

Ch 13 Nuclear Magnetic Resonance (NMR) - Mapping C and H frameworks

Nuclear Spin Resonance

- Atomic nuclei spin about an axis, which is normally oriented in a random direction.
- Some nuclei, such as ^1H and ^{13}C interact with an applied magnetic field (B_0).
- Essentially, any nucleus with an odd number of either protons or neutrons will interact with the magnetic field.
- These nuclei will align their spin axes either parallel or anti-parallel to the field.
- Parallel is lower energy and is favored.
- The nuclei will “spin-flip” from parallel to anti-parallel if the correct $E = h\nu$ is applied.
- Magnetic field strengths used for analysis are typically 4-7 Tesla (sometimes >20 T).
- The energy needed for a spin-flip is a function of the magnetic field strength.
So, the field strength can be varied at constant frequency, or vice-versa.
- At typical field strength's, the frequencies needed for spin-flips are ~ 200 MHz for ^1H and ~ 50 MHz for ^{13}C .
- These frequencies are all in the radio range.

NMR Absorptions

- The field strength ($B_{\text{effective}}$) felt by the nucleus is always less than the applied field strength (B_{applied}). This occurs because the e^{-} 's (B_{local}) shield the nucleus from the full field strength.
- This gives us $B_{\text{effective}} = B_{\text{applied}} - B_{\text{local}}$.
- The time scale of NMR absorptions (10^{-3} s) is much slower than that of IR (10^{-13} s).
So, NMR can give us information about rates of reactions and activation energies.
For instance, cyclohexane H's bonds in NMR at 25°C will be blurred between axial and equatorial positions due to ring flips, but are resolved into two separate signals at -90°C .

Chemical Shifts

- As a result of e^{-1} shielding, each unique C or H will absorb at a unique applied field strength.
- On an NMR spectrum, the field strength increases from left (downfield) to right (upfield).
- A very shielded nucleus will require higher field strength, and its absorption will be on the right side of the spectrum.
- The position of the absorptions is measured by comparison with that of a reference molecule: $\text{Si}(\text{CH}_3)_4$ (tetramethylsilane or TMS). Its C's and H's are well-shielded due to the low electronegativity of Si, so that they absorb further upfield than those of practically all other organic molecules. The TMS calibration peak can, therefore, be seen on the far right side of the NMR spectra.
- The absorption's position is measured as a chemical shift in δ (delta) units, or ppm, which are found by $\delta = (\text{Hz away from TMS}) / (\text{MHz of TMS})$.
- The chemical shift will be the same regardless of the operating frequency (MHz).
- The chemical shift of TMS will always be calibrated as 0 δ .

^{13}C NMR

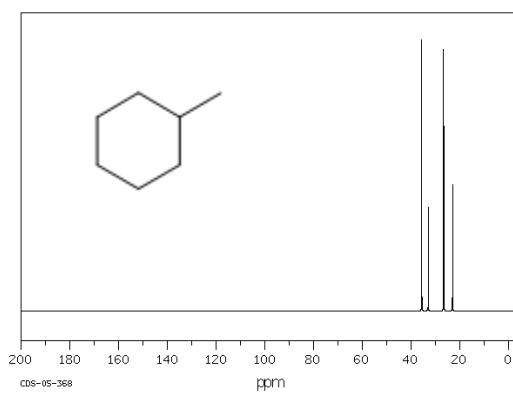
- Although ^{12}C is not observable with NMR, 1.1% of natural carbon is ^{13}C . ^{13}C is observable because it has an odd number of neutrons.
- The relatively low abundance of ^{13}C is overcome by using signal averaging (reduces noise) and Fourier transforms (increases analysis speed).
- Chemical shifts range from 0 - 220 δ units, depending on a nucleus' e^{-1} environment.
- Electronegative elements, such as O, N, and halogens, deshield the C, and will increase its δ (shifted to the left).
- Π bonds will also deshield the C as the Πe^{-1} 's are farther from the nucleus than hybridized orbitals.
- Although chemically different C's will have different absorptions, note that identical C's will share the same absorption.
- The height of the peak lines varies considerably from signal to signal. But the signal size does not provide any information at all about the number of identical C's that share a particular signal.

Specific δ Values for ^{13}C NMR

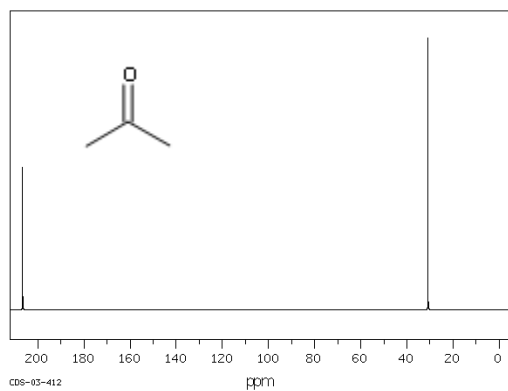
- Alkyl (sp^3) C's are at 0 - 90 δ . (upfield/right)
- Alkenyl (sp^2) C's are at 110 - 150 δ .
- Alkynyl (sp) C's are at 75 - 95 δ .
- Aromatic (sp^2) C's are at 110 - 135 δ .
- Carbonyl ($\text{C}=\text{O}$) C's are very deshielded and are at 160 - 220 δ . (Very downfield/left)



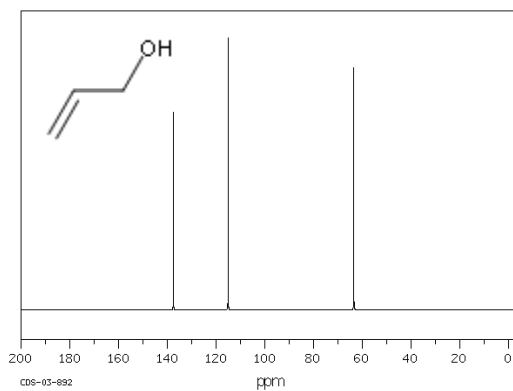
Cyclohexane



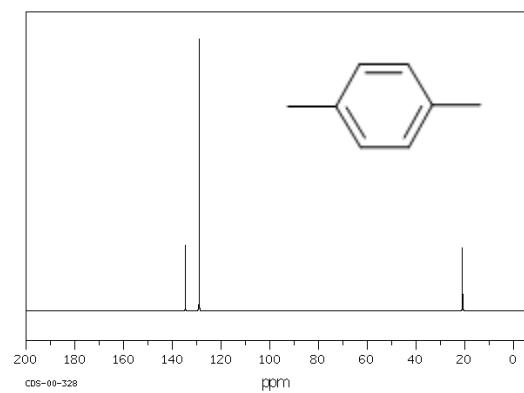
Methylcyclohexane



Acetone (2-propanone)



Allyl Alcohol (prop-1-en-3-ol)



p-Xylene (1,4-dimethylbenzene)

Proton (^1H) Equivalence in NMR

- Each chemically distinct ^1H has its own unique absorption.
- Chemically identical (equivalent) ^1H 's will share the same signal.
- Determine if two protons on the same molecule are equivalent by comparing the two possible structures when one ^1H is replaced w/ another atom (X). Compare the structures in order to determine if they are identical.
- If the ^1H 's are chemically unrelated, the two structures will be constitutional isomers.
- If the ^1H 's are identical, the two structures will also be identical.
- If the ^1H 's are on a prochiral center of a molecule that is *achiral*, then they are enantiotopic, and the two structures will be enantiomers.
- If the ^1H 's are on a prochiral center of a molecule that is *chiral*, then they are diastereotopic, and the two structures will be diastereomers.

^1H NMR Chemical Shifts

- Chemical shifts range from 0 - 12 δ units, depending on a nucleus' e^{-1} environment.
- Electronegative elements, such as O, N, and halogens, deshield the H, and will increase its δ (shifted to the left).
- Π bonds will also deshield the H as its e^{-1} 's can partially occupy empty Π^* (anti-bonding) molecular orbitals.

Specific δ Values for ^1H NMR

- Alkyl H's (on sp^3 C's) are at 0.7 - 1.8 δ , which is upfield (right).
The exact δ depends on whether the H is on a CH_3 (generally 0.7 - 1.3), a CH_2 (generally 1.2 - 1.6), or a CH (generally 1.4 - 1.8).
- Allylic H's ($\text{C}=\text{C}-\text{C}-\text{H}$) are at 1.6 - 2.2 δ , which is slightly downfield due to the adjacent C's Π bond.
- Methyl Ketone H's ($\text{O}=\text{C}-\text{C}-\text{H}$) are at 2.0 - 2.4 δ , somewhat more downfield due to the adjacent C's Π bond with the electronegative O.
- Terminal Alkynyl H's (on sp C's) are at 2.5 - 3.0 δ .
These are less downfield than might be expected because the linear geometry allows the H to be shielded by the C's Πe^{-1} 's.
- Alkyl Halide H's ($\text{X}-\text{C}-\text{H}$) are generally at 2.5 - 4.0 δ , somewhat downfield due to the electronegative halide.
- Hydroxyl / Alcohol H's ($\text{O}-\text{H}$) can vary somewhat in their positions from 2.0 - 5.0 δ .
Sometimes, they do not even show an absorption at all.
- H's on alcohol or ether C's ($\text{O}-\text{C}-\text{H}$) are at 3.3 - 4.5 δ , relatively downfield due to the electronegative O.
- Alkenyl H's (on sp^2 C's) are at 4.5 - 6.5 δ , downfield due to their connection with Π bonded C.

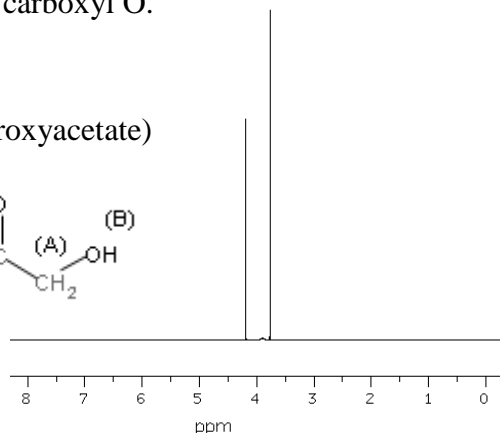
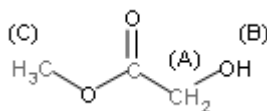
- Aromatic H's are at 6.5 - 8.0 δ , further deshielded by the proximity of multiple Π bonds.
- Aldehydic H's (attached to a Carbonyl C=O) are at 9.5 - 10.0 δ . They are very deshielded/left due to the C's Π bond with the electronegative O.
- Carboxylic Acid H's (COOH) are at 12.5 δ . They are the most deshielded due to the very polarized bond with the carboxyl O. They are farther left than any other H's.

^1H NMR (right) for Methyl Glycolate (methyl hydroxyacetate)

A 4.2 δ rel. area = 1.00

B 3.9 δ (small)

C 3.8 δ rel. area = 1.50

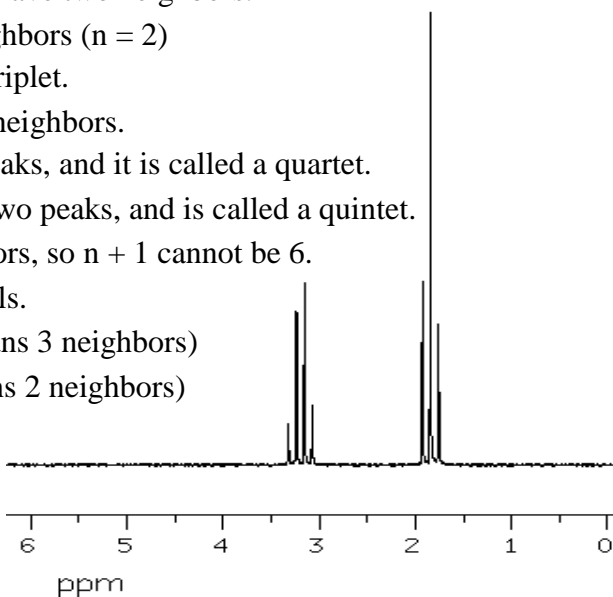


Integration (Proton Counting) for ^1H NMR

- The area under a signal reveals ratios for the numbers of each type of H.
- Sometimes the relative area values are provided with the spectrum.
- And sometimes this area is integrated from left to right and displayed as a line that moves up like a "stair step" as it crosses a signal. The heights of these stair steps can be measured with a ruler to determine the relative area values for each signal.
- The height of the stair steps can be compared with each other to obtain ratios of their numbers of H's.
- For instance, if one stair step is twice the height of another stair step, its signal has twice as many H's as the other signal.
- Because the value is only a ratio of signal sizes, each signal could have multiple H's. For instance, a ratio of 2:1 could be obtained not only from 2 H's and 1 H, but also by 4 and 2, or by 6 and 3 as well.
- How does the ratio of 1.50 : 1.00 for methyl glycolate (above) translate to integers?
- For methyl acetate ($\text{CH}_3\text{COOCH}_3$), we would get a chart of relative area values that reads: rel. area = 1.00 at 3.7 δ and rel. area = 1.00 at 2.0 δ . How does that compare with the actual number of H's for each signal?

Spin-Spin Splitting for ^1H NMR

- A signal for equivalent H's is split by H's on neighboring C's.
- This occurs because these neighbor H's can be aligned either with or against the applied field, so that the effective field can have either of two similar but different values.
- Equivalent H's do not split each other though, whether they are on the same C or not.
- The result of the splitting is that signals are "multiplets" with $n + 1$ peaks, where n is the number of neighbors.
- For instance, if there is one neighbor, then $n + 1 = 2$.
The signal has two peaks, and is called a doublet.
- In an ethyl group, a CH_3 is attached to a CH_2 , which is chemically different from the CH_3 . So the CH_3 protons have two neighbors.
- The signal for the CH_3 protons with two neighbors ($n = 2$) will have $n + 1 = 3$ peaks, which is called a triplet.
- Also, the CH_2 attached to the CH_3 has three neighbors.
In this case, $n + 1 = 4$, the signal has three peaks, and it is called a quartet.
- If $n + 1 = 5$ (four neighbors), the signal has two peaks, and is called a quintet.
- It is impossible to have five identical neighbors, so $n + 1$ cannot be 6.
- Iodoethane (ICH_2CH_3) at right has two signals.
 CH_2 at 3.2δ is a quartet (4 peaks, which means 3 neighbors)
 CH_3 at 1.8δ is a triplet (3 peaks, which means 2 neighbors)



Coupling Constants

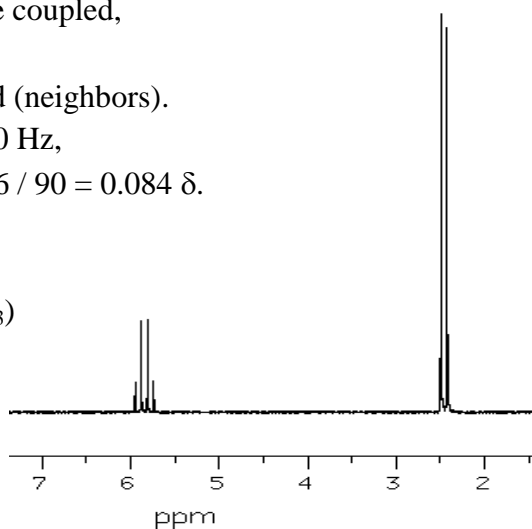
- The distance in δ between peaks of a multiplet is called the coupling constant (J).
- Neighbor protons that split each other are said to be coupled, and both signals have the same J .
- For iodoethane (above), the two signals are coupled (neighbors).
Both have $J = 7.6 \text{ Hz}$. In that spectrum, $1 \text{ ppm} = 90 \text{ Hz}$,
So, the distance between peaks in each signal is $7.6 / 90 = 0.084 \delta$.

^1H NMR (right) for 1,1-dibromoethane (Br_2CHCH_3)

5.8δ (quartet) rel. area = 1.00

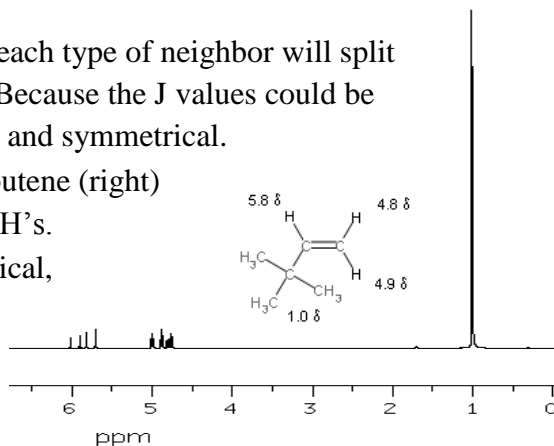
2.5δ (doublet) rel. area = 3.00

$J = 6.4 \text{ Hz}$

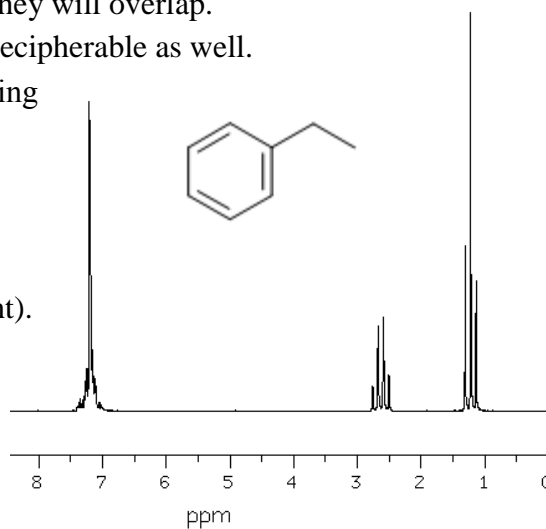


Complex Splitting

- If a set of H's has more than one type of neighbor, each type of neighbor will split the signal separately, and with a different J value. Because the J values could be very different, the splitting will not usually be even and symmetrical.
- For instance, the signal at 5.8 δ in 3,3-dimethyl-1-butene (right) is split differently by each of the other two alkenyl H's. Because those two H's (4.8 and 4.9 δ) are not identical, the signal at 5.8 δ is not a triplet, but two unequal splits that result in a "doublet of doublets".

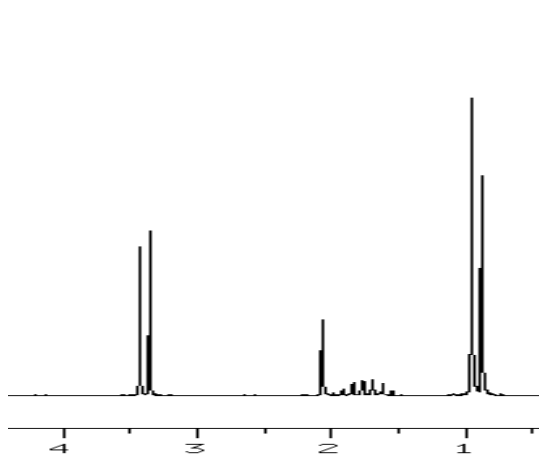
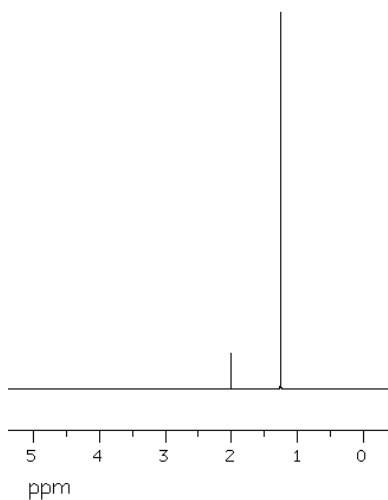


- Another common example occurs with the middle CH₂ in a propyl group (-CH₂CH₂CH₃), which has two neighbors on one side and three on the other. Generally, the J values are different enough that the signal appears complex and undecipherable, rather than like five identical neighbors, which is not truly possible. Occasionally though, the J values are similar enough that the six (n + 1) peaks are observed.
- If more than one signal occupies the same δ range, they will overlap. Overlapped signals usually appear complex and undecipherable as well.
- For instance, all of the H's attached to an aromatic ring will have absorptions between 6.5 and 8.0. They normally split each other, and are often superimposed together.
- We can see this with the complex, overlapping aromatic ¹H signals (at 7 - 8 δ) in ethylbenzene (right). These signals all superimpose together at the base, so that it is practically impossible to determine what their splitting patterns actually are.



Analytical Uses of ^1H NMR

- NMR can often distinguish between potential products of a reaction, so that the method can be used to verify what was obtained.
- For instance, if alkene hydration could yield either a Markovnikov or non-Markovnikov product, the analysis could reveal which molecule was created.
- If $(\text{CH}_3)_2\text{C}=\text{CH}_2$ (2-methyl-1-propene) is hydrated, the product could be either $(\text{CH}_3)_2\text{CHCH}_2\text{OH}$ (2-methyl-1-propanol) or $(\text{CH}_3)_3\text{COH}$ (1,1-dimethylethanol, or t-butyl alcohol). The first alcohol has three types of alkyl protons, in addition to the hydroxyl proton. These protons would display three different signals, each with splitting as well. The second alcohol, however, has only one type of alkyl proton. These nine identical protons would display only one signal, and the signal would be a singlet.
- The spectrum on the left is the product of hydration with $\text{Hg}(\text{OAc})_2$ followed by NaBH_4 . The spectrum on the right is the product of hydration with BH_3/THF followed by H_2O_2 . Which spectrum is from $(\text{CH}_3)_3\text{COH}$ and which is from $(\text{CH}_3)_2\text{CHCH}_2\text{OH}$?



Chemical Shifts (in δ or ppm) for ^1H NMR

Alkane or Alkyl Group (H on an sp^3 C)	CH_3	0.7 - 1.3
	CH_2	1.2 - 1.6
	CH	1.4 - 1.8
Allylic (H-C that is next to alkene $\text{C}=\text{C}$)	$\text{C}=\text{C}-\text{C}-\text{H}$	1.6 - 2.2
Next to Carbonyl ¹	$\text{O}=\text{C}-\text{C}-\text{H}$	2.0 - 2.5
Next to Aromatic Ring ²	Ar-C-H	2.4 - 2.7
Terminal Alkyne	$\text{C}\equiv\text{C}-\text{H}$	2.5 - 3.0
Alkyl Halide (X = Cl, Br, or I)	X-C-H	2.5 - 4.0
Alcohol (on the O) ³	-O-H	2.0 - 5.0
On a C that has an O (alcohol or ether)	O-C-H	3.3 - 4.5
Alkene (same as vinylic)	$\text{C}=\text{C}-\text{H}$	4.5 - 6.5
Aromatic (on a benzene ring) ²	Ar-H	6.5 - 8.0
Aldehyde	$\text{O}=\text{C}-\text{H}$	9.7 - 10.0
Carboxylic Acid ⁴	$\text{O}=\text{C}-\text{O}-\text{H}$	11.0 - 12.0

1. The compound can be either a ketone or an aldehyde.
2. An aromatic ring has 6 members with 3 alternating double bonds.
It is not an alkene, and alkenes are not aromatic.
3. The alcohol oxygen has one H. Usually, its signal is not split and it does not cause other H's signals to split. Also, its position varies considerably, particularly due to solvent effects.
4. The carboxylic acid H is not the same as the H on an alcohol O.

Chemical Shifts (in δ or ppm) for ^{13}C NMR

Alkane or Alkyl Group (sp^3 C)	CH_3	5 - 30
	CH_2	20 - 45
	CH	35 - 60
Alkyl Halide (X = Cl, Br, or I)	C-X	10 - 75
Amine	C-N	45 - 75
C that has an O (alcohol or ether)	C-O	50 - 90
Alkyne	$\text{C}\equiv\text{C}$	75 - 95
Alkene (same as vinylic)	$\text{C}=\text{C}$	105 - 150
Aromatic (on a benzene ring)	Ar	110 - 135
Nitrile	$\text{C}\equiv\text{N}$	115 - 130
Carbonyl	$\text{O}=\text{C}$	160 - 220