = T_2$ (simplest case – fast motion)

Relaxation must be induced by exchange of energy at the resonance frequency $\nu$

Energy provided by fluctuating magnetic field – here we’ll consider unpaired electrons as a source
Relaxation Mechanisms

- Dipole-dipole
  - Most important
  - Through-space interaction between magnetic moments and fluctuating magnetic field
  - Modulated by molecular tumbling
- Quadrupolar \((I>1/2)\), scalar
- Spin rotation
- Chemical shift anisotropy
- Others…
Dipole-dipole Relaxation

- The relaxation of one spin (dipole) by through-space interactions with other dipoles
- A fluctuating field is needed, and this is generated by molecular motion
- Relaxation rate depends on $\mu_1^2 \mu_2^2$, $r^{-6}$, $\tau_c$

$\tau_c$: correlation time

$\tau_c = \frac{4\pi a^3 \eta}{3kT}$
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Dipole-dipole Relaxation

- Depends on $\mu_1^2 \mu_2^2$, $r^{-6}$, $\tau_c$
- An unpaired electron’s $\mu$ is 658x greater than $\mu$ for $^1$H.
- Unpaired electron has a large impact on $^1$H relaxation

For dipole-dipole nuclear relaxation by unpaired electron:

$$T_{1,2}^{-1} = R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_I^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \tau_c$$

Note dependence on $S$, $\gamma_I$, $r^{-6}$, $\tau_c$

But there is more to $\tau_c$ …
The correlation time $\tau_c$ actually contains three contributions:

1. molecular tumbling time ($\tau_r$), 2. electron spin relaxation time ($\tau_s$), 3. chemical exchange ($\tau_M$).

The overall correlation $\tau_c$ time is:

$$
\tau_c^{-1} = \tau_r^{-1} + \tau_s^{-1} + \tau_M^{-1}
$$

Assuming no chemical exchange:

$$
\tau_c^{-1} = \tau_r^{-1} + \tau_s^{-1}
$$

In a diamagnetic system, no chemical exchange:

$$
\tau_c^{-1} = \tau_r^{-1}
$$
Correlation Time

In a paramagnetic molecule, especially if it is not too large (large means long $\tau_r$), $\tau_s$ usually dominates $\tau_c$

$\tau_r$ ranges from $10^{-9}$ s (small protein) to $10^{-7}$ s (large for NMR)

$\tau_s$ ranges from $10^{-13}$ s to $10^{-8}$ s; but values $10^{-13}$ to $10^{-10}$ most feasible for high-resolution NMR.

Thus $\tau_r^{-1} \ll \tau_s^{-1}$ and $\tau_s$ dominates $\tau_c$ for metalloproteins.

Example: Fe(III)cytochrome c (MW = 12 kDa):

$\tau_c^{-1} = \tau_r^{-1} + \tau_s^{-1} = (10^{-9} \text{ s})^{-1} + (10^{-13} \text{ s})^{-1}$

$\tau_c = 10^{-13} \text{ s} = \tau_s$
Correlation Time

In a paramagnetic molecule, especially if it is not too large (large means long $\tau_r$), $\tau_s$ usually dominates $\tau_c$

Note for small molecules, especially with long $\tau_s$, instead you may have $\tau_c = \tau_r$

Small Cu(II) complex, $\tau_s = (10^{-8} \text{ s})$, $\tau_r = (10^{-12} \text{ s})$

In this case, $\tau_s^{-1} < \tau_r^{-1}$ and $\tau_c = \tau_r$. 
Dipole-dipole Relaxation – e⁻/nucleus

\[ R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_I^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \]

\( \tau_c = \tau_s \)

For NMR of metalloproteins, variations in \( \tau_s \) are the most important factor determining line widths. It also can be important for small molecules.

Long \( \tau_s \) => large \( R_{1,2} \) => small \( T_{1,2} \) => large \( \Delta\nu \) (broad line)
Electron Spin Relaxation Times $\tau_S$

$$R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_I^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \tau_S$$

<table>
<thead>
<tr>
<th>Metal</th>
<th>Ox state</th>
<th>S</th>
<th>C.N.</th>
<th>$\tau_S$ (s)</th>
<th>Linebroadening (Hz)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>+3</td>
<td>1/2</td>
<td>5,6</td>
<td>$10^{-12} - 10^{-13}$</td>
<td>0.5-20</td>
</tr>
<tr>
<td>Fe</td>
<td>+3</td>
<td>5/2</td>
<td>4,5,6</td>
<td>$10^{-9} - 10^{-11}$</td>
<td>200-12000</td>
</tr>
<tr>
<td>Fe</td>
<td>+2</td>
<td>2</td>
<td>4</td>
<td>$10^{-11}$</td>
<td>150</td>
</tr>
<tr>
<td>Fe</td>
<td>+2</td>
<td>2</td>
<td>5,6</td>
<td>$10^{-12} - 10^{-13}$</td>
<td>5-20</td>
</tr>
<tr>
<td>Cu</td>
<td>+2</td>
<td>1/2</td>
<td>any</td>
<td>$(1-5) \times 10^{-9}$</td>
<td>1000-5000</td>
</tr>
<tr>
<td>Mn</td>
<td>+2</td>
<td>5/2</td>
<td>4,5,6</td>
<td>$10^{-8}$</td>
<td>100000</td>
</tr>
<tr>
<td>Mn</td>
<td>+3</td>
<td>2</td>
<td>4,5,6</td>
<td>$10^{-10} - 10^{-11}$</td>
<td>150-1500</td>
</tr>
</tbody>
</table>

*for $^1$H 5 Å from metal

Coord. Chem. Rev. 1996, 150, p. 84
Paramagnetic Relaxation Enhancement

\[ R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_I^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \tau_s \]

- Measure distances \( r \) and/or refine structures by measuring effects of a paramagnetic probe on line widths and relaxation times \( R_{1,2} \)

- Need to be in regime where dipolar relaxation dominates

- Other effects on relaxation:
  - Contact, applicable mostly for small molecules (rapid tumbling) with large \( \tau_s \) (slow electron relaxation)
  - Curie, most relevant for very large molecules with high \( S \)
  - Effects of quadrupolar nuclei
Contact Relaxation

Contact:
(in absence of exchange phenomena)

\[ R_{1,2} = 2/3 \ S(S+1) \ (A/h)^2 \ \tau_s \]

Dipolar:
(when \( \tau_s^{-1} \gg \tau_r^{-1} \))

\[ R_{1,2} = 4/3 \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_I^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \ \tau_s \]

- Depends on \( S, A^2, \) and \( \tau_s \)
- Never depends on \( \tau_r \) (why not)?
- May be in effect when hyperfine coupling is strong over a number of bonds (so not extremely small \( r \))
- Will be in effect when \( \tau_s/\tau_r \) is relatively large
- May be in effect for very large \( A \) values.
What can I do with these broad peaks?

- **Try some cool tricks, and learn what you can!**
- Change metal or metal oxidation state (although you may want to study the native metal in a particular oxidation state, of course).
- Take advantage of the situation! Fast relaxation times means you can use a short acquisition time and recycle time, and get many scans in a short period of time while enhancing intensity of broad peaks.
- Increase the temperature – faster tumbling (shorter $\tau_r$) and faster electron relaxation (shorter $\tau_s$) (and faster exchange if present) can help significantly.
- Detect nuclei other than $^1$H – especially $^{13}$C, $^{15}$N, or $^2$H. Relaxation enhancement and line widths depend on $\gamma^2$. 
Finding Hidden Peaks

*P. aeruginosa* Cu(II) azurin

\[ S = 1/2 \]
\[ \tau_s \sim 10^{-9} \text{ s} \]

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**JACS 2000, 3701**

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Finding Hidden Peaks

Saturation transfer experiment

Az Cu(I)* + Az Cu(II) ⇔ Az Cu(II)* + Az Cu(I)

Saturate Cys $^1$H in diamagnetic Cu(I), observe change in intensity in spectrum of Cu(II)
What can I do with these broad peaks?

Why does this have a 120,000 Hz line width?

1. It is very close to Cu(II)
2. But... line width can’t be explained by dipolar relaxation
3. Contribution from contact relaxation because of large $A$
4. Observation consistent with efficient spin delocalization onto Cys residue

$S = 1/2$
$\tau_s \sim 10^{-8} \text{ s}$
What can I do with these broad peaks?

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• Change metal or metal oxidation state (although you may want to study the native metal in a particular oxidation state, of course).
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Metal Substitution

Ni(II) azurin

\[ S = 1, \tau_s \approx 10^{-12} \text{ s} \]
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Finding Hidden Peaks

$^1$H-$^{15}$N HSQC spectra of 1 mM *Hydrogenobacter thermophilus* $[U-^{15}$N]-ferricytochrome $c_{552}$ showing the effect of a decreased INEPT delay on intensity of the peak correlating the heme axial His $\delta$HN nuclei.

From *Encyclopedia of Inorganic Chemistry* DOI: 10.1002/0470862106.ia319
What can I do with these broad peaks?

- Try some cool tricks, and learn what you can!
- Change metal or metal oxidation state (although you may want to study the native metal in a particular oxidation state, of course).
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Effect of Temperature

\[ ^1H \text{ resonances of heme methyl groups of } \text{Hydrogenobacter thermophilus ferricytochrome } c_{552} \]

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Detection of $^{13}$C

2-D in-phase-anti-phase spectrum correlating backbone $^{13}$C and $^{15}$N nuclei, with detection of $^{13}$C (CON-IPAP experiment). Data were acquired on a 1.5 mM sample of $^{13}$C,$^{15}$N labeled reduced monomeric superoxide dismutase (see ID779-) with a 14.1 T Bruker Avance spectrometer equipped with a cryogenically cooled probehead optimized for $^{13}$C detection at 298 K.

Detection of $^{13}\text{C}$

$$R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_i^2 g_e^2 \mu_e^2 S(S+1)}{r^6} \tau_s$$

Detection of $^{13}$C

$R_{1,2} = \frac{4}{3} \left( \frac{\mu_0}{4\pi} \right)^2 \gamma I^2 \frac{g_e^2 \mu_e^2 S(S+1)}{r^6} \tau_s$

Relaxation Summary

- Properties of metal site have a profound effect on relaxation and thus line widths, with $\tau_s$ being most important.

- A number of systems show minimal line broadening – especially LS Fe(III), 4-coordinate HS Ni(II), 5- and 6-coordinate HS Co(II), 5- and 6-coordinate HS Fe(II). Also – most Ln(III), (not Gd(III)), Ru(III), and many bi- and multinuclear sites.

- Line broadening is diminished for low $\gamma$ nuclei (by $\gamma^2$ factor).

- Relaxation enhancement provides information on molecular and electronic structure.

- We have ways to deal with it!
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Paramagnetic Chemical Shifts

- Values are not necessarily related to amount of line broadening
- Can be higher or lower than diamagnetic (positive or negative; to high frequency or low frequency)
- Are caused by two primary mechanisms: contact (through-bond) and dipolar (through-space)
- Unlike with relaxation, both contact and dipolar often play a role
- Contain information on electronic structure, molecular structure, spin delocalization, magnetic anisotropy
Paramagnetic Chemical Shifts

$$\delta_{obs} = \delta_{para} + \delta_{dia}$$

$$\delta_{para} = \delta_{con} + \delta_{pc}$$

$$\delta_{dia}$$ is shift in isostructural diamagnetic molecule

$$\delta_{con}$$ is contact shift – through-bond electron-nucleus interaction

$$\delta_{pc}$$ is pseudocontact (also called dipolar) shift – through-space electron-nucleus interaction
Contact Shift

\[ \delta_{\text{con}} = \frac{(2\pi A/h) g_e \beta_e S (S+1)}{3 k_B T \gamma_I} \]

Note dependence on:

- Hyperfine coupling constant \( A \)
- Spin \( S (S+1) \)
- Temperature \( 1/T \)
- Value \( \gamma_I \) in denominator cancels with part of \( A \)
Contact Shift

\[ \delta_{\text{con}} = \frac{\left(2\pi A/h\right) g_e \beta_e S (S+1)}{3 k_B T \gamma_I} \]

- Reflects electron spin density at the nucleus
- Sign (+/-) reflects positive or negative spin density
- Often dominant for nuclei 1-3 bonds from metal
- Can be significant over more bonds in \( \pi \) system
- Independent of nucleus
- Temperature dependence \( (1/T) \) helps identify these peaks, but deviations from ideal are common.
- Can be used to estimate \( A \)
Paramagnetic Chemical Shifts

Sign of $\delta_{\text{con}}$ can change depending on delocalization mechanism.

From *Encyclopedia of Inorganic Chemistry* DOI: 10.1002/0470862106.ia319
Contact Shift Examples

CN-Fe(III) M80A cytochrome $c$, $D_2O$

Heme methyl protons have large, positive spin density through 1) delocalization through $\pi$ system, 2) polarization through two nuclei (C, H) outside of $\pi$ system
Contact Shift Examples

CN-Fe(III) M80A cytochrome c, D$_2$O

Heme methyl proton shift pattern reflects axial His orientation
Contact Shift Examples

CN-Fe(III) M80A cytochrome c, D$_2$O

Tyr67 OH $\delta_{\text{para}}$ has a ~5 ppm contribution from $\delta_{\text{con}}$, supporting H-bonding

(Also $T_1 = 9 \pm 3$ ms, So $r \sim 4 \text{ Å}$)
Contact Shift Examples

*P. aeruginosa* Cu(II) azurin

\[ S = \frac{1}{2} \]

800, 850 ppm
Contact Shift Examples

\textit{P. aeruginosa Cu(II)} azurin

\begin{align*}
\text{A} & \quad \text{B} \quad \text{C} \quad \text{D} \quad \text{E} \quad \text{E}' \quad \text{G} \quad \text{G} \quad \text{I} \quad \text{J} \quad \text{J} (\text{H}\alpha) \\
\delta, \text{ ppm} & \quad 60 \quad 50 \quad 40 \quad 30 \quad 20 \quad 10 \quad 0
\end{align*}

\[ A/h = 28, 27 \text{ MHz} \]

2\% unpaired spin density
Contact Shift Examples

*P. aeruginosa Cu(II) azurin*

$A/h$ values

Asn47 $H_{\alpha}$

$A/h = 0.52$ MHz

H bond

$\delta$, ppm

JACS 2000, 3701

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Contact Shift Examples

*T. thermophilus* Cu\textsubscript{A} domain

Cu(I)Cu(II) S = 1/2

pH 8.0, H\textsubscript{2}O

pH 4.5, H\textsubscript{2}O
Paramagnetic Chemical Shifts

\[ \delta_{\text{obs}} = \delta_{\text{para}} + \delta_{\text{dia}} \]

\[ \delta_{\text{para}} = \delta_{\text{con}} + \delta_{\text{pc}} \]

\( \delta_{\text{dia}} \) is shift in isostructural diamagnetic molecule

\( \delta_{\text{con}} \) is contact shift – through-bond electron-nucleus interaction

\( \delta_{\text{pc}} \) is pseudocontact (also called dipolar) shift – through-space electron-nucleus interaction
Pseudocontact Shift

\[ \delta_{pc} = (12\pi r^3)^{-1}[\Delta \chi_{ax}(3\cos^2\theta - 1) + 3/2 \Delta \chi_{rh}(\sin^2\theta \cos 2\Omega)] \]

Note dependence on:

- Magnetic anisotropy \((\Delta \chi_{ax}, \Delta \chi_{rh})\)
- Position/structure \((r, \theta, \Omega)\) in magnetic axis system
Pseudocontact Shift

$$\delta_{pc} = (12\pi r^3)^{-1}[\Delta \chi_{ax}(3\cos^2\theta-1) + 3/2 \Delta \chi_{rh} (\sin^2\theta \cos 2\Omega)]$$

Axial system ($\Delta \chi_{rh} = 0$); $r = 5$ Å, $\Delta \chi_{ax} = 3 \times 10^{-32}$ m$^3$

- $\theta = 54.7^\circ$; 0 ppm
- $\theta = 90^\circ$; -6.4 ppm
- $\theta = 180^\circ$; +12.7 ppm

Note position as well as distance determines magnitude and sign of shift.
Pseudocontact Shift

Isopseudocontact shift surfaces

\[ \Delta \chi_{\text{rh}} = 0 \quad \text{Positive shifts are in dark gray, negative in light gray.} \]

\[ \Delta \chi_{\text{rh}} = 1/3 \Delta \chi_{\text{ax}} \]

From *Encyclopedia of Inorganic Chemistry* DOI: 10.1002/0470862106.ia319
Pseudocontact Shift

Assuming $\Delta \chi_{rh} = 0$ and nucleus in axial position ($\Omega = 0^\circ$)

<table>
<thead>
<tr>
<th>Metal ion</th>
<th>S or J</th>
<th>$\Delta \chi_{ax}$ (10^{-32} m^3)</th>
<th>$\delta_{pc}$ (ppm) r = 7 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe(II)</td>
<td>2</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Fe(III) (LS)</td>
<td>1/2</td>
<td>2.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Fe(III) (HS)</td>
<td>5/2</td>
<td>3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Co(II) (HS, 5-6 coord.)</td>
<td>3/2</td>
<td>7</td>
<td>3.7</td>
</tr>
<tr>
<td>Co(II) (HS, 4 coord.)</td>
<td>3/2</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>Cu(II)</td>
<td>1/2</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Gd(III)</td>
<td>7/2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Ce(III)</td>
<td>5/2</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>Tb(III)</td>
<td>6</td>
<td>35</td>
<td>19</td>
</tr>
</tbody>
</table>

Magnetic Axes Determination Using $\delta_{pc}$

$$\delta_{pc} = (12\pi r^3)^{-1}[\Delta\chi_{ax}(3\cos^2\theta-1) + 3/2 \Delta\chi_{rh} (\sin^2\theta \cos 2\Omega)]$$

- Measure $\delta_{obs}$
- Subtract diamagnetic component
- Fit resulting shifts to above equation to determine $\chi$ orientation and anisotropy

$\delta_{pc} = \delta_{obs} - \delta_{dia}$ (when $\delta_{con} \sim 0$)
Structure Refinement with $\delta_{pc}$

From Encyclopedia of Inorganic Chemistry DOI: 10.1002/0470862106.ia319

Take-home Messages

- Yes, you can take NMR spectra of paramagnetic molecules
- These spectra are rich in information content – line widths, relaxation times, and chemical shifts all reflect electronic and molecular structure
- The electronic relaxation time is key in determining line broadening extent
- Magnetic anisotropy determines magnitude of pseudocontact shifts
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