Week 3

Where NMR Spectra Come From

3.1 The Basic NMR Experiment

2/20:

- Announcements.
  - PSet 1 feedback should be back to us by the end of the weekend.
  - What Walt is really looking for is that we understand the material well enough to take it home with us and use it in the lab.
- Today: The most complicated/boring part of the class.
  - Going over the highlights of the basic NMR experiment. This is how we go from the sample in the spectrometer to generating an FID.
  - Many terms will be used that we may or may not know. If we don't know anything, ask Walt questions. These terms will be on the PSet!
  - After this, we'll get back to doing chemistry problems.
- Most simple experiment: 1D acquisitions of a single nucleus.
  - We rest for a while (where we're at equilibrium).
  - Radiofrequency pulse translated through probe/detector.
  - Get a signal that we can digitize.
  - We'll discuss some of the parameters we get to set and how they help us.
- Two properties of a spectrum that we care about: **Sensitivity** and **resolution**.
  - These are *not* interchangeable.
  - *Don't* say: "I'm not getting enough resolution. Do I need more sample in my tube?"
- **Sensitivity**: The amount of signal we get over the noise background.
  - I.e., how *big* is the signal.
  - The amount of noise is determined by the hardware, particularly the NMR probe. We can't do anything about this.
  - The signals that we generate are on the order of µV. So to be able to see these, the noise has to be much lower than even that!
  - The total signal we have is proportional to the number of scans.
    - We can't have a prime number of scans, for reasons we'll discuss later.

    - The amount of signal is proportional to the number of scans. The amount of noise is proportional to the square root of the number of scans (that's a statistical thing; the noise signals will not add up, while the signals will constructively interfere when we add them together).
    - Thus,
$$\text{Signal-to-noise ratio} = \text{S/N} = \text{SNR} \propto \frac{n}{\sqrt{n}} = \sqrt{n}$$
  - Consider a 2 mM sample in a 5 mm tube with 8 scans. To double the SNR, either double the concentration to 4 mM or quadruple the scans to 32.

- **Resolution**: How close together we can observe different peaks. *Given by*
$$\text{Resolution} := 2 \cdot \left(\frac{\text{SW}}{\text{NP}}\right)$$
  - I.e., how *sharp* is the signal (how close can the peaks be and we can still tell them apart).
  - Depends on two parameters: The number of points (NP) that we acquire for each spectrum, and the spectral width (SW) we wish to observe.
  - Now we have to get into the whole Fourier transform business.
  - With an analog oscilliscope, we could measure continuous data. We acquire digitally by taking various points. The time between points is called the **dwell**.
    - Preview: In 2D NMR, we have a dwell in the **direct dimension** and **indirect dimension**.
    - Usually on the order of µs.
    - The spectral width and dwell are related to each other: Larger spectral width requires acquiring more points per time.
  - Resolution: Intensity in frequency comes from intensity in time.
  - Walt gives a brief explanation of how the Fourier transform works.
  - In order to get decent resolution in the frequency axis, we need enough points in the time axis to differentiate.
  - With many fewer points, it's harder to identify complex behavior.
    - Note: There is a way to view the individual points composing the NMR spectrum!
  - Long acquisition time and normal spectral width leads to more resolution.
    - Total **acquisition time** is NP · dwell.
  - Acquisition time, dwell, spectral width, and number of points are all related to each other. Changing one necessarily changes the others. If you fix spectral width and increase number of points, you will necessarily increase the acquisition time but also increase resolution??
    - Smaller hertz per point means higher resolution.

- NMR economics.
  - When we do an NMR experiment, our advisors pay for the amount of time that our sample is in the system.
  - A 5 minute experiment costs $1 on a $12/hour machine.
  - If we have to buy more material, it's less expensive to just acquire longer. If we have material in a bucket somewhere, it's less expensive to just put more material in the tube (unless our time is worth something).
  - This matters more when we are doing 1D carbon of 1 mg of 800 MW sample (e.g., in a natural product lab). Then you have to put it on the 600 for 20 hours and hope you get something, only because the reviewers asked for it.

- FID plots are in voltage vs. time.

- ppm vs. Hz.
  - Goes over the calculation.
    - Example: 1 ppm at 400 MHz is 400 Hz.
  - Hertz is the currency with which we think about pulses.
- Radiofrequency (RF) pulses.
  - Pulses at the resonance frequency of the nucleus in which we're interested.
  - So on a 400 MHz spectrometer, we need a 400 MHz pulse to affect protons and a 100 MHz pulse to affect carbon.
    - Nice thing: Since pulses are orthogonal, we can use a pulse sequence to make nuclei talk to each other!
  - RF pulses are defined by their **frequency**, **tip angle**, **power**, **RF bandwidth**, and **phase**.
  - When we apply a strong pulse, it excites a wide bandwidth. Weak pulses, on the contrary, excite a narrow bandwidth.
  - Relaxation and frequency are inversely proportional: When we pulse a system in the ultraviolet or visible, it relaxes in ns, ps, fs. When we pulse a system with RF, it decays in the ms to s range.
    - Thus, we have time to do a whole bunch of stuff that we can't do, unless we're in the Schlau-Cohen lab and have really fancy equipment.
  - You can do solvent suppression by dialing in a pulse of the certain power that you need.
- **Tip angle**: The amount that the magnetization is moved away from the equilibrium position.
- **Power**: The strength of the RF pulse. *Units* W, dB.
- **RF bandwidth**: The range of frequencies that the RF pulse can affect.
- **Flip angle**: The angle between where a magnitized spin started, and where it ends.
- Next topic: Extrapolation from 1D to 2D acquisition. This will lead into COSY, TOCSY, etc. spectra.