Learning Guide for Chapter 5 - NMR Spectroscopy

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I. Introduction to NMR spectroscopy

To introduce you to NMR spectroscopy, we will first compare it to IR spectroscopy.

<table>
<thead>
<tr>
<th>IR spectroscopy</th>
<th>NMR spectroscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>type of light:</td>
<td>type of light:</td>
</tr>
<tr>
<td>infrared</td>
<td>radio waves</td>
</tr>
<tr>
<td>what causes light to be absorbed:</td>
<td>what causes light to be absorbed:</td>
</tr>
<tr>
<td>vibration of a bond with a dipole</td>
<td>transitions in energy state</td>
</tr>
<tr>
<td>at the same frequency as the light</td>
<td>of nuclei of atoms</td>
</tr>
<tr>
<td>complicated - we won't worry</td>
<td>about how it works</td>
</tr>
<tr>
<td>what bands represent:</td>
<td>what peaks represent:</td>
</tr>
<tr>
<td>bonds</td>
<td>atoms</td>
</tr>
<tr>
<td>x-axis:</td>
<td>ratio of magnetic field strength</td>
</tr>
<tr>
<td>frequency in cm^{-1}</td>
<td>in ppm</td>
</tr>
<tr>
<td>what we learn about a compound:</td>
<td>what we learn about a compound:</td>
</tr>
<tr>
<td>functional group</td>
<td>structure of the compound</td>
</tr>
</tbody>
</table>

Which kind of spectroscopy can distinguish each pair of compounds?

IR

- functional group: yes C=O vs O-H, C-O
- no

NMR

- structure: yes
- yes

Which type of spectroscopy is more powerful?

NMR - more powerful, more complication, more expensive!
What characteristic allows an atom to be detected by NMR?

atomic weight is an odd number

What elements are commonly found in organic molecules? Which are suitable for NMR?

<table>
<thead>
<tr>
<th>element</th>
<th>isotopes</th>
<th>NMR?</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon</td>
<td>$^{12}\text{C}$</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>$^{13}\text{C}$</td>
<td>yes - not as useful, only 1% of C's</td>
</tr>
<tr>
<td>hydrogen</td>
<td>$^{1}\text{H}$</td>
<td>yes - most common kind of NMR (also called proton NMR)</td>
</tr>
<tr>
<td>oxygen</td>
<td>$^{16}\text{O}$</td>
<td>no</td>
</tr>
<tr>
<td>nitrogen</td>
<td>$^{14}\text{N}$</td>
<td>no</td>
</tr>
</tbody>
</table>

A typical proton NMR spectrum looks like this:

Each cluster of spikes is called a: peak

Where can you find each of the following, and what does it tell you about the peak?

- chemical shift: where it is on the x-axis what other atoms are nearby
- integration: area under the peak how many H's are in that peak
- splitting: how many spikes how many neighbors

What should you be able to do?

1. Assign peaks on a compound to a spectrum.
2. Sketch the spectrum of a compound.
3. Deduce the structure of an unknown compound from its spectrum.
II. Distinguishing Equivalent Hydrogens

When do we say that two H's are equivalent?  
same nearby atoms, same # of neighbors

What happens on a spectrum when two H's are equivalent?
both part of the same peak, gets more area  
(draw two peaks on top of each other, then show the integration getting larger)

Draw in all H's for the following compounds. Circle those that are equivalent, and then count the number of sets.

Rules of thumb:

1 - H's on the same carbon are equivalent (except on C=C)

2 - H's on different carbons are not equivalent (except on identical groups)

More exact rule:

If you can separately replace two H's with a Cl, and the same compound results, they are equivalent.

How many sets of equivalent H's are present in each of the following molecules?

- 4
- 5
- 6
- 3
- 6
- 4
- 1
- 4
- 4
- 6
III. Chemical Shift

What compound is used to establish "0" on the chemical shift axis? Why do you think this would make a good reference compound?

\[
\text{tetramethylsilane (TMS) } \quad \text{H}_3\text{C} \quad \text{Si} \quad \text{CH}_3 \\
\quad \text{CH}_3
\]

12 equivalent H's - strong signal with small amount of compound

H's near Si are to the right of nearly all other compounds

Draw arrows showing the direction of upfield and downfield:

<----- downfield upfield ----> 0

Predict which set of hydrogens will be farthest downfield. When will this rule be useful?

1) \( \text{CH} > \text{CH}_2 > \text{CH}_3 \)

\( \begin{align*}
1.4 & \quad 1.3 & \quad 0.9 \\
\text{CH}_3'\text{s - farthest upfield} & \quad \text{can tell CH and CH}_2 \text{ apart} \\
\text{fewer H's - farther downfield}
\end{align*} \)

2) \( \text{:Br} \)

\( \begin{align*}
3.4 & \quad 1.7 & \quad 1.3 & \quad 0.9 \\
\text{closer to EN atom} & \quad \text{farther downfield} \\
\text{farther downfield} & \quad \text{good for detecting H's next to} \\
\text{alcohols, amines, alkyl halides} & \quad \text{more EN atom} \\
\text{farther down} & \quad \text{two EN groups} \\
\text{(effect is additive)} & \quad \text{farther downfield}
\end{align*} \)

3) \( \text{H}_2\text{C} \equiv \text{CH} \quad \text{HC} \equiv \text{CH} \quad \text{H}_3\text{C} \equiv \text{CH}_3 \)

\( \begin{align*}
4.5 - 6.5 \text{ ppm} & \quad 2.5 - 3.0 \text{ ppm} & \quad 0.5 - 1.5 \text{ ppm} \\
\text{sp}^2 \text{ downfield} & \quad \text{sp} & \quad \text{sp}^3 \text{ upfield} \\
\text{makes H's attached to C} \equiv \text{C easy to spot}
\end{align*} \)
4) 

\[
\begin{array}{c}
\text{Huge effect - easy to identify H's on benzene rings} \\
7.2 \text{ ppm} & 1.3 \text{ ppm} \\
\text{aromatic - way downfield}
\end{array}
\]

5) 

\[
\begin{array}{c}
1-5 \text{ ppm} & 1-5 \text{ ppm} & 7.5-9.5 \text{ ppm} & 10-13 \text{ ppm} \\
\text{hydrogen bonding - wide range possible} \\
\text{affects alcohols, amines, amides, and carboxylic acids} \\
\text{affected by concentration of sample - same compound may have different} \\
\text{values under different conditions} \\
\text{also affects width of band - may be so wide you can't see (except in} \\
\text{integration line)} \\
\text{skinny peak} & \text{broadened peak} & \text{very broad peak}
\end{array}
\]

Which of the set of H's shown on each compounds will appear furthest downfield?

CH > CH$_2$ closer to O sp$_2$ > sp$_3$

aromatic

CH$_2$ > CH$_3$ next to 2 Cl's

How many peaks should the following compound have? Which two would be most likely to overlap?

should be 6

only 5 actually show up

two sets are too close to separate
What are some useful ranges to remember?

- H's on C next to C=O: 2.0-2.5 ppm
- H's on C with N: 2.5-3.0 ppm
- H's on C with O or X: 3-4 ppm
- OH or NH in alcohols or amines: 1-5 ppm
- H's on C=C: 4.5-6.5 ppm
- H's on aromatic ring: 6.5-8.5 ppm
- H's on amides: 7-9 ppm
- H's on C=O: 9-11 ppm
- OH in carboxylic acids: 9-13 ppm

These are not rules, only guidelines. Not all H's are covered here. If more than one thing affects an H, both will pull it downfield.

Give the range at which you would expect to find the following H's:

- 3-4 ppm
- ~7 ppm
- 2-3 ppm
- 2.0-2.5 ppm

What H's should stand out on the following compounds?

- 3-4 ppm
- 1-5 ppm (broad)
- 4-6 ppm
- ~7 ppm
- 9-13 ppm (broad)
IV. Integration

What does integration mean, mathematically?  the area under a curve

What does the integration tell us on an NMR spectrum?  how many H's are in that peak

Why does the area under a curve increase when there are more H's in a peak?
  the peaks exactly overlap, so that they just get bigger (more area)

Identify the sets of equivalent H's in the following compound. Which is furthest downfield? Which will have a greater integration?

\[
\begin{align*}
3-4 \text{ ppm} & \quad \text{less than } 3 \text{ ppm} \\
3:9 & = 1:3
\end{align*}
\]

Compare the integration ratios for the following compounds. Can you tell them apart?

\[
\begin{align*}
\text{O} & \quad 2:3 & \quad 4:6 & = 2:3 & \text{integration would look the same}
\end{align*}
\]

Predict the integration ratio for each of the following compounds.

\[
\begin{align*}
3:2:1:6 & \quad 3:2:1:3:1:1:1 & \quad 1 & \quad 2:4:1:3 & \quad 2:4:6 \\
(1:2:3) & & & & \\
\end{align*}
\]

\[
\begin{align*}
2:2 & \quad 1:2:1 & \quad 1 & \quad 2:2:3 & \quad 1:1:1:3
\end{align*}
\]
How do we measure the integration?

measure how far up the integration line goes from the beginning of the peak to the end

Identify each set of equivalent H's in the following compound. Give the chemical shifts you would expect. Give the integration. Match up the H's with the peaks in the spectrum.

What does the height of a peak tell you? nothing! only the area matters

short, broad peak  
same area!  
same # of H's  
tall, narrow peak
V. Spin-spin splitting

What does splitting mean? the number of spikes in a peak

What happens when H's are separated by more than one atom? they are both singlets

What happens when a set of equivalent H's has one or more neighboring H's? the peak is split into cluster of spikes

How can you tell what splitting a peak will have? original spike + one for every neighbor

Sketch the spectra of the following compounds:

1 neighbor = doublet (equal height) sometimes lean toward each other

H's that split each other are said to be "coupled"

2 neighbors = triplet (1:2:1)

3 neighbors = quartet (1:3:3:1)

if they are equivalent, they don't count as neighbors

4 neighbors = quintet
5 neighbors = multiplet(6)
6 neighbors = multiplet(7) etc
Assign splitting to each set of equivalent H's in the following compounds.

H's on either side count

H's in the same set can't split each other
H's can only see their own neighbors (not equivalent's neighbors)

What happens when the chemical shifts of two separate peaks are so similar that they overlap?

it forms a multiplet

When is this common? H's on benzene rings, lots of CH$_2$'s in a row
What is complex splitting? neighbor + 1 rule doesn't work

What kind of H's commonly show this? H's on C=C

What causes it? coupling constants are not the same, so splitting doesn't overlap

Example:

Do H's on alcohols and amines usually participate in splitting? no - H-bonding causes splitting to average out

CH₃OH (regular sample)
- a: 3-4, 3H, s
- b: 1-5, 1H, s

CH₃OH (dilute, no water)
- a: 4-6, 3H, d
- b: 1-5, 1H, q
VI. Deuterium in NMR

What is deuterium?

\[ ^1\text{H} \quad \text{regular hydrogen} \quad \text{H} \quad \text{same chemical behavior} \]
\[ ^2\text{H} \quad \text{deuterium} \quad \text{D} \]

Why is it useful in NMR? doesn't show up on an NMR spectrum - it is invisible!

Why are deuterated solvents needed in NMR?

to take a spectrum, the sample must be dissolved in a solvent
we don't want the solvent to show up, only the sample compound

What are the most common NMR solvents?

\[
\begin{array}{c}
\text{CDCl}_3 \\
\text{Cl} - \text{C} - \text{D} \\
\text{Cl}
\end{array}
\quad \begin{array}{c}
\text{DMSO-d}_6 \\
\text{D}_3\text{C} - \text{S} - \text{CD}_3
\end{array}
\]

nonpolar, moderately polar compounds

more expensive, absorbs water

Do deuterated solvents show up on an NMR spectrum? no

Is there a peak that shows up because of the solvent? Why?

contamination with regular H

\[
\begin{array}{c}
\text{CHCl}_3 \\
7.25 \text{ ppm}
\end{array}
\quad \begin{array}{c}
\text{DMSO} \\
2.5 \text{ ppm}
\end{array}
\]

If water is present in the compound or the solvent, where will it appear on the spectrum?

depends on the solvent

\[
\begin{array}{c}
\text{water in CDCl}_3 \quad 1.5 \text{ ppm}
\end{array}
\quad \begin{array}{c}
\text{water in DMSO-d}_6 \quad 3.35 \text{ ppm}
\end{array}
\]

What will happen if D\textsubscript{2}O is added to a sample containing an alcohol?

H will be replaced with a D - won't show up on the spectrum

\[
\begin{array}{c}
\text{OH peak} \\
\quad \require{cancel} + \\
\text{no peak}
\end{array}
\quad \begin{array}{c}
\text{no OH peak} \\
\quad \require{cancel} + \\
\text{H shows up}
\end{array}
\]

\[
\begin{array}{c}
\text{OH peak} \\
\quad \require{cancel} + \\
\text{no peak}
\end{array}
\quad \begin{array}{c}
\text{no OH peak} \\
\quad \require{cancel} + \\
\text{H shows up}
\end{array}
\]
spectrum before adding \( \text{D}_2\text{O} \): 

\[
\begin{array}{c}
\text{a - 6H, d} \\
\text{b - 1H, m(7)} \\
\text{c - 1H, s}
\end{array}
\]

spectrum after adding \( \text{D}_2\text{O} \):

\[
\begin{array}{c}
\text{a - 6H, d} \\
\text{b - 1H, m} \\
\text{c - nothing!}
\end{array}
\]

What functional groups will have H's that disappear when shaken with \( \text{D}_2\text{O} \)?

- anything with OH or NH 
- amine
- amide
- carboxylic acid
- alcohol (not aldehyde)

VII. Carbon-13 NMR

Why isn't \( ^{13}\text{C} \) NMR as useful as \( ^{1}\text{H} \) NMR?

- \( ^{13}\text{C} \) isn't as common - only 1% of all C atoms
- takes longer, need more concentrated samples, more noise

Why isn't integration used?  

interference from H atoms

How is the peak affected by the number of H's attached to the carbon?

- \( \text{CH}_3 \) taller than \( \text{CH}_2 \), then \( \text{CH} \), then C w/ no H's

Why won't you see any carbon-carbon splitting?  

no \( ^{13}\text{C} \)'s next to each other

Why is carbon-hydrogen splitting usually eliminated?  

usually makes the spectrum too hard to read

What do you call a spectrum with no C-H splitting?

- proton-decoupled
- all singlets

- proton coupled
What is the most useful information you can get from a $^{13}$C NMR spectrum?

*the number of non-equivalent C's*

What are some common chemical shift ranges?

- sp3 carbon atoms  
  0-80 ppm

- C=C in alkenes and aromatic rings  
  100-160 ppm

- C=O  
  160-220 ppm

In the following spectrum of vanillin, assign the carbon atoms to the peaks where possible.

How many peaks would you expect each of the following compounds to have? What chemical shift ranges would they fall in?

- 5 peaks  
  all 0-80 ppm

- 5 peaks  
  3 0-80 ppm  
  2 100-160 ppm

- 6 peaks  
  1 0-80 ppm  
  4 100-160 ppm  
  1 160-220 ppm

Where does the solvent peak appear for CDCl$_3$?

78 ppm - small triplet
VIII. Practice with NMR spectra

Match the peaks in the following compounds with the H's in the structures shown.

- **a**: 2H, t (4-6)
- **b**: 4H, q
- **c**: 4H, t

- **a**: 1H, t ~7
- **b**: 2H, t ~7
- **c**: 2H, d ~7
- **d**: 1H, m(7) 3-4
- **e**: 6H, d

- **a**: 3H, t
- **b**: 2H, m(6)
- **c**: 2H, t 2-2.5
- **d**: 3H, s 3-4
Sketch the spectrum of the following compounds.

$$\begin{align*}
\text{a: } &3\text{H, s } 2-2.5 \\
\text{b: } &2\text{H, q } 2-2.5 \\
\text{c: } &3\text{H, t} \\
\text{b} &> \text{a} > \text{c}
\end{align*}$$

Deduce the structure of the following compounds.

Integration:
only 3 H's - integrations must add to 3
so, 1:2

Splitting:
triplet - 2 neighbors
doublet - 1 neighbor

Chemical shifts:
a is at 5.7 - next to 2 Cl's
b is at 3.9 - next to one Cl, two more nearby
(there are only 2 options with this formula as well; all evidence points to Br in the middle instead of on the end)

integration:
7 H's - 1:6

splitting:
a - multiplet(7): 6 neighbors
b - doublet: 1 neighbor

gerjection:
12 H's, but only two peaks
1:3 = 3:9

splitting:
both singlets
no neighbors!

chemical shifts:
a is at 4.2 ppm
b is at 1.7 ppm
a is next to Br

not an alcohol, ester, COOH, aldehyde, ether, or anhydride
must be a ketone

C₄H₈Cl₂

1.60 ppm (3H, d)
2.15 ppm (2H, q)
3.75 ppm (2H, t)
4.27 ppm (1H, m(6))

4 C's, 4 peaks - each C has one set of H's;
only one 3H - an end;
it has only one neighbor - a CH

CH₃-CH-CH₂-CH₂

4 3 2 1

CH has 5 neighbors - 3 + 2
must be 2 CH₂'s
add Cl's