

Chapter 19

Nuclear Magnetic Resonance Spectroscopy (NMR)

23 pages 2 weeks worth!

Problems : 1, 2, 3, 4, 7, 10, 11, 19, 20, 22, 24, 27, 30, 34, 35

Absorption of radio-frequency E from 4 -900 MHz (wavelengths 33 cm - 75m!)

Nuclei absorb the E, not the electrons

Nuclei have to be in an intense magnetic field

Extremely useful for determining the structure of a molecule

Somewhat useful for quantitation

Theoretical basis proposed by Pauli in 1924

Demonstrated independently by Bloch and Purcell in 1946 (Got Nobel Prize in 1952)

First commercial machine by Varian in 1953

2 major types of machines

- Continuous wave (CW)

- Pulsed or Fourier Transform (FT)

All early work was done with CW machines

FT hit the market about 1970's has dominated the market since

The magnet of our machine was built in ? 70's Varian 21.14kG field (2.114 T) as a CW machine. Original electronic junked and replaced with FT electronics in 2000

CW analogous to UV machine. Put sample in magnetic field, scan with EM radiation at different frequencies, detect how much is absorbed at each frequency and record on a chart paper

FT machine. Hit with a single pulse of EM radiation that excites all frequencies at one time, watch sample radiate EM radiation as the excited molecules lose E to return to their ground state. Use FT transform to change this signal (F time) to Signal (F of Frequency)

Although most machine now are FT machines, and CW are not used much, will start discussion based on CW absorbance because it is easier to understand, and then switch to FT theory later in the chapter.

19A Theory of NMR

As usual, can use either quantum theory or classical mechanical theory, but works best if look at both

19A-1 Quantum Description of NMR

Certain nuclei rotate about their axis, therefore have property call *spin*

If you have spin, then you have *angular momentum*, p

Spin is quantized, must be integral or half integral multiple of $h/2\pi$

Maximum value of p for a particular nucleus is *Spin Quantum Number I*

Nuclei with EVEN # Proton and EVEN # Neutrons 0 spin

Even atomic mass 0 or integral spin numbers

Odd atomic mass $\frac{1}{2}$ integral spins

Nucleus then has $2I+1$ discrete spin state from $-I$ to $+I$ in steps of 1

In absence of magnetic field, E of state is degenerate, IE all the same

Will focus here on experimentally most useful nuclei, ^1H , ^{13}C , ^{31}P , and ^{19}F

Spin quantum number of these nuclei is $\frac{1}{2}$

Hence only 2 spins states $+1/2$ and $-1/2$

Spinning charge nucleus creates a magnetic field

resulting magnetic moment is oriented along spin axis and is proportional to angular momentum

$$\mu = \gamma p$$

γ called the magnetogyric ratio has a different value for each nucleus (see Table 19-1)

Energy Levels (Figure 19-1)

The above 4 nuclei are all spin $\frac{1}{2}$, so they have 2 quantum states

$+\frac{1}{2}$ $-\frac{1}{2}$

We tell these E states apart by how they interact with an external magnetic field

$$E = -\gamma m \hbar / 2\pi B_0$$

If $m = +1/2$

Get + E

Have to put E into the system to get to this state

Higher E state

If $m = -1/2$

Get -E

Releases E as system drops to this E
Lower E state

Change in E going from one state to the other

$$\begin{aligned}\Delta E &= -\frac{\gamma - \frac{1}{2}h}{2\pi} B_0 - \left(-\frac{\gamma \frac{1}{2}h}{2\pi} B_0 \right) \\ &= \frac{\gamma h}{2\pi} B_0 \\ ; E &= h\nu, \nu = E/h \\ \nu &= \frac{\gamma B_0}{2\pi}\end{aligned}$$

So the frequency of the absorption you observe is directly proportional to the magnetic field and the γ of the nucleus. And absorption will occur as the nucleus changes from being aligned with the magnetic field to being aligned against it.

Distribution of Particles between magnetic quantum states

In absence of magnetic field, E of 2 states are identical so # of nuclei in 2 states are equal

In magnetic field the nuclei want to be oriented with the magnetic field so they are in their lowest E state. When we were in UV we used the Boltzmann distribution to calculate the # of atoms in ground and excited states, and found that the number in the excited state was incredibly small. Even in the IR we found that the number in the excited state was usually < 1% of the molecules. What about the NMR, where we are using very low frequencies and Energies

Our machine has a 2.11 T field
protons have a γ of 2.67×10^8 radians $T^{-1}s^{-1}$

$$\begin{aligned}\Delta E &= \gamma h B_0 / 2\pi \\ &= 2.11 \times 6.626 \times 10^{-34} \text{ Js} \times 2.67 \times 10^8 / 2\pi \\ &= 5.94 \times 10^{-26} \text{ J}\end{aligned}$$

$$\begin{aligned}\text{Boltzmann } N_e/N_0 &= e^{-\Delta E/kT} \\ &= e^{-1.4 \times 10^{-5}} \\ &= .999986\end{aligned}$$

Let's assume there are 1 million atoms in the ground state (1×10^6)

Then there are $1 \times 10^6(.999986)$ or 999,986 in the excited state, or for about 2 million molecules a difference of about 14 between the upper and lower states! so they have almost the same population

This points to one of the problems of NMR. You only get signal from the slight excess of atoms in the ground state relative to the excited state, so even when you have 2 million nuclei in your machine, you only get a useful signal from the 14 excess relative to the excited state. Thus NMR is a technique with an inherently poor signal.

One way to increase your signal, is to increase the energy difference between the upper and lower states. This can be done how? The only variable in your ΔE equation is the field strength. To a first approximation the relative numbers increase directly with the field strength. Thus if you increase the field strength a factor of 10, you get 10x larger signal. Hence the big superconducting magnets found in research schools, 10x bigger than our magnet or better

19A-2 Classical Description of NMR

Precession of Nuclei in a magnetic field

What happens when you first pull a magnet out of your pocket and try to find north? Needle swings back and forth. Only settles down to true north as fluid in compass and friction slow its oscillations down.

In a nucleus gets a bit more complex. Magnet is imbedded in a spinning nucleus. Spinning mass of nucleus has angular momentum. So in nucleus instead of swinging east-west, whole nucleus spins around due to angular momentum, like a gyroscope.

This rotation of the spinning nucleus around the magnetic field is called *precession*

The angular velocity that this precession occurs can be found from the magnetic field and the magnetogyric ratio

$$\omega_0 = \gamma B_0$$

And converting angular velocity to frequency we get

$\nu = \gamma B_0 / 2\pi$, which is exactly the same equation we had for the quantum treatment

Absorption in CW experiments

While the nucleus will precess around the magnetic field, its potential E will depend on the angle between B_0 and the magnetic dipole as shown in [figure 19-2](#)

$$\text{And } W = -\mu_z B_0 = -\mu B_0 \cos \theta$$

(Should make sense $\cos 0 = 1$ all aligned and max negative E)

As θ approaches 90, $\cos \theta$ goes to 0 and E neutral

As $\theta > 90$, $\cos \theta$ is negative, and get + E , with max at 180

If we absorb E then we must take a μ that is pointing up, and make it point downward.

We do this by having an EM oscillator coil oriented at 90° to the B_0 field and have it oscillate at the exact frequency the nucleus absorbs at

Why at 90° etc. That is a little hard at this level let's skip

How can we make the μ move from pointing up to pointing down?

Need another magnetic field for it to rotate around

if it is currently rotating around a magnetic field pointing up, what direction does our new magnetic field have to be to make it swing around and point down? It must be at 90° to the current field. Not only that, but it has to be going around at the same frequency

Relaxation process in NMR

Well, now we can get the nuclei to absorb E . What happens when our 14 nuclei in 2 million are pushed from the ground state to the excited state? We have equal number of atoms in both states, and nothing more can be absorbed until somebody loses E and goes back to the ground state

This is called *saturation*

In UV and IR one way to get rid of this E is to radiate it back IE fluorescence. Reemission of photons is proportional to ν^3 . We are at low frequency, so reemission doesn't happen

There are two other processes for relaxation in NMR

Spin-Lattice Relaxation (or longitudinal relaxation)

Spin-Spin Relaxation (transverse relaxation)

Easy to observe relaxation in FTNMR signal. Watch how quickly the signal goes to zero following an exponential decay.

Relaxation effects important for several reasons

1. Limit how quickly you can take your next scan on the NMR
If don't wait long enough, nuclei saturated and you don't get a signal

2. Sharpness of peak (width) related to lifetime or relaxation time
 - a. Long lifetime - sharp peak
 - b. Short lifetime - broad peak

Spin-Lattice Relaxation

The absorbing nucleus is just 1 in large sea of other nuclei. The entire collection of nuclei is called the lattice, regardless of whether the sample is solid, liquid or gas

In gas and liquids in particular the lattice is undergoing lots of vibrations and rotations

The vibration and rotation of these other nuclei makes a complex, fluctuating magnetic field, and some component of this magnetic field has the right frequency to interact with our precessing nucleus

This allows our nucleus to pass its E to the other nuclei and vibrate and rotate the E away

Characterized by a first order exponential decay

Refer to as relaxation time T_1

Where T_1 reflects the average lifetime of an excited nucleus

Depends on magnetogyric ratio of nucleus

Also depends on mobility of lattice

- Crystals and viscous solids, little vibration or rotation
Hard to get rid of E, so T_1 is long
- In liquids have more vibration and rotation, more E exchange, shorter T_1
- At high T, have so many vibrations that chance of having the right frequency gets small so T_1 goes back up
- Net - have a min T_1

Spin-Spin Relaxation

Refers to a number of additional mechanisms that shorten lifetime and broaden lines

Again an exponential decay, but this time characterized by a transverse or spin-spin relaxation time, T_2

(Measured under different conditions than T_1)

T_2 usually very short in crystalline solids and viscous liquids
 This makes line so broad that can't be measured
 Thus can do NMR of solids or viscous liquids without special techniques to get around this relaxation mech

Called spin-spin because E is passed to neighboring, identical nucleus that is in a different quantum state
 No net change in E so does not change saturation

But since excited nucleus is no longer excited, lose its signal

Net effect can lose signal quickly, so you think can run another pulse, but since still saturated don't get any signal from the next pulse!

Short lifetime - Broad lines

More on difference between T_1 and T_2 in a bit

Other line broadening (lifetime shortening) problems

If B_0 slightly different from one nucleus to the next
 Then precession frequency is slightly different

Can be due to slight inhomogeneities in Magnetic field

- Spin sample to average out inhomogeneities
- Shimming - process of using electromagnets to make field more homogeneous to give longer, fuller signal and sharper peaks

Can be due to other magnetic nuclei in matrix

- Not significant in normal liquids because molecules move and inhomogeneities cancel out
- Significant in solids and viscous liquids because last long enough to be a problem

19-3 Fourier Transform NMR

Put nuclei into a strong magnetic field

Hit with a brief pulse (1-10 μ s) of EM radiation tuned to the precession frequency

This excites all the nuclei

Let it sit for a second or 2

While it is sitting, have electronics picking up the signal emitted into space of the nuclei's magnetic moments spinning in the electric field.

Once nuclei have relaxed back, hit it again and repeat as many times as you want

Figure 19-5, but doesn't show output and not to scale

How does pulse excite the nuclei, and where does signal come from?

Figure 19-6

Since sample has been sitting in B_0 before the pulse, nuclei have oriented to there is an excess aligned with B_0 the magnetic field (b) Use this net vector sum of all individual nuclei for the remainder of explanation

Pulse of Em radiation is oriented so it makes a magnetic field at 90° to B_0 . The nuclei 'see' this magnetic field and rotate around it (c)

Pulse time is set so moves μ 90° so it is in XY plane
(Hence term 90° pulse)

Now when turn off pulse μ is at 90° to B_0 so what does it do?
Will precess

As precess you have a magnetic field that oscillated between + and - X and + and - Y

Use a coil of wire like a radio antennae to detect this oscillation.

Record and plot this oscillation. This is your signal

Use FT to interpret signal in terms of frequencies

Relaxation in Pulsed NMR Figure 19-7

How long should the above signal last?

In a frictionless work with no relaxation mechanisms, forever

But just talked about 2 relaxation mechanisms,

Spin-Lattice (T_1 - Longitudinal)

Spin-Spin (T_2 -Transverse)

Said were measured in different ways, but didn't say how and didn't make connection to second names, longitudinal and transverse. Let's to that now

If ONLY T_1 Spin -Lattice relaxation occurs, what happens?

Precession occurs, but some of the spins lose there E to the lattice. When this occurs, what happens to the μ of the vector? (Now in lower E state, so now lined up with B_0)

So get picture (a) or T_1 Can also think of as vector that has been

tipped down to XY plane is spiraling back to be aligned with B_0

Called Longitudinal because experimentally measure the recovery of signal to the Z or longitudinal axis

If only T_2 or spin-spin relaxation

Precession occurs, but E exchanged with other nuclei with same precession frequency. Not loss of E so nothing moves to Z axis. However exchanges with other nuclei so signal fans out in X-Y plane. As fans out, net vector dies, so signal disappears

See picture (b) or T_2

Called transverse because is measure of disappearance of signal in transverse (X-Y) plane

Free Induction Decay (FID)

As said earlier Magnetic vector in X/Y plane is a magnetic oscillation that can be picked up just like a radio signal by a coil or antenna

Lets talk a bit about what the FID looks like

(Figure 19-8 and 19-9)

For any given experiment the NMR is tuned to one exact frequency. The transmitter is set for that frequency and the receiver is also tuned to that frequency. This frequency is then the frequency in the exact middle of your spectrum

If your signal is exactly on the tuning frequency, then you get a signal that looks like figure 19-8. Here you see just the exponential decay of the signal, not the oscillations of the signal because the signal and the NMR are in sync, and you will get a single peak dead center in your spectrum

If your signal is not at the same frequency as the NMR you will get a signal like 19-9. If you measure the frequency of the oscillations you can measure the distance between the peak and the middle of the spectrum so you get a peak offset from the middle. (Also not the decay as the signal disappears from the X/Y Plane)

If you have more than one signal, then you have lots of different oscillations all superimposed on top of each other and things get really complicated

19-4 Types of NMR spectra

2 major types, wide line or high resolution

Wide Line Figure 19-11

Large bandwidth (if large range of frequencies)
 Can't see fine structure due to chemical environment
 Looking to see what isotopes are in a sample, not the details of chemistry around each isotope
 Used in low magnetic field strength, not too useful for chemists

High Resolution Spectra (Just about any other figure)

Working with a single isotope or nucleus
 Looking at difference between nuclei of .00000001 in frequency or less (.01 ppm)
 Generally several peaks, each peak related to chemical environment of the nucleus

This is what chemists use, so rest of chapter is on High-Res NMR

19B Environmental Effects on NMR Spectra

Just said that in high res NMR the position of a peak is related to chemical environment
 What does this mean?

Chemical Environment in NMR is the nearby electrons and nuclei.

Will discuss in term of ^1H since this is most common NMR nucleus
 but discussion is applicable to any other spin $\frac{1}{2}$ nucleus

19B-1 Types of Environmental effects

Will worry about 2 major environmental effects in this class

Chemical Shift - overall position of peak changes due to shielding of magnetic field by other nearby nuclei

Spin-Spin Coupling - Fine structure or splitting within a peak due to other nuclei that are 1,2 or 3 chemical bonds away

How can you tell a splitting interaction from a chemical shift interaction?

Go to a different magnet

- Coupling does not depend on magnetic field so peaks will be same distance apart (when measured in Hz)
- Chemical Shift does depend on Field, so overall frequency will change
- Actually, since all NMR plot data on ppm scale, so chemical shift is independent of field, gets a little more confusing
- in ppm the chemical shift will remain the same as you go to a higher magnetic field
- in ppm the splitting will appear to get narrower (because there are more Hz/ppm) as the Magnetic field increases

Origin of Chemical Shift

All electrons in a molecule are moving charges, so all are making a magnetic field

The magnetic field of the electrons is usually OPPOSED to the external magnetic field

So the magnetic field 'observed' by a nucleus is usually a little bit smaller than B_0 because the electrons around the nucleus 'shield' it from the external magnetic field

CH_3 Protons more shielded so further to right

OH Protons less shielded so further to left

CH_2 protons intermediate shielding so in between

Isolated H nucleus - assume no shielding somewhere off to left

Talk just a bit about terms upfield, downfield etc.

- In original CW machine could do two things to set up absorption
 - change frequency of EM E with electronics
 - Change magnetic field with small electromagnets on top of the main magnet
- **Convention was that to right was higher magnetic field (figure 19-12)**
- So now stuck with terminology that things to right are upfield and things to left are downfield

For myself, because I sometimes get confused magnetic field increases as we go to the right, but frequency increases as we go to the left Why? The rightmost peak is the most shielded nucleus, hence experiences the lowest magnetic field and so would have the lowest frequency. All the other nuclei are less shielded, hence 'see' a higher magnetic field, hence have a higher resonance frequency, so frequency (and E) increases as you go to the left, just the opposite of the magnetic field

Origin of Spin-Spin Splitting

Magnetic moment of nucleus interacts with electrons in bond to another nucleus

This change in electron interaction causes adjacent nucleus to see slightly different magnetic fields

Sometimes called a polarization interaction

for spin $\frac{1}{2}$ nuclei get a 2-way split for each coupled nucleus

Effect is independent of applied field, and is superimposed on chemical shift effect

Abscissa Scales of NMR

Almost impossible to determine absolute magnetic field hence getting X axis exactly right is almost impossible

On other hand is very easy to get difference in magnetic field from some set point to high accuracy (ppb)

Thus use a relative scale, measure relative to some reference point

Usually an internal standard included in sample

Nonpolar solvent TMS tetramethyl silane $\text{Si}(\text{CH}_3)_4$
 Very shielded high field (off to right assigned 0)
 Away from everything else
 Inert
 Very soluble in nonpolars
 Easy to remove by distillation (BP 27)

Water DSS 2,2-dimethyl-2-silapentane-5-sulfonic acid
 $(\text{CH}_3)_3\text{SiCH}_2\text{CH}_2\text{CH}_2\text{SO}_3\text{Na}$
 I used
 TSP Trimethylsilylpropionate
 $(\text{CH}_3)_3\text{SiCH}_2\text{CH}_2\text{CO}_2\text{Na}$

In both cases methylene H's are deuterated so don't show up
 The remaining CH_3 's almost identical to TMS

This relative scale nice because when measure using this chemical shift scale, peak position becomes independent of magnetic field so you can compare data obtained on different machines directly.
 (See figure 19-13)

19B-2 Theory of the Chemical Shift (Do I want to cover?)

Chemical shift occur from secondary magnetic field produced by circulation of electrons

These are called local *diamagnetic currents*

Can either enhance or diminish the field 'observed' by a nucleus

Very complex theory

Applied magnetic field tend to make electrons circle nucleus in 1 direction
 (Figure 19-14)

Once electrons circle in this direction, the circulating charge makes magnetic field that is in opposite direction. Thus nucleus in very center sees a slightly reduced magnetic field so it is *shielded*

Shielding directly related to electron density around nucleus

As more electronegative atoms around a nucleus, less electron density, so should be less shielded (downfield shift)

CH ₃ X	X=	Ppm
	I	2.16
	Br	2.68
	Cl	3.05
	F	4.26

Part of reason TMS is so far upfield is that Si Electronegativity 1.8
Is less electronegative than C(2.5) or H(2.1) so electrons pushed toward C and H making them shield more (move upfield)

Magnetic Anisotropy

Other effects in compounds with double or triple bonds

CH ₃ -CH ₃	0.9
CH ₂ =CH ₂	5.8
CH≡CH	2.9
No Clear trend	
RCHO	10
C ₆ H ₆	7.3

In these cases the electrons are no longer circling a single nucleus, **but they are in larger molecular orbitals (figure 19-15, 19-16)**

The circulation of electrons in these larger orbital will follow the same rules, but the amount of 'ring current' will vary with the molecule's orientation to the field. Further the shielding or deshielding will depend on the nucleus orientation relative to the 'ring current' origin

Correlation of chemical shift with structure

A number of empirical tables for correlate chemical shift and **structure (Figures 19-17 and table 19-2)**

Note that chemical shift of protons that can hydrogen bond can undergo major solvent effects

19-3 Spin-Spin Splitting

Let's look at the origin of the spin-spin splitting

Origin

One nucleus interacts with another via the electrons bonds the two nuclei together

Look at Ethanol (fig 19-12 again)

First CH₂ effect on CH₃

2 CH₂ protons

Since low E 50:50 aligned with and against magnetic field

Therefore

↑↑, ↓↑, ↑↓, and ↑↑ (Assume external field is ↑)
Are the possible alignments

These magnetic field transmitted by bonding electrons
-If fields augment external field, Nucleus 'sees' the higher field, so you get a downfield shift
- If fields oppose magnetic field, CH₃ sees a slightly lower mag field, so peak is shifted slightly upfield.
- if one each way, not change so no shift

- so end up with triplet, 1 low 1 high and 2 in middle, this also explains relative sizes of the peaks

Now look at three methyl protons on CH₂

External ↑ ↑↑↑ ↑↑↓ ↓↓↑ ↓↓↓
 ↑↑↑ ↓↓↑
 ↓↓↓ ↑↑↓

So get 4 peaks in a 1:3:3:1 ratio

General rule for *multiplicity* if n equivalent protons, will split the resonance on an adjacent C into n+1 peaks

This applies best to a 1st order spectrum, i.e. chemical shifts of 2 peaks are far apart. Second order spectra, where the chemical shifts are fairly close are a lot more difficult to interpret

Rule Governing Interpretation of 1st order spectra

1. Equivalent nuclei do not interact with each other to give

- multiple peaks (the three H's on CH₃ do not split each other)
2. Coupling constants decrease with number of bonds between atoms (1 bond strong coupling, >4 bonds almost 0 coupling)
 3. Multiplicity of a band determined by n, number of magnetically equivalent protons on neighboring atoms, =n+1
 4. If proton on B have two different nonequivalent neighbors, then multiplicity = (nA+1)(nB+1)
 5. Approximate relative areas are symmetric around midpoint and proportional to (X+1)ⁿ
 N=3 (adjacent to methyl group) should get 4 peaks

$$(X+1)^3 = (X+1)(X+1)(X+1)$$

$$= (x^2 + 2X + 1)(X+1)$$

$$= X^3 + 2X^2 + X + X^2 + 2X + 1$$

$$= 1X^3 + 3X^2 + 3X + 1$$
 So ratios are 1:3:3:1
 6. Coupling constant independent of field so can differentiate coupling from chemical shift by running spectrum on a different magnet

Effect of Chemical Exchange

Compare figures 19-19 pure ethanol and 19-12 everyday ethanol

Why is OH a triplet in one and a singlet in the other?

First of all what should the OH be a singlet or a triplet?

Triplet - split by CH₂

OH is an example of an *exchangeable* proton, a proton that can exchange with the solvent over the course of the NMR experiment

When this happens can see some interesting effects

1st the one you see here, you loose coupling.

This occurs because the exchange is so fast that for 1 fraction of the experiment the OH is coupled to a ↓↓ ethanol, for another a ↑↑ ethanol, and for another a ↑↓ ethanol, so the effects all average out to give you a single, somewhat broader peak

2nd effect you see when look at what a peak can exchange with

For instance what if there were a pinch of water in this ethanol

In that case you should see 2 OH peaks, one for HOH and one for ethanol OH. Since this proton can exchange between these two different peaks, see some other interaction effects

-If exchange is fast compared to the difference in chemical shifts, you get a single sharp peak right in between where the two different peaks should be.

- If the exchange rate is about the same as the difference in chemical shift, you get a broad peak

- if the exchange rate is slower than the difference
you see the two separate peaks

19B-4 Double Resonance techniques

Key to many advanced techniques, but I don't want to hit too hard. Simply put, radiate sample with a particular frequency during the experiment. When that frequency corresponds the frequency of a resonance in you sample, what happens?

Since putting E in at that frequency that make upper and lower state have equal populations, so peak disappears from spectrum. Not only that, but anything that was coupling pattern associated with that peak collapses, just like it wasn't there to be coupled to.

19C NMR Spectrometers

Concentrate on high resolution

Fields from 1.4 to 21 T (Protons 60 to 1,000 Mhz)

<1970 all CW

now all manufactured are TR, and most have supercooled superconducting magnets for higher fields

19C-1 Components

Figure 19-21 Block diagram of electronics

Highly stable Magnet with a very uniform field where sample sits

sample surrounded by transmitter/receiver coil (not shown)

RF transmitters and amplifiers, etc.

19C-2 Magnets

sensitivity and resolution depend directly on field

Hence the stronger the field the better the machine

Our 90 MHz is right near the bottom

Field must be uniform and reproducible

This makes magnet most expensive part of NMR

3 types of magnets

Permanent magnets

older machines,

30,60 and 90 MHz

Field drifts with T so not good for long experiments

Conventional electromagnets - Not presently used

Superconducting magnets

most modern machines

>90 Mhz

Coil of Ni/Sn or Ni Ti wire

Held in liquid He at 4K

Help keep that cool that is surrounded by liquid N₂ (77K)

Run current through like an electromagnet
But since superconducting, once current starts circling it doesn't stop, so can detach from current source

Add more N₂ every week
Add more He every 3-6 mo.

Also drifts with time so has special compensation

Locking the field

Keep track of a second nucleus (usually D)
Automatically add and remove small amount of additional mag field with electromagnet to keep overall field steady
Note: our machine doesn't do this!

Shimming the field

Need the field around the sample to be uniform
Have small loop of wire for electromagnets to do this too
On older machines you adjusted these manually by looking for the max signal
On new machines have computer program that will automatically optimize
Should do this before every run!

Sample Spinning

To further make field uniform spin sample on its axis to average out any inhomogeneities

This does make lines sharper
But if certain shims are off can lead to *sidebands* or *spinning sidebands*

Pay attention and do additional shimming if you have spinning sidebands

19C-3 The sample probe

hold the sample in proper spot of magnetic field
spins the sample

Contains coils for primary transmitter and receiver of EM radiation
Often contains an additional coil for transmitter and receiver of EM radiation at a second frequency
(Can even contain yet a third or fourth coil)

Transmitter/Receiver coils

loop of wire built into probe both to transmit and receive RF signal. If > 1 coil, the inner coil is always the most sensitive

Pulse Generator - Skip

Receiver System - Skip

19C-4 Detector and Data Processing

Part of the NMR electronics works at the primary frequency of the nucleus, IE the 90 MHz ^1H frequency (or C or what ever frequency). The useful signal is mixed on top of that by variations in frequencies of ppm. So part of the electronics demodulates the actual signal down to these frequencies, that happen to be audio frequencies

In acquiring the digital data there are two important parameters to watch out for

Sampling frequency - How often you get a data point

Total sample time - How long or how many data points you acquire

Sampling frequency

As shown in figure 19-22 if you have a very high frequency in your signal, but you are sampling at a low rate, the FT transform will misinterpret the high frequency for a low one.

This results in peaks getting 'folded over' into your spectrum in inappropriate places

This demonstrates that the sampling time is related to the range of frequencies observed or the sweep width (SW), so when you use SW to set your instruments sweep width, you are actually varying the sampling rate! (Note with our spectrometer there is an additional digital filter that eliminates fold-over, so you will probably not observe this on our machine. But It might be an interesting thing to try!)

of data points

The other important parameter is how many data point you take. Naturally your digital resolution (points/Hertz) is going to depend on the number of data points you acquire. Thus the more data points or the longer you acquire a signal, the better your potential resolution.

Your total *acquisition time* (The time it takes to acquire a spectrum) is the Time / point X total number of points. On our machine this is determined

for you , but on other machines you can make tradeoffs between # of points and time/point to optimize this value

Quadrature Detection

One final point. The instrument's frequency is set to be right in the middle of the spectrum you observe. How does it distinguish peaks that are upfield by, say 1ppm, from things that are downfield by the same amount. This bit of magic is done by *Quadrature detection*

While quad detection is actually done by splitting the signal and comparing its phase to a standard, what is being done with signal processing is like have 4 detector coils, one on X, one on Y, one on -X and the fourth on -Y (Hence the term quad) When you have 4 detector you can tell when something is going clock wise (X, Y,-X,-Y) from something that is going counterclockwise (X,-Y,-X, Y) So you can tell the + ppm frequencies from the - ppm frequencies.

This quad detection has a couple of important ramifications

1. When I set my NS or number of scans, I always set it in multiples of 4, so I get all 4 principle directions equally represented. (If you don't do this you can get some nasty artifacts)

2. Often the axes of your detector aren't precisely aligned with the start of your signal. When this happens your signal is said to be *out of phase*. You can tell your signal is out of phase when you see the peaks are distorted (Usually high on one side and dipped on the other) instead of being nice and symmetric.

You almost always have to correct this error in your spectra. Fortunately our software has a pretty good phase correction routine so all you have to do is to apply the appropriate command any you get a pretty good correction. (QP is fast and works fine for ^1H , AP is slower but works best for ^{13}C) If you are finicky, or you have some particular kind of experiment that doesn't phase correct using the automatic routines, you can do a manually phase correction if you want.

Signal Integrators - built into the software, good to 1-2%

19C-5 Sample Handling

Liquids – Must be low viscosity

Solvent should have no protons, so CCl_4 ideal, but not everything is

soluble

If has protons, then must obtain solvent that has deuterium instead of protons so no solvent signal

Our machine not very sensitive, so need lots of sample

Pure material is preferred

For Protons can go as low as 5% or about 0.5M

For C if have 100% then will take about 1 minute

If have 1M will take about 5 minutes

This is because C is Less sensitive and <1% natural abundance
(More on this in a bit)

High field research machines >600 MHz

Low end used to be at mmolar. Now probably .1 mM

19D Applications of Proton NMR

19D-1 Identification of compounds

Can't absolutely identify a compound, but, when combined with one or two others methods like mass spec and IR all together are pretty convincing. Several examples in text.

19D-2 Quantitative Analysis

Since peak area is proportional to # of protons, can use peak areas of resolved peaks for quantitative work.

Usually overlap problems and cost of instrument makes it so some other method is used

19E ¹³C

¹³C gyromagnetic ratio about 4X smaller than ¹H

natural abundance of ¹³C is 1.6%

Overall this means that ¹³C is about 6000 X less sensitive than ¹H

In some ways more useful

information about backbone of organic

chemical shift range in the 200 ppm so much more spread out

No C-C coupling because chances of have 2C next to each other is

.016*.016

(Still coupled to adjacent ¹H, but this is easy to remove with decoupling)

19E-1 Proton Decoupling

3 main types, Broadband, off-resonance, and gated

Broad-Band

Put in E at Proton frequency so Saturate all ^1H resonances. Once saturated upper and lower state are equal so no coupling to C

See figure 19-30

Off-Resonance, pulsed and NOE - skip. Not enough detail in our text

19E-2 Application to Structure determination

Chemical Shift values of various functional groups shown in figure 19-32

Continue to use TMS as 0 ppm

Note that substituents can have fairly long range effects

A Cl on 1 will shift that C by 31ppm

The next C by 10

The next by 5.3

The next by .5

And the last by .1

Can be done on solids, but we will skip this section

19F Other Nuclei**19F-1 ^{31}P**

100% abundance, gyromagnetic ratio about 1/3 of H so .07 as sensitive as ^1H

Chemical shift range of 700 ppm!

Useful in Biochem

ATP

Phosphorylated compounds

DNA

See figure 19-34 ATP

19F-2 ^{19}F

100% abundance, gyromagnetic ratio about same of H so .8 as sensitive as ^1H

Chemical shift range of 300 ppm

Large solvent effects

Not as many compounds with F so not as much known

19G 2-D NMR

Multipulse experiments

Pulse-incremented time-pulse-acquisition
 Do FT in acquisition. Then line up and do FT in incremented delay

Get spread out over 2 frequencies

See figure 19-36

Real power is in adding other pulses and clever timing events. Can select different interactions between nuclei that are passed from one dimension to another

COSY
 NOESY
 ETC

19H Magnetic Resonance Imaging

New field of NMR (Last 3 decades)

Not as much chemistry, but let's see how it works

First why? Low E so less damaging than X-rays

Can tune for particular interactions, so good on soft tissue

Basic idea Figure 19-37

In solution NMR we tried our darndest to keep the magnetic field constant so all the protons had the same frequency

In Imaging we make the magnetic field not constant, but vary it across an object

So protons have different frequencies, and if pulse at 1 frequency, only get protons from 1 slice because at 1 magnetic field

To get X, and Y do further ticklings use gradient and pulse to flip nuclei an 1 plane then turn off Z gradient and turn on X and Y gradients at timed intervals to see what they do to signal. Then recombine with FT to get image. (I know this is very vague, but that is as much detail as I want to get into.

Lots of future applications