Week 9

NMR

9.1   NMR Spectroscopy

2/28:

- Announcements.

    - Second HW is due Friday at noon.

        ■ We should have everything we need for it after today.

    - The final will be from 8:00-9:20am on Tuesday.

        ■ It is solely on Anderson's lectures (it's just a second midterm).

        ■ Not open note. Shouldn't be too many things to memorize: $g\beta H$, magnetic moment formulas, gnarly stuff like the EXAFS formula we don't need to have memorized.

- We now start the lecture.

- Relation between EPR and NMR.

    - There are many parallels.

    - NMR is more common than EPR, and much more complicated.

- We will start with some simpler NMR examples to build a foundation.

- NMR background/underlying principles.

    - Like an electron has $S = \pm 1/2$, nuclei also have a given spin I.

    - While a single electron can only be $S = 1/2$, a single nucleus can be $I = 0, 1/2, 1, 3/2, \ldots$.

- A few rules about I.

    1. A nucleus with an odd mass number has a half-integer spin.

    2. A nucleus with an even mass number and an odd atomic number has an integer spin.

        - Examples: Deuterium, ^{14}N, etc.

    3. A nucleus with an even mass number and an even atomic number has zero spin.

- We now investigate the **Zeeman splitting** of an $I = 1/2$ nucleus.

    - Like electron spins in EPR, nuclear spins align with or against applied magnetic fields.

    - The splitting is as in Figure 6.2a.

    - We know that $\Delta E = \gamma \hbar B_0$, where γ is the gyromagnetic ratio and B_0 is the applied field.

- The notes also consider the $I = 1$ case.

- **Zeeman splitting**: The energy difference between a spin aligned with and against a magnetic field.

- **Larmor frequency**: The frequency of electromagnetic radiation that induces a spin flip. *Also known as* **resonant frequency**. *Denoted by* $\boldsymbol{\nu_0}$. *Given by*

$$\nu_0 = \frac{\gamma B_0}{2\pi}$$

  - Takeaway: A nucleus's resonant frequency is determined by γ and B_0.

- Typical values for B_0, γ, and ν_0.

  - B_0: 1.4-14 T.
  - ν_0: 60-600 MHz, though we can go higher.

- Example: The Larmor frequency of some common NMR nuclei under a 9.4 T magnet.

  - ^{1}H: We have that

$$\nu_0 = \frac{\gamma B_0}{2\pi} = \frac{(26.8 \times 10^7 \,\mathrm{T^{-1}\,s^{-1}})(9.4\,\mathrm{T})}{2\pi} = 4.0 \times 10^8 \,\mathrm{s^{-1}} = 400\,\mathrm{MHz}$$

  - ^{13}C: 100 MHz.
  - ^{31}P: 162 MHz.
  - ^{2}H: 61 MHz.

- The key limitation of NMR is *sensitivity*.

  - The sensitivity for NMR is pretty atrocious. This is because all relevant energies are pretty small (radiofrequency region) and thus hard to detect.
  - Quantitatively, sensitivity is proportional to the magnetogyric ratio cubed times the number of nuclei (equivalently, the concentration).
  - This is why MRI is really tough.
  - Also why you need really big magnets for NMR.
  - Additional limitation: The signal increases by the square of the applied field strength.
    - How is this limiting??

- Aside: Hyperpolarization for NMR.

  - Goal: Enhance signal intensity by further polarizing nuclear spins.
  - Essentially, if you have four particles in the spin ground state and three in the spin excited state, exciting one of the ground state spins won't cause a significantly measurable change. However, if you *hyperpolarize* the system so that there are, for example, six particles in the ground state and only one in the excited state, then inducing an excitation causes a far greater change.
    - You can do this with **dynamic nuclear polarization**, particularly **triplet DNP**.
    - Also something akin to ENDOR with Zeeman splitting and microwaves to get a huge polarization buildup. Nobody has pulled this off *in situ* yet, but that's a goal.
  - There's a scientist in Texas (possibly Christian Hilty??) looking into **parahydrogen**.

- **Dynamic nuclear polarization**: A technique for hyperpolarization involving the transfer of spin polarization from electrons to nuclei. *Also known as* **DNP**.

- **Triplet DNP**: Photoexciting a singlet to a triplet and then harnessing intersystem crossing to selectively populate the $M_s = 0$ state before transferring this polarization to the nuclei.

- **Parahydrogen**: The spin isomer of hydrogen with the two proton spins aligned antiparallel.

- The key advantage of NMR is *resolution.*

    – The specific frequency of a given nuclei is often exquisitely sensitive to its chemical environment.
    – NMR is a Qbit technique: We're using the nuclear spin as a quantum sensor for the system.
    – This really comes down to shielding.

- Shielding.

    – A useful (but technically inaccurate) classical analogy.
        ■ If we have an electron and we apply a magnetic field H_0 to it in the z-direction, our electron will begin to circulate around it and induce a magnetic field in the opposite $(-z)$ direction.
        ■ The angular frequency ω_1 equals $eH_0/2m_e$.
    – Takeaway: Applied magnetic fields result in slight changes depending on the nuclear environment.
    – Because nuclei have very small energy splittings, we can resolve very small energy changes in our NMR spectra; this is the origin of the ppm splitting we're familiar with.

- Shielding originates primarily from three places.

    1. Nucleus: Specifically how electron-rich or -poor it is.
    2. Solvent: The electrons therein will strongly influence the magnetic field felt by the nuclei.
    3. Chemical environment: Bonds, functional groups, other nuclei, electrons, etc.

- Parts 1 and 3 (electron richness and nuclear factors) are related to each other and are important.

    – We usually correct for part 2 using a known solvent shift and an internal standard.

- Measuring and describing the **chemical shift**.

    – $1\,\mathrm{ppm}$ is a shift in the resonant frequency of a given nucleus. Specifically,

    $$1\,\mathrm{ppm} = \frac{\nu_1 - \nu_{\mathrm{ref}}}{\nu_0} \times 10^6$$

        ■ ν_1 is the measured Larmor frequency for a given nucleus.
        ■ ν_{ref} refers to a single compound that we reference against, e.g., TMS.
        ■ ν_0 is the predicted Larmor frequency for said nucleus based on its γ.
    – Thus, at $60\,\mathrm{MHz}$ (for example), $1\,\mathrm{ppm} = 60\,\mathrm{Hz}$.
    – Chemical shift lingo.
        ■ More *shielded* nuclei require *higher fields*, have a *lower chemical shift*, and are positioned relatively *upfield.*
        ■ More *deshielded* nuclei resonate at *lower fields*, have a *higher chemical shift*, and are positioned relatively *downfield.*

- Line widths.

    – Recall from EPR: τ denotes **lifetime**.
    – We're limited by the Heisenberg uncertainty principle

    $$\Delta E \Delta t = \hbar \quad \Longleftrightarrow \quad \Delta E = \frac{\hbar}{\tau}$$

    – It follows that a long lifetime τ gives you a small ΔE and a sharp line.
    – Typical lifetimes: $\tau_{\mathrm{NMR}} = 1 - 100\,\mathrm{s}$, $\tau_{\mathrm{rot}} = 10^{-9}\,\mathrm{s}$, $\tau_{\mathrm{vib}} = 10^{-6}\,\mathrm{s}$.

- **Lifetime**: The time that a signal will remain polarized. *Denoted by* $\boldsymbol{\tau}$, $\boldsymbol{\Delta t}$.

- **Chemical shift**. *Denoted by* $\boldsymbol{\sigma}$. *Given by*

$$\sigma = \sigma_d + \sigma_p + \sigma_R + \sigma_e + \sigma_{\text{int}}$$

  – Each of the five variables represents a contribution to the nucleus from some magnetic component.
  – σ_d is our diamagnetic term.
    ■ Usually positive, so it causes signals to shift downfield.
    ■ Most important for ^{1}H NMR.
    ■ Correlates with the s-electron density at the nucleus; thus can give us a direct readout of the electron density of the nucleus. Also, more electron rich means more shielded.
  – σ_p is our paramagnetic term.
    ■ Usually negative, so it causes signals to shift upfield.
    ■ Most important for heavier elements (e.g., ^{31}P, ^{119}Sn, etc.).
    ■ A large term in general (larger than σ_d??).
    ■ Distinct usage from paramagnetic *samples* (diamagnetic nuclei can have paramagnetic terms).
  – σ_R is for ring currents.
    ■ Consider a benzene ring for instance. The large induced ring current creates two cones of positive shift and negative regions outside.
    ■ Other multiple bonds also contribute in various ways.
    ■ For more details, see the discussion associated with Figure 9.1 below.
  – σ_e is for electric fields.
  – σ_{int} is for intermolecular effects.
  – The latter three are often combined into σ_N.
  – Recall...
    ■ $\sigma > 0$ means an upfield shift (lower ppm)
    ■ $\sigma < 0$ means a downfield shift (higher ppm).
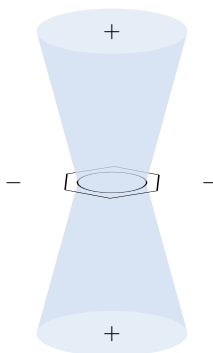
- Benzene ring current effects.

Figure 9.1: The effect of the ring current in benzene.

  – It's a fake ring current.
  – It's a quantum mechanical effect from the interaction of the magnetic field with the degenerate π system.
  – But still, it's a useful classical picture.
  – Something with Zwitterionic character may be able to give you a "real" ring current.

- Most of us have probably seen some of this before. But now we'll move onto something we haven't seen: Heavier nuclei.

- With heavier nuclei, σ_p dominates.

  - The spread is much bigger than with ^{1}H NMR.
  - σ_d is still there but is typically small and much more constant.

- Contributions to σ_p.

  - The orbital angular momentum, largely from the p, d, f orbitals.
    - We do *not* consider electron spin here, just orbital spin.
  - The magnitude of σ_p is controlled by mixing.
    - Mixing in other states mixes in their angular momentum.
    - Most common when there is lowered symmetry, low-lying excited states, and lots of EWGs.
    - Mathematically, we describe σ_p with the **Ramsey equation**.

- **Ramsey equation**: The equation giving the relative magnitude of σ_p. *Given by*

$$\sigma_p \propto -\left[\frac{1}{E_{\mathrm{es}}} - E_{\mathrm{gs}}\right]\left\langle\frac{1}{r^3}\right\rangle [\pi\text{-bonding term}]$$

  - es denotes the excited state.
  - gs denotes the ground state.
  - Rationalizing the energy separation (first) term.
    - Alkanes have strong bonds and no low-lying excited states, while alkenes will have lower excited states.
    - Thus, σ_p is greater for alkenes than alkanes, for example.
    - Takeaway: Unsaturation typically leads to larger paramagnetic terms.
  - Rationalizing the $1/r^3$ term.
    - It is related to how close electrons are to the nucleus.
    - EWGs decrease electron-electron repulsions, moving electrons closer to the nucleus, thus increasing σ_p and shift heavier nuclei more downfield.
  - The π-bonding term is complicated; we will not discuss it further.
    - It is summed over all relevant interactions.
    - Depends on the system at hand.

- Thus, the chemical shift can provide important chemical information.

- However, it can also provide other useful information, such as on **coupling**.

- **First order system**: A system in which the spread of the nuclei is much higher in ppm than the coupling constant, i.e., in which the following equation is satisfied.

$$\Delta\nu = |\nu_{\mathrm{A}} - \nu_{\mathrm{X}}| \gg J_{\mathrm{AX}}$$

  - ν_{A} is the frequency/ppm shift of nucleus A.
  - ν_{X} is the frequency/ppm shift of nucleus X.
  - J_{AX} is the coupling constant between A and X.
  - Coupling is relatively simple in first order systems.
  - We will not get into second order splitting, which occurs when the above inequality is not satisfied and is very complicated.

- Example: Consider the following molecule, which has two nuclei of interest (each with $I = 1/2$).
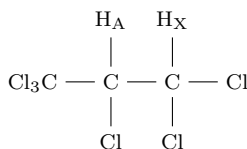
$$
\begin{array}{cccc}
& H_A & H_X & \\
& | & | & \\
Cl_3C \;-\!\!\!- & C \;-\!\!\!- & C \;-\!\!\!- & Cl \\
& | & | & \\
& Cl & Cl &
\end{array}
$$

Figure 9.2: NMR coupling of two neighboring nuclei.

  - Comments on the molecule.
    - ■ A nasty molecule chemically; would probably destroy the ozone layer and such.
    - ■ Only two spin-active proton nuclei.
    - ■ We stick on the CCl_3 group to put the two protons in different chemical environments (gets rid of the reflection plane that would be there if CCl_3 were just Cl).
  - Let's look at the peak structure of A first.
    - ■ X can have one of two values: $M_I = \pm 1/2$.
    - ■ Thus, A can be in two marginally different chemical environments, and hence should appear as a doublet.
  - The same is true of X.
  - Thus, the full ^1H NMR spectrum should consist of a pair of doublets.

- There are two types of coupling.

  1. **Dipolar coupling**. Occurs "through space."
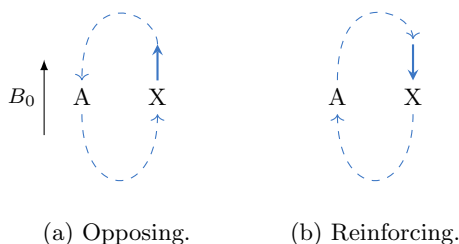

(a) Opposing.   (b) Reinforcing.

Figure 9.3: Dipolar coupling.

  - Having a nearby element X that is magnetized is like bringing an additional magnet close to A, affecting its chemical environment.
  - X can oppose or reinforce the applied magnetic field B_0 at A (see Figure 9.3).
  - The field is given by

$$
B_{AX} = \gamma_A \gamma_X \cdot \frac{3\cos^2\theta - 1}{r_{AX}^2}
$$

    - ■ γ's are gyromagnetic ratios.
    - ■ r_{AX} is assumed to be big; thus distance is important.
      - ➢ Is the exponent a 2 or a 3??
    - ■ θ is the angle between the two nuclear spin axes (of A and X).
    - ■ What exactly is this field??
  - Dipolar coupling averages to zero in solution but still affects relaxation.
  - When ^{31}P NMR is run, it is done proton decoupled to get bigger shifts.
    - ■ How is this relevant??

2. **Scalar coupling**. Occurs "through bond."

   – Dominates in solution.
   – We have that

   $$E_{\text{scalar}} = hJM_{I,\text{A}}M_{I,\text{X}}$$

   – J is our coupling constant in Hertz.
   – Notes on J.
     ■ Can be positive or negative, but in most cases, we don't care what its sign is. We can determine this experimentally if we need it, though.
     ■ Proportional to the s-character of the bond.
     ■ Independent of H, so the same on all instruments.

• Dipolar coupling example: The $C_3Cl_6H_2$ doublets.
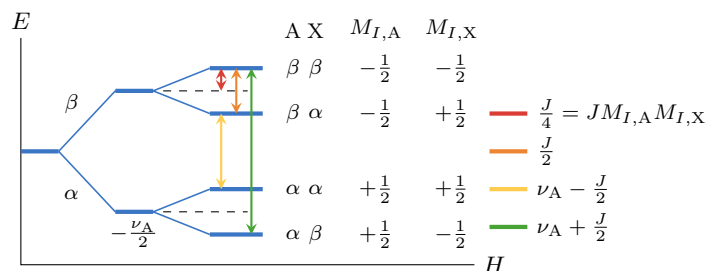
Figure 9.4: Formation of a pair of NMR doublets.

   – Analysis of the first splitting (originates from the applied magnetic field).
     ■ Of the left two connecting lines, the lower one is referred to as the **α-manifold** and the upper one is referred to as the **β-manifold**.
       ➤ What exactly are these?? Relation to α, β designation of spin from Labalme [1].
     ■ The energy of the upper state at the end of the β-manifold is given by

     $$E = -\frac{\gamma}{2\pi}B_0(1 - \sigma_\text{A})M_{I,\text{A}} = -\nu_\text{A}M_{I,\text{A}} = \frac{\nu_\text{A}}{2}$$

       ➤ There is a sign flip in the last equality because $M_{I,\text{A}}$ is negative.
     ■ Per the definitions of the green and yellow gaps in Figure 9.4, the energy difference between the two states at the end of the α- and β-manifolds will just be ν_A.
     ■ Takeaway: In the absence of coupling, one peak corresponds to A at the frequency ν_A.
   – We now factor in the second splitting (originates from coupling).
     ■ We label the resultant states with a second set of β's and α's.
       ➤ The signs are related to the signs of the fields from the other nucleus.
     ■ Selection rule: $\Delta M_I = \pm 1$.
       ➤ Thus, only $\alpha\alpha \to \beta\alpha$ (yellow) and $\alpha\beta \to \beta\beta$ (green) are allowed.
     ■ From the frequencies of these two transitions, the splitting in the doublet is

     $$J = \left(\nu_\text{A} + \frac{J}{2}\right) - \left(\nu_\text{A} - \frac{J}{2}\right)$$

     ■ J is typically small compared to ν_A.
     ■ Takeaway: Factoring in coupling, we will observe a *doublet* centered around ν_A. However, ν_A is no longer an allowable transition; only the yellow and green ones are (note that these are centered around ν_A). The peaks corresponding to the yellow and green transitions will be separated by J, as described above.

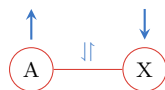- Scalar coupling example: A diatomic molecule.

Figure 9.5: Scalar coupling in a diatomic molecule.

  - How scalar coupling works in more detail (very complicated, but a nice simplistic picture).
    - Empirical observation: Electrons and nuclei prefer to align antiparallel.
    - Notice how each nucleus in Figure 9.5 is aligned antiparallel to the nearest electron.
    - Naturally, the electrons are also aligned antiparallel since they are in the same bonding orbital.
    - Thus, the neighboring nuclei prefer to be anti-parallel because of the indirect interaction chain of nucleus-electron, electron-electron, electron-nucleus.
  - At this point, some of our previous observations should make more sense.
    - Example: Scalar coupling scales with s-character because greater s-character maximizes electron-nucleus interactions.
  - We have no way of measuring the sign of J in an NMR experiment. In order to do the transition, we can see why s-character matters: The more the electrons interact with the nucleus (higher s-character means closer to nuclei), the stronger the effect will be.
    - What is the effect?? What is scalar coupling? How does it show up? How do all of the equations fit together?
  - On the sign of J for neighboring nuclei.
    - If we have a single bond, then $J > 0$ and antiparallel spins are more stable.
    - If we have a double bond, then $J < 0$ and parallel spins are more stable.
    - In general, an odd number of bonds means $J > 0$ and an even number of bonds means $J < 0$.
      - ➢ There are many exceptions, though.
  - On the magnitude of J.
    - 2-bond: $^2J_{\text{HH}} = 10 - 25\,\text{Hz}$. Are these values negative?? sp^2 can be $+41\,\text{Hz}$.
    - 3-bond: $^3J_{\text{HH}} = 0 - 25\,\text{Hz}$.

- Coupling constants and electronic proximity to the nucleus.

Compound	Hybridization	J_{CH} (Hz)	EWG	χ	J_{CH} (Hz)
Ethane	sp^3	125	$CH_3 - F$	4.0	150
Ethene	sp^2	156	$CH_3 - Cl$	3.2	150
Benzene	sp^2	159	$CH_3 - OH$	3.4	141
Cubane		160	CH_4	2.2	125
Acetylene	sp	248	$Cp_2Zr(CH_3)(I)$	1.3	120
$H - H$	s	284	$CH_3 - Li$	0.98	98

Table 9.1: Coupling constants and molecular electronics.

  - The last coupling constant on the left is technically a J_{HH}, not a J_{CH}.
  - The left exhibits the expected trend based on s-character: Compounds that maximize s-character and place electrons closer to the nucleus have higher coupling constants.
  - The right exhibits the expected trend based on **Bent's rule**: Compounds with less electronegative EWGs must give more s-character to bonding; thus, there is less s-character to promote (scalar) coupling and the coupling constant diminishes.

   – You can quantitatively derive this stuff with MO theory.

   – Observing these coupling constants: They show up under ^{13}C NMR that isn't proton decoupled.

• **Bent's rule**: More electronegative elements prefer p-character.

   – See Labalme [2] for more.

• Aside: Diamond vacancy centers in quantum computing.

   – One of the first things used for a quantum computer was an NMR.

   – The first quantum computation was performed via NMR spectroscopy.

   – It was a funky molecule, just enough stuff to do quantum computation, but it worked.

• A couple more notes about coupling constants.

(a) *cis* vs. *trans*.   (b) Viscinal hydrogens.   (c) Olefins.
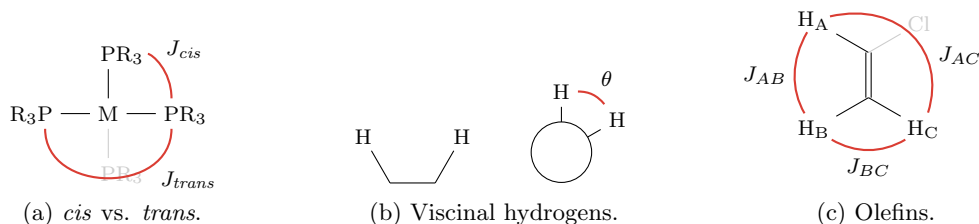
Figure 9.6: Special cases in coupling.

1. *cis* vs. *trans* metal complexes.

   – $J_{trans} > J_{cis}$.
   – Example: If we have a square planar coordination compound with four phosphenes, the two pairs of *trans* ligands will (independently) couple more than any of the four pairs of *cis* ligands.
   – Why: Same argument as *trans* effect; make an MO argument that *trans* will overlap better.

2. Viscinal coupling: Coupling of atoms separated by two other atoms.

   – Example: Two hydrogens on different carbons of ethane.
   – Coupling magnitude: Depends on the dihedral angle θ from the Newman projection.
   – For syn and anti conformers, J will be larger.
   – For gauche conformers, J will be smaller.

3. Olefins.

   – Example: Vinyl chloride.
   – $J_{AC} = 12 - 18\,\text{Hz}$. Sometimes referred to as *trans*.
   – $J_{BC} = 0 - 3\,\text{Hz}$. Sometimes referred to as *gem*.
   – $J_{AB} = 6 - 12\,\text{Hz}$. Sometimes referred to as *cis*.

• A more realistic view of spins under a magnetic field.

   – We may treat the collection of polarized molecules as an ensemble of spins in space.

   – However, just because a magnetic field has been applied doesn't mean that each nuclear spin is perfectly poised along the z-axis.

   – Rather, there are still residual x- and y-components that will precess around the z-axis.

     ■ We have, in fact, a whole distribution of spins which are arranged in some cone around the z-axis. We do indeed have a random and equally dispersed x, y-spins.

     ■ The precession is called a **Larmor precession** and occurs at the **Larmor frequency**.

- The NMR experiment.

    - What we do is take the ensemble of spins and apply a 90° radiofrequency pulse to project the net magnetization onto the x-axis. Then, we monitor the precession rate about the xy-plane.
    - This is called a **Hahn echo experiment**.
        - We also use this technique in pulsed EPR experiments.
    - We then Fourier transform the wave to get it back to normal.
    - Misc. notes.
        - The x- and y-components vary in time.
        - Both α and β (up and down) spins precess at the same frequency.
        - Chemically equivalent nuclei precess at the same frequency, but are not necessarily in phase.
        - While the x- and y-components are scattered, there is still net polarization along z and hence a net magnetization in this direction.

- Next time.

    - Wikipedia description of the Hahn Echo experiment (really good).
    - A bit more on NMR, too, to be wrapped up at the beginning of the lecture.

9.2 NMR Wrap-Up and Examples from the Literature

3/2:
- HW extended until Friday at *midnight*.

- Today: Finish up NMR and then some examples. We'll finish about 15 mins early, most likely.

- We begin today by discussing **spin-spin relaxation**, the time constant of which is denoted by T_2.

    - See Lecture 7.1 on EPR for more.

- Recall that under the influence of a magnetic field applied along the z-axis, the spins align along H_z.

- **90° radiofrequency pulse**: A pulse of electromagnetic radiation in the radiofrequency region, the intensity and time of which is calibrated to rotates all Larmor precessions by 90° so as to align them along the x-axis.
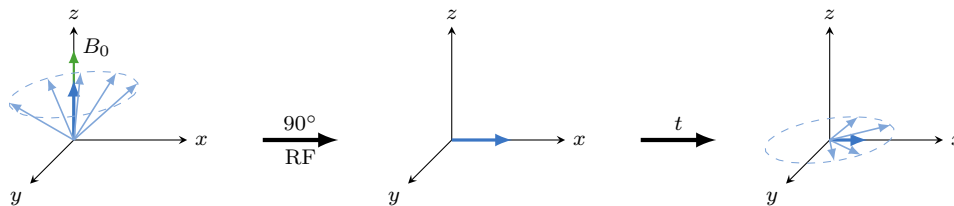

Figure 9.7: A 90° pulse.

- Once there, the precessions continue about the applied magnetic field and return to z-equilibrium.
- Decoherence occurs because the spins that are offset in phase spread out.
    - We can watch the frequency of this with respect to time to learn the precession frequencies for each proton.
- At $5T_2$'s, we'll have about 99.3% decay.
    - T_2 is on the order of seconds.
- See Labalme [3] for more.

- **Hahn echo experiment**: A 90° pulse, followed by decoherence, followed by a 180° pulse, followed by recoherence. *Also known as* **HE**, **spin echo experiment**.

  - The echo: After the 180° pulse, things feel the opposite field, so the ones that are slow speed up and the ones that are fast slow down. This is what results in decoherence.
  - See the GIF on Wikipedia (link).
  - We can measure the decoherence time using such an experiment.
    - In particular, the intensity of the echo relative to the initial signal is proportional to

    $$e^{-2t/T_2}$$

    - Rigorously, we derive the above result from the rate law.

    $$\frac{\mathrm{d}M_y'}{\mathrm{d}t} = -\frac{M_y'}{T_2}$$
    $$M_y' = M_0 e^{-t/T_2}$$

    - T_2 is equal to half the time until the echo. T_1 is related to the magnitude of the echo because that will tell us what proportion of the magnetization has gone back to the z-axis??

- The other decay is **spin-lattice** (T_1).

  - We put the spin on the y-axis, making the z-component zero.
  - Then it slowly grows back.
  - Rate law.

  $$\frac{\mathrm{d}M_0 - M_z}{\mathrm{d}t} = \frac{M_0 - M_z}{T_1}$$
  $$M_z = M_0[1 - e^{-t/T_1}]$$

- Both T_1 and T_2 happen simultaneously, but $T_1 > T_2$.

- Signal-to-noise (S/N) ratio:
  $$S/N \propto \sqrt{n}$$

  - n is the number of scans.
  - The moral of the story is make your samples concentrated so you can use fewer scans.

- Nuclear Overhauser Effect (NOE): Decoupling.

  $$\eta_{A(X)} = \frac{I_A \mu_{aX} - I_X}{I_X} = \frac{\gamma_X}{2\gamma_A}$$

  - Basic idea behind decoupling/the NOE: Blasting your sample with magnetism in the x-direction to constantly flip the spins and saturate them. Essentially, we saturate a given frequency or transition with rf radiation.
    - Do I have this right??
  - Decoupling can increase or decrease the intensity of a given nuclear signal.
  - By the above equation, the NOE depends on the sign and the magnitude of the gyromagnetic ratios of the two elements, where we are taking the spectrum of A with X decoupled.
  - We sum this over all different nuclei that are contributing.
  - We denote a spectrum that's been proton-decoupled with squiggly brackets, e.g., $^{13}\text{C}\{^1\text{H}\}$ denotes a proton-decoupled ^{13}C NMR experiment.

– Dipole relaxation.

$$R_{1DDA(X)} \propto r_{AX}^6$$

   ■ We expect a large NOE when A and X are close, and A relaxes primarily by dipole-dipole (DD) from X.

– Example: Consider the following olefin.
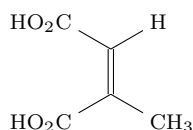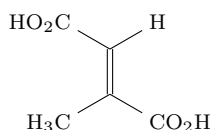

(a) *cis* protons.   (b) *trans* protons.

Figure 9.8: Determining olefin stereochemistry with the Nuclear Overhauser Effect.

   ■ The resultant NOEs are

$$\eta_{cis} = 0.29 \qquad\qquad\qquad \eta_{trans} = 0.06$$

   ■ If the methyl protons and lone proton are *cis* to each other, we'll see a large NOE.
   ■ Barely any NOE for the *trans* case.

– This is a good NOESY way to determine if a compound is *cis* vs *trans*.

   ■ Technically, this is a simplistic treatment and we would need to consider all relaxation pathways in reality.
   ■ NOE only measures the contribution from DD relaxation.
   ■ What does the acronym NOESY mean??

• Aside: Acronyms in NMR.

– Only works for diamagnetic compounds, but it's ok.

– There's a lot of nasty acronyms in NMR (that's just a thing), but if we ever want to do any of them, Josh in the NMR facility knows how they're preprogrammed into our spectrometers.

• Last kind of experiment we're interested in: DEPT.

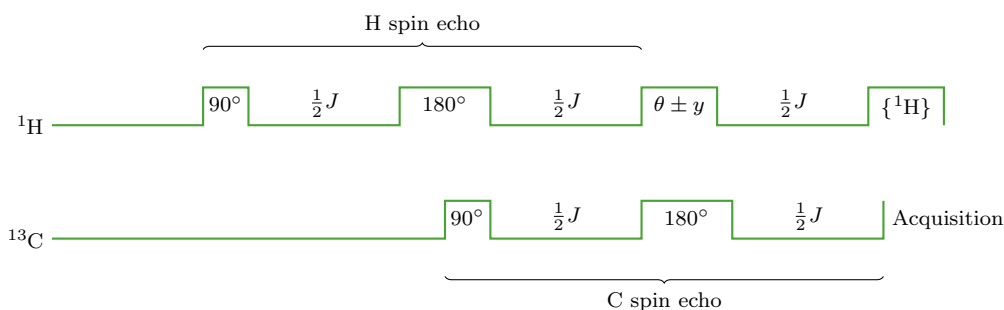• Distortionless enhancement by polarization transfer (DEPT).

Figure 9.9: Pulse sequence in a DEPT experiment.

– This method allows for information on the multiplicity, e.g., of hydrogens on carbons.

– This is between a proton and another nucleus, unlike NOESY which was between two protons.

– Notes on the method.

- ■ We do a Hahn echo for both the proton and carbon.
  - ■ We'll end up with positive and negative peaks corresponding to the number of attached methyls.
  - ■ The last thing for carbon is acquisition. We measure by varying y.

- This concludes NMR.

  - Do we need to know anything about the rest of the experiments in the notes??

- We now look through some literature examples.

- Zadrozny et al. [4].

  - First example: A beautiful Mossbauer spectrum.

- Rittle and Green [5].

  - P450 is kind of the blow-torch of the cell; breaks things down.
  - Jon Rittle is now a professor at Berkeley, but he was an undergrad at Penn State when he published this pretty seminal paper.
  - Anderson worked with Rittle in a glovebox for many years, which is why he knows so much of this story.
  - First up: UV-Vis. One of the hallmarks is green color, and Rittle found this and was very excited.
  - Mossbauer: At $4\,\mathrm{K}$, you get magnetic splitting.
  - EPR: Gives more info on where an electron is in an enzymatic environment.

- Chillemi et al. [6].

  - They do a lot of EXAFS fitting, and eventually find that the best fit is a sevenfold coordination model.

- Anderson et al. [7].

  - Anderson's PhD work.
  - Used a whole bunch of techniques to pin down the identity of their compound.

- Harkins and Peters [8].

  - Electron is fully delocalized.

- That's it.

- Do we have to know anything about the examples for the final, or was that just for our own enrichment?

- PSet 2 questions.

- Question 1: Did you mean to put the $N-H$ stretching frequencies in the 3000's?

  - These are likely bending modes.
  - NH_2 can have a symmetric and asymmetric bending mode.

- Question 2.

  - We *could* draw out the whole splitting of one copper followed by splitting of another copper, but it will be easier if we just add the contributions of the two coppers and split once.
  - Essentially, we use the $2nI+1$ rule to get 7 lines. Then we sum the M_I's of the two copper nuclei and split over $-3, -2, \ldots, 3$ for our fine splitting after we've originally Zeeman split the electron spin. This gives us the number of lines. For intensity, think about how many *microstates* can add to -3, -2, etc.
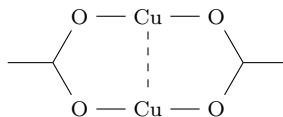
Figure 9.10: Copper (II) acetate structure.

- This intensity rule is allowed. That's what our EPR spectrum is telling us, that it's ok to sum the contributions of the nuclei.

- Our electron is kind of equally coupled to both copper nuclei. That's also what our spectrum is telling us. It may well be in one MO over the two of them. This also makes sense because of the paddle-wheel structure of copper (ii) acetate.

- The compound is a ground state triplet; the 1/2 spin of both copper centers sum to 1 if we are to see any EPR (i.e., have unpaired electrons). We could also get a singlet, but this would not be particularly helpful. We assume that there is no zero field splitting.

- Summing the spins of these electrons gives our electron coupling splitting.

- So EPR looks at the spins of *both* unpaired electrons orbiting the copper centers. They Zeeman split into three states giving two equal allowed transitions (from $M_S = -1$ to $M_S = 0$ and from $M_S = 0$ to $M_S = 1$; our selection rule states that $M_S = -1$ to $M_S = 1$ [$\Delta M_S = 2$] is forbidden, and this is actually pretty forbidden; we won't see this happening).

- Each of these triplet energy levels will then split into seven hyperfine levels, leading to seven pairs of identical transitions. In each allowable transition, we excite an electron from the Boltzmann population in the $M_S = -1$ or $M_S = 0$ level up a level. Example Boltzmann populations may be 50, 30, 20.

- Question: Why does whether the negative value is higher or lower energy flip in Figure 7.3?

  ■ Electrons are negative vs. protons; so an electron aligned *with* the magnetic field is higher in energy than one aligned against??

  ■ External nuclei increase or decrease the local magnetic field. So if a $M_S = +1/2$ electron (already high in energy) experiences an augmented field, it will split even more (go higher). On the other hand, if a $M_S = -1/2$ electron (already low in energy) experiences an augmented field, it will go even lower in energy.

- How can a $M_S = 0$ state split??

- If we draw out the nuclear splittings sequentially, remember that they are to the same magnitude, so we get overlap that implies intensity like Pascal's triangle a bit.

- Question 3.

  - Chemical shift is backwards; it should be 10^6 in the numerator.

- Question 4.

  - Order of importance in determining splitting: Row (second-third has strong preference for LS), then geometry dominates (tetrahedral has a strong preference for high spin), then oxidation state but this isn't really even a factor.

  - So just check (1) what row the element is in and if first-row, (2) continue on to check whether tetrahedral or octahedral.