

NMR is our third topic. Five NMR Lectures are Planned

- 3a. Background information about H and C NMR (slides 1-32)
- 3b. Qualitative and quantitative H and C chemical shift values and recognizing different types of H and C (slides 33-55)
- 3c. Coupling, splitting, when N+1 rule works and when it does not work, listing of J values (slides 56-70)
- 3d. Predicting H and C NMR, interpreting simple H and C NMR, the DEPT experiment (slides 71-86)
- 3e. Using 2D NMR to solve complex organic structures (slides 87-116)

link to copies of NMR slides: http://www.cpp.edu/~psbeauchamp/pdf_videos/lecture_3_NMR.pdf

Topic 3 - Index of slides on NMR

(link to copies of slides: http://www.cpp.edu/~psbeauchamp/pdf_videos/lecture_3_NMR.pdf)

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What does NMR tell us?

¹H-NMR - Provides information on:

1. The types of protons present (δ_{H} = chemical shift and is given in parts per million, ppm, of the energy to flip a nuclear spin in a magnetic field, the usual range is δ_{H} = 0-12 ppm).
2. The number of such protons (integration counts the relative numbers of hydrogen atoms as a whole number ratio by summing the area under the peaks).
3. How many neighbor protons there are, via interactions (coupling) to adjacent protons.
 - a. splitting patterns = multiplicity = number of peaks (singlet = s, doublet = d, triplet = t, quartet = q,...etc.)
 - b. J values = coupling constants (distance that peaks in a multiplet are separated in frequency units, given in Hz = cycles per second). These provide information about neighboring nuclei (protons and carbons).

^{13}C -NMR - Provides information on:

1. The types of carbon atoms present (δ_{C} = chemical shift is given in parts per million, the usual range = 0-250 ppm). Carbons are more dispersed than protons (have a wider range of chemical shifts, so there is less overlap of peaks).
2. The number of distinct kinds of carbon atoms present equals the number of peaks in a proton decoupled ^{13}C spectra. All carbon peaks appear as singlets when decoupled from the protons.
3. Reveals how many protons are on each carbon.
 - a. DEPT experiment (Distortionless Enhancement by Polarization Transfer) is a series of three ^{13}C experiments with different mixing of proton coupling to display CH , CH_2 or CH_3 's as distinct patterns. Carbons without hydrogen do not show up and are determined by comparison with a normal proton decoupled ^{13}C spectrum. DEPT is hard to understand, but easy to interpret.
 - b. Off resonance experiment reveals coupling between protons and carbons which shows up in the multiplicity of a ^{13}C peak as follows: a singlet (s) = C (quaternary carbon, has zero C), doublet (d) = CH (methine carbon, has one C), triplet (t) = CH_2 methylene carbon, has two C) or quartet (q) = CH_3 (methyl carbon, has three C). This is an older method that is seldom used anymore.

2D Methods of NMR that we will consider

1. COSY: Proton-proton correlation spectroscopy provides proton connectivity patterns using proton spin systems based on coupling between interacting protons (${}^nJ_{\text{HH}}$).
2. HETCOR or HSQC: Indicates what protons are on what carbon atoms via direct one bond coupling between C and H (${}^1J_{\text{CH}}$).
3. HMBC: Indicates what protons are two or three bonds away from a carbon atom (${}^2J_{\text{CH}}$, ${}^3J_{\text{CH}}$). It is especially helpful for connecting spin systems through quaternary carbon centers and heteroatoms.

COSY = correlation spectroscopy (H,H coupling)

HETCOR = heteronuclear correlation spectroscopy (C,H, 1 bond coupling)

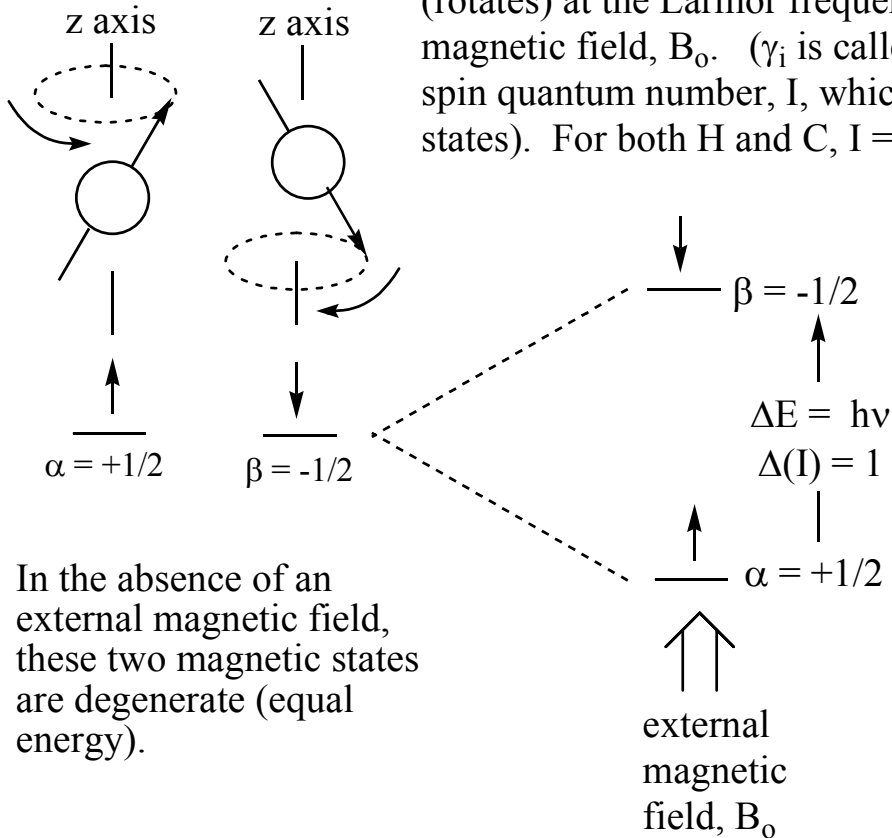
HSQC = heteronuclear single quantum correlation (C,H, 1 bond coupling)

HMBC = heteronuclear multiple bond correlation (C,H, 2 and 3 bond coupling)

When you know how to use all of this information, you can solve most organic structures! It may seem intimidating at first, but this is something you can learn how to do! As you start to understand the process, it actually becomes fun!

What is NMR? (nuclear magnetic resonance)

ν_H NMR spin states



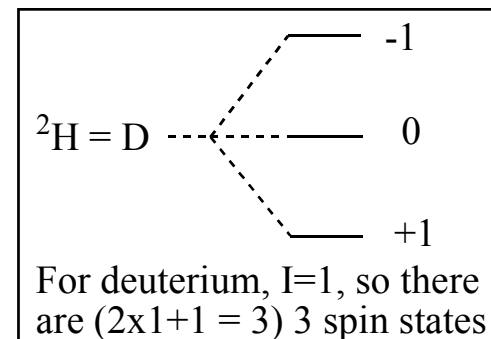
In the absence of an external magnetic field, these two magnetic states are degenerate (equal energy).

^1H , ^{13}C , ^{15}N , ^{19}F and ^{31}P all have 2 spin states so we can use our experience with magnets (north pole and south pole) as an analogy, opposite poles are lower energy (attract) and similar poles are higher energy (repel).

The spinning nuclear particles generate an oscillating magnetic field which precesses (rotates) at the Larmor frequency, ν , dependent on the nucleus, γ_i , and the external magnetic field, B_0 . (γ_i is called the gyromagnetic ratio.) Each type of nucleus has a spin quantum number, I , which predicts the number of quantum states ($= 2I + 1$ spin states). For both H and C, $I = 1/2$, so there are two magnetic quantum states.

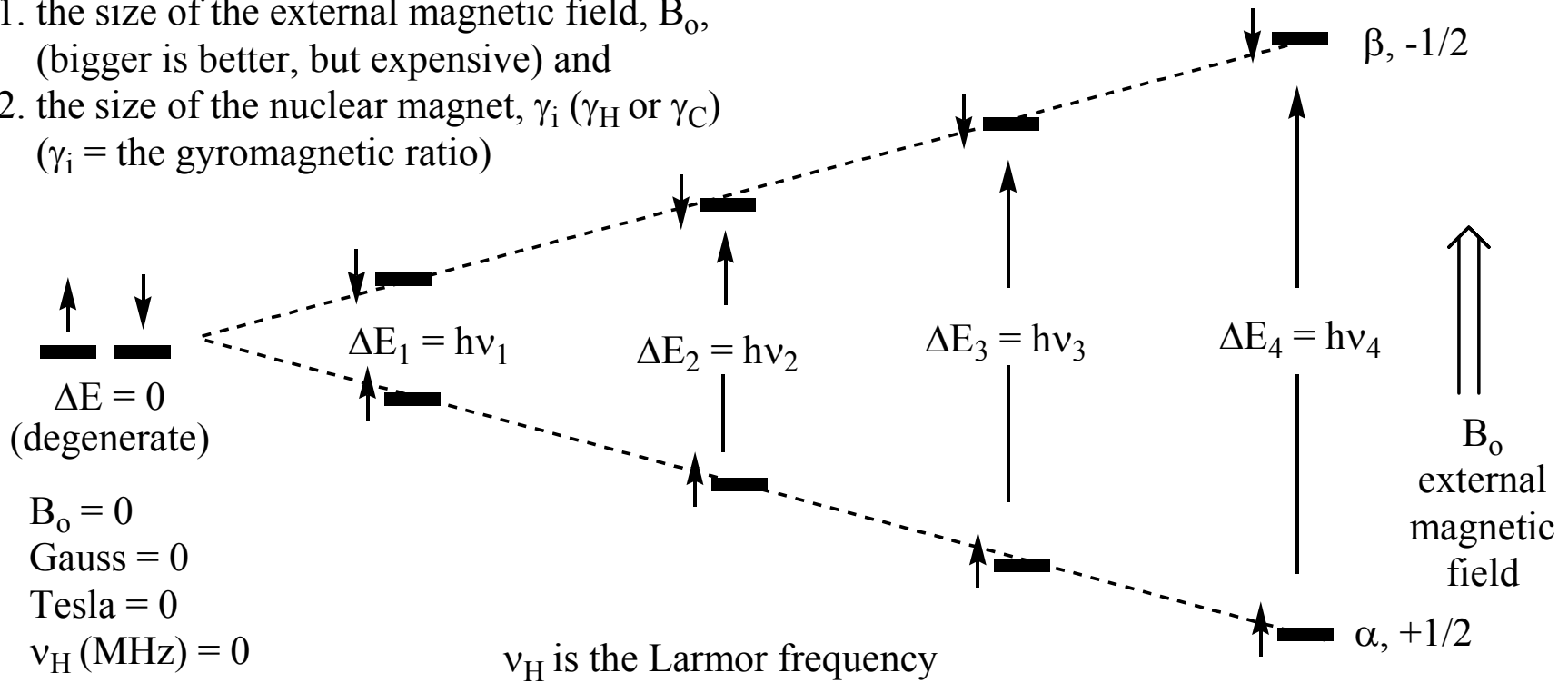
The ΔE between the energy states depends on two magnets:

1. the external field = B_0
(This is what you buy when purchasing the instrument.)
2. the nuclear magnet = γ_i ($i = ^1\text{H}$, ^{13}C ,...),
(This is the nucleus observed when a sample is placed in the instrument.)



The size of ΔE depends on:

1. the size of the external magnetic field, B_o ,
(bigger is better, but expensive) and
2. the size of the nuclear magnet, γ_i (γ_H or γ_C)
(γ_i = the gyromagnetic ratio)



Size of external magnetic field =

Gauss = 14,100
 Tesla = 1.4
 ν_H (MHz) = 60*
 ν_C (MHz) = 15*

Original commercial instrument

* assumes a proton nucleus

Gauss = 23,500
 Tesla = 2.4
 ν_H (MHz) = 100*
 ν_C (MHz) = 25*

Largest solid core electromagnet

Gauss = 70,500
 Tesla = 7.1
 ν_H (MHz) = 300*
 ν_C (MHz) = 75*

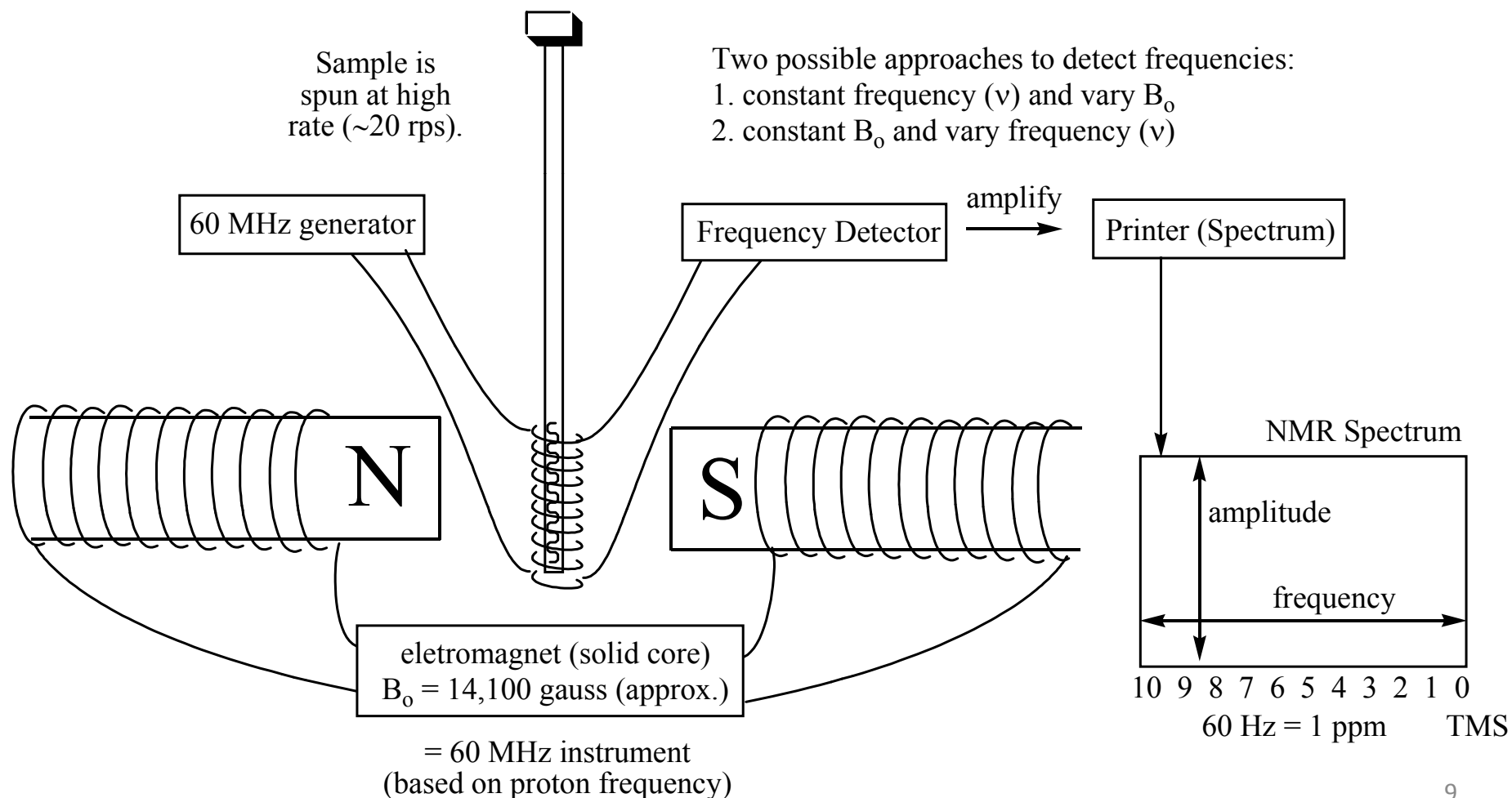
Current routine instruments range from 300-400 MHz

Gauss = 141,500
 Tesla = 14.2
 ν_H (MHz) = 600*
 ν_C (MHz) = 150*

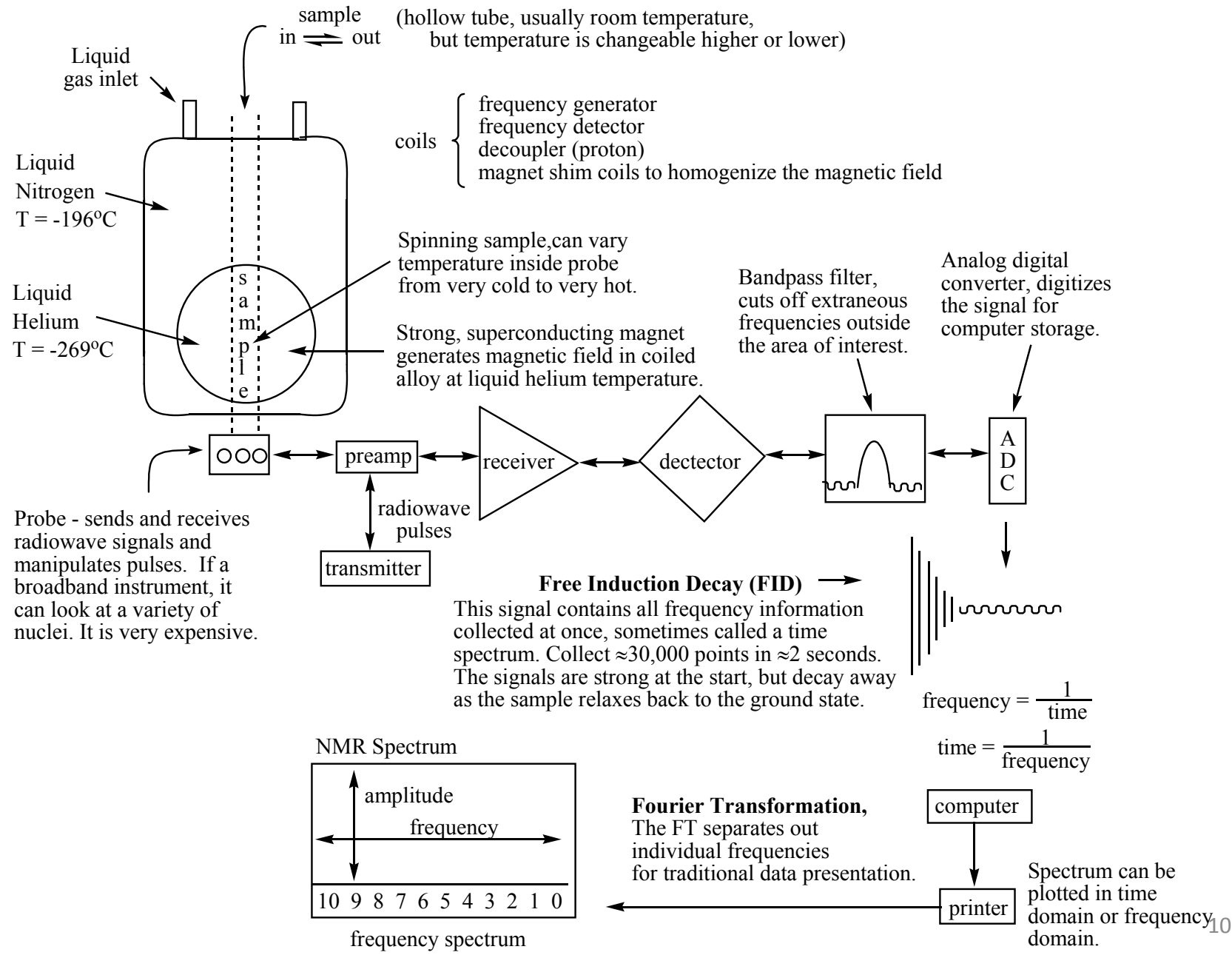
Very large field magnet, very expensive largest $\nu_H \approx 900$ MHz

How do we generate the large external magnetic field?

1. Continuous Wave Instrument - older variations of NMR's, analyzed each frequency point by point using a solid iron core electromagnetic. Typical magnet sizes in the early years of NMR were around 60-100 MHz (ν_H frequency). A 60 MHz instrument might scan 600 Hz at a rate of 1 Hz per second to record an NMR (≈ 10 minutes). There are some 45-60 MHz commercial, table-top magnets sold today, but they use Fourier Transform analysis (FT) instead of continuous wave analysis (CW).



2. Superconducting FT-Instrument - modern variation of NMR, excite all frequencies at once and perform a Fourier transform on the raw time data (FT).



Older Continuous wave NMR.
Notice the large solid core magnet.
Field sizes were smaller, 60-100
MHz. Collecting a spectrum ran
from left to right on a chart and
could take several minutes to run.



Modern FT NMR. Uses a liquid helium
cooled super-conducting magnet having
a very large field, 300-900 MHz. All
frequencies are collected in about 2
seconds and converted to a typical
frequency spectrum using Fourier
Transformation. Many scans can be run
and stored on a computer for better
signal to noise ratio.



Typical Sample Preparation

1-10's mg
of liquid
or solid
sample

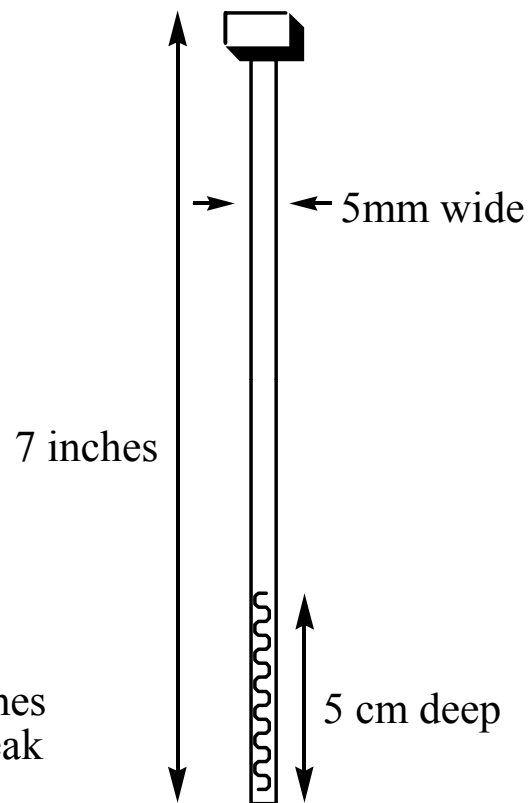
mixed
with

about 700 mg
deuterated
solvent

in 5 mm x 7 inch high precision glass NMR tube

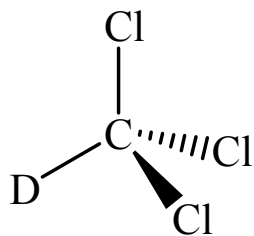


Most NMR solvents are deuterated ($\approx 99.8\%$ of hydrogen atoms are switched with deuterium) because deuterium does not show up in the proton NMR spectrum. Deuterium is like a different radio station in the NMR. However, a tiny percent of the solvent (about 0.2%) is not deuterated and has protons which will show up in the proton NMR spectrum. The solvent signal is sometimes used as a reference peak, if not covered by the sample's signals.



deuteriochloroform, invisible to H NMR, but has observable C (3 peaks because of deuterium, with middle peak at 77.0 ppm, sometimes used as the C reference peak)

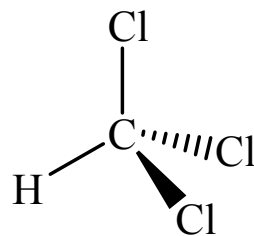
common
NMR
solvent



99.8%

$\delta_C = 77.0$ ppm

chloroform,
has observable H, sometimes
used as the H reference peak



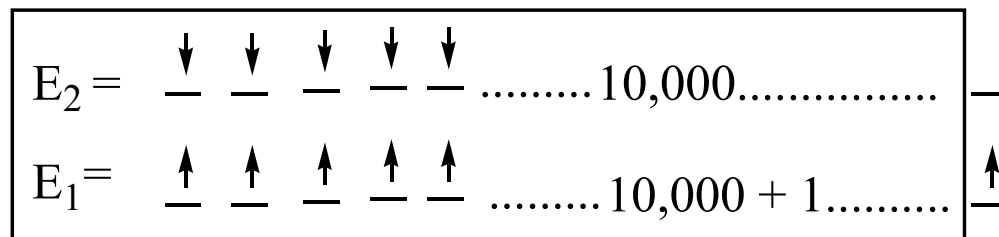
0.2%

$\delta_H = 7.26$ ppm

ν_H NMR energy level populations - almost identical populations, but not quite!

Boltzman distribution = $\frac{N_2}{N_1} = \exp\left(-\frac{\Delta E}{RT}\right) = \exp\left(-\frac{0.028 \text{ cal / mole}}{(1.98 \text{ cal / mol-K})(298 \text{ K})}\right) = \left(\frac{0.99995}{1.00000}\right)$

N_i = number of nuclei in a particular energy state.



ΔE is very small ≈ 0.03 cal / mole

A difference of 1 out of about 20,000 because of ΔE , though the populations levels are still about 50/50.

1 food calorie = 1 kcal = 1,000 cal

The NMR Radio Dial (NMR uses very low energy radiowaves)

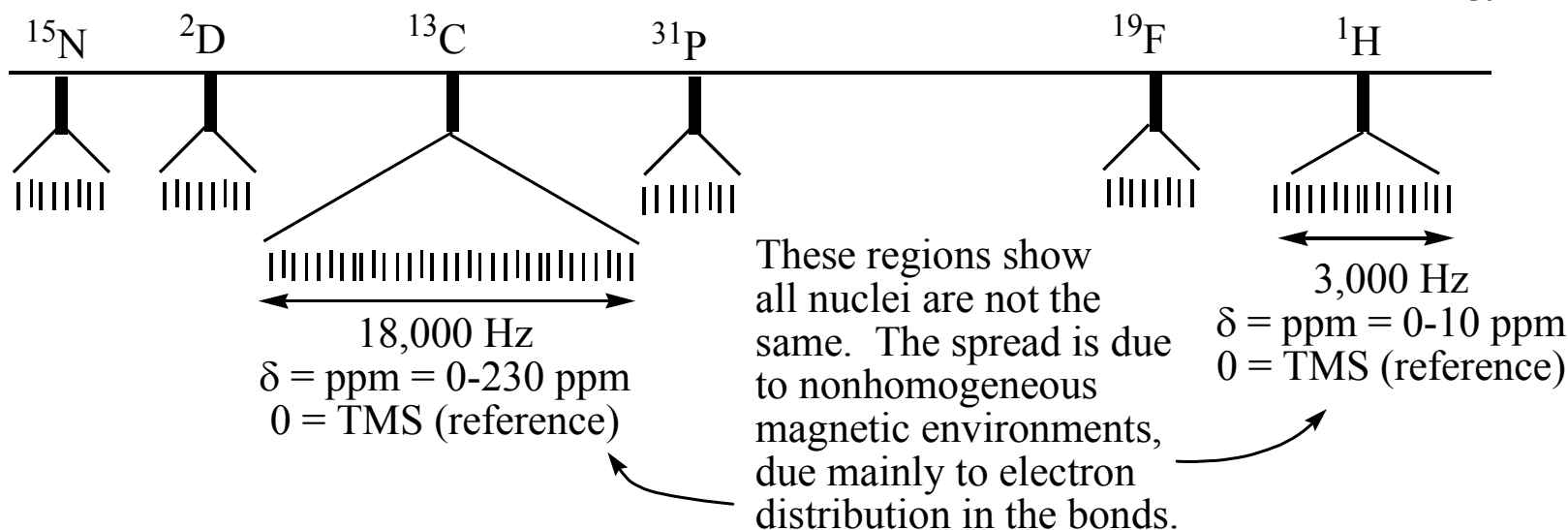
This is what we observe.

$$\Delta E = h\nu = \left(\frac{h}{2\pi}\right) (\gamma_i) (B_o) = (\text{constants}) \times (\text{type of nucleus}) \times (\text{external magnetic field})$$

This is what we buy.

lower energy

higher energy

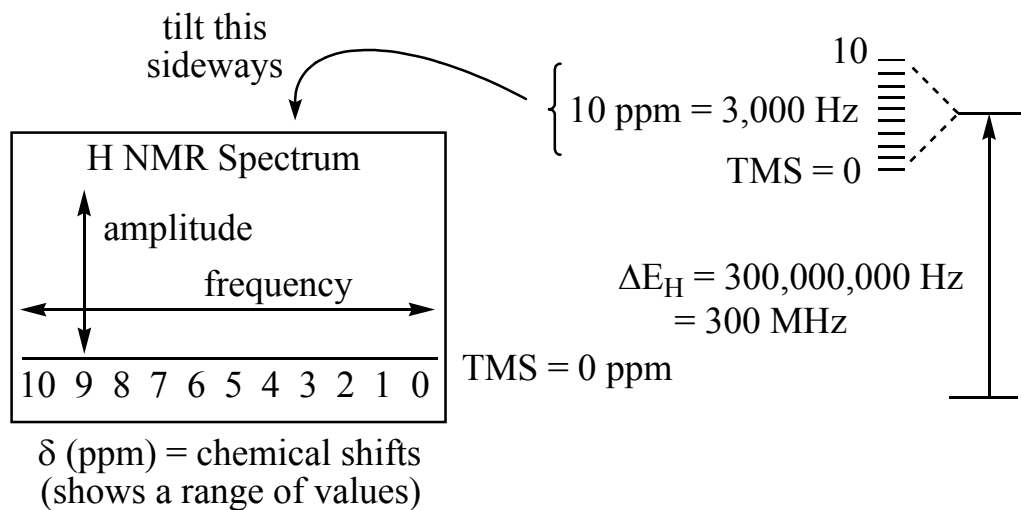


$\gamma_H = 26,751$ radians/(sec-gauss)
$\gamma_{F19} = 25,166$ radians/(sec-gauss)
$\gamma_{P31} = 10,829$ radians/(sec-gauss)
$\gamma_{C13} = 6,726$ radians/(sec-gauss)
$\gamma_D = 4,106$ radians/(sec-gauss)
$\gamma_{N15} = 2,712$ radians/(sec-gauss)

γ_i = magnetogyric ratio (\approx size of the nuclear magnet)

(Think of this as the number on your radio dial.)

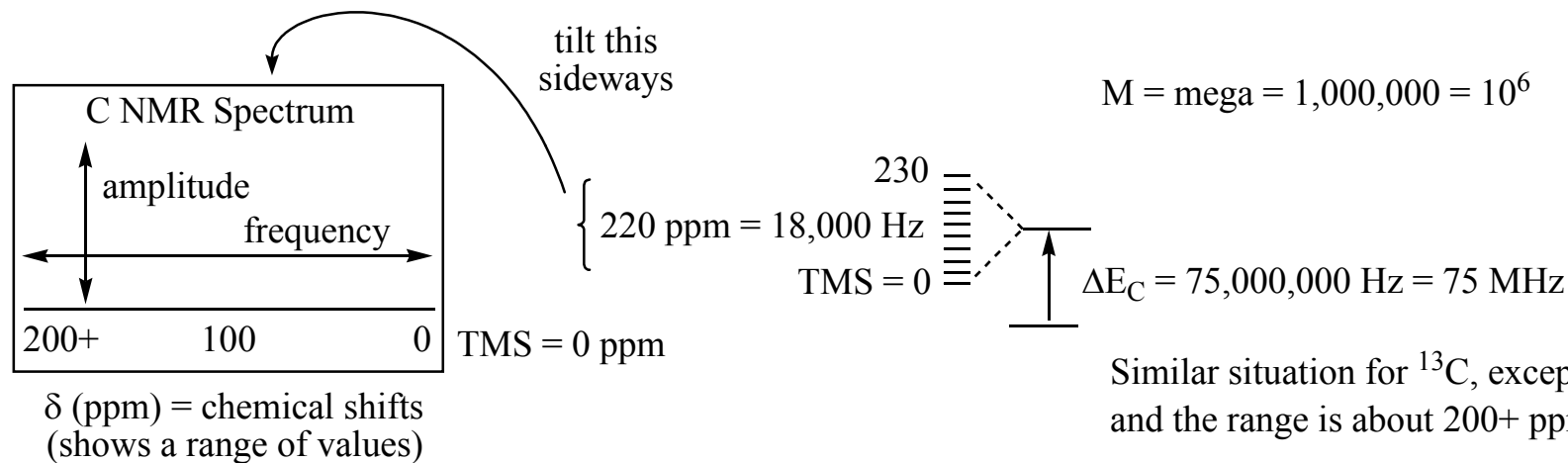
The range of chemical shifts (δ_H , δ_C)



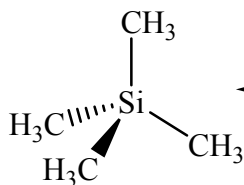
1 ppm in Hz depends on B_0 (size of the external magnetic field: $1/1,000,000$ of ΔE of ν in Hz).
The size of an NMR is specified by ΔE_H in MHz.

B_0	1.0 ppm (= Hz)
60 MHz	60 Hz = 1 ppm
100 MHz	100 Hz = 1 ppm
300 MHz	300 Hz = 1 ppm
600 MHz	600 Hz = 1 ppm

On a 300 MHz instrument the range of differences in chemical shifts is about 3000 Hz. This is only a small portion of the total energy to cause a proton to flip (about 300,000,000 Hz = 300 MHz).

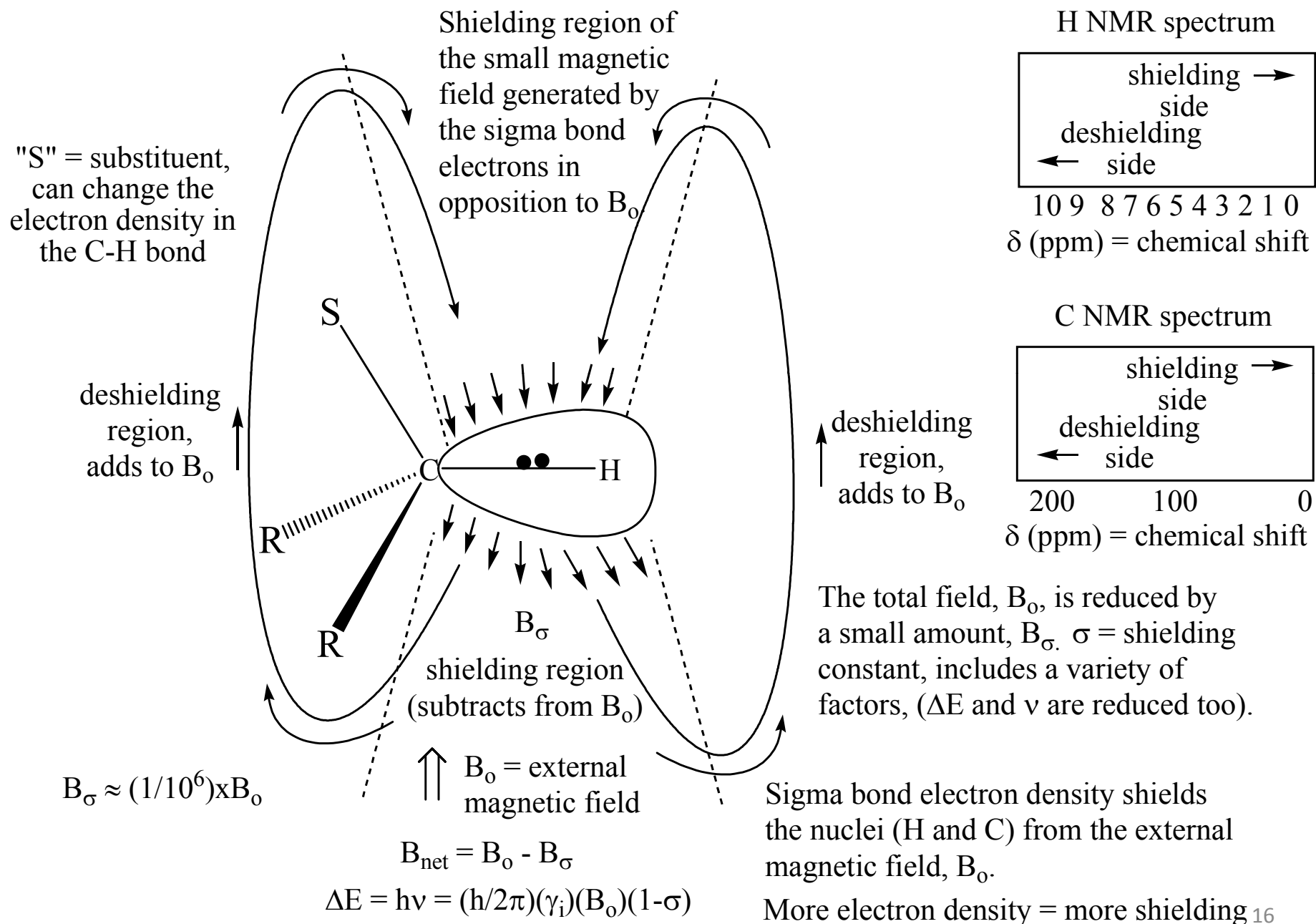


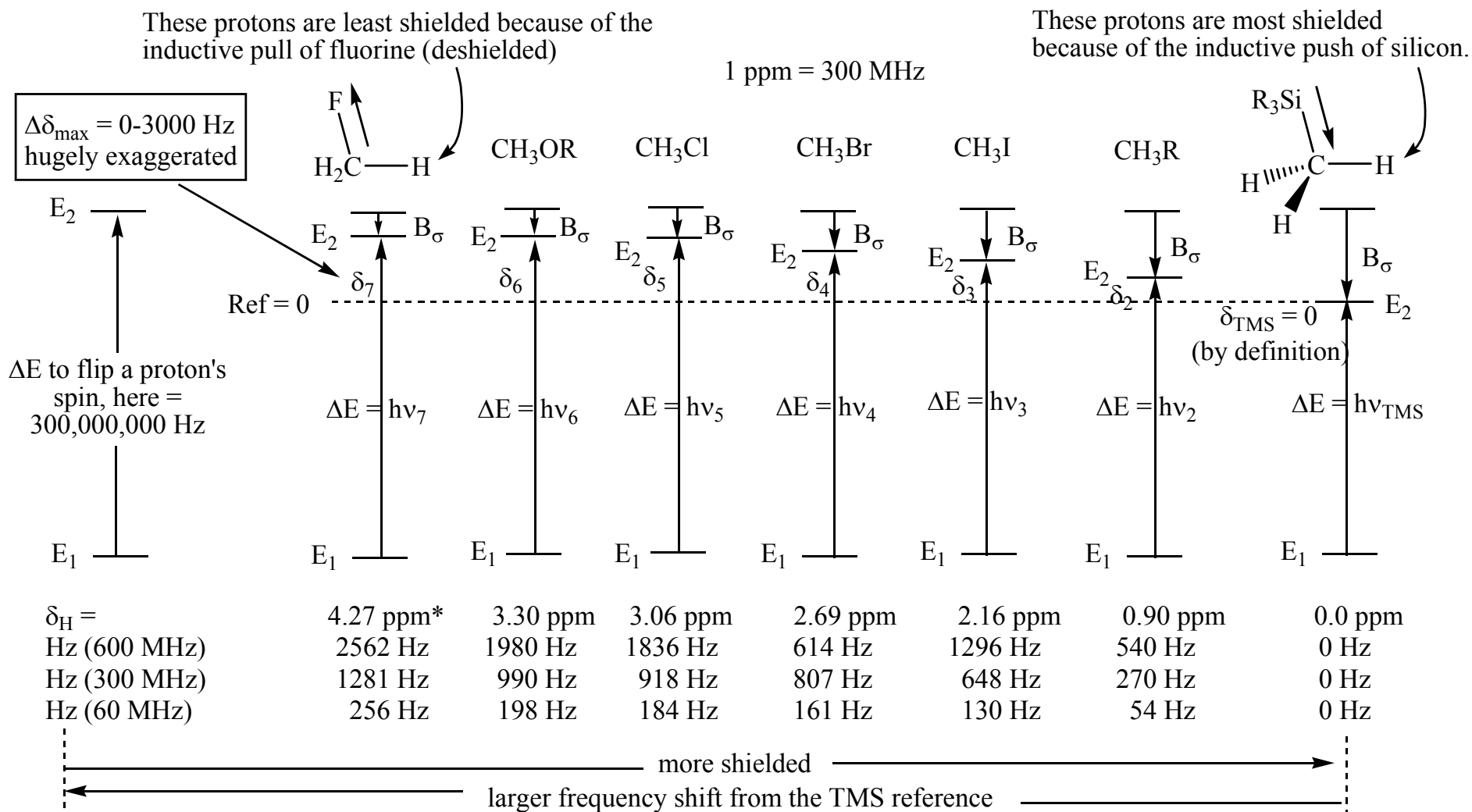
Similar situation for ^{13}C , except $\Delta E = 75 \text{ MHz}$ and the range is about 200+ ppm.



TMS = tetramethylsilane, defines 0 in both H and C NMR,
all the Hs are equivalent and all of the Cs are equivalent.
The boiling point is 28°C , so easily removed.

Differences in δ (chemical shifts) are partly based on differences in electronegativity (inductive effects).

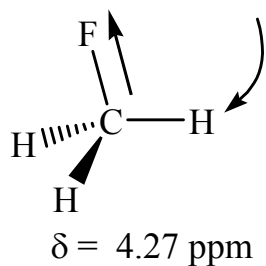




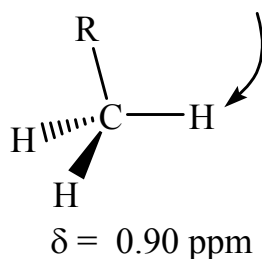
$$*\delta_{\text{H}} = (4.27 \text{ ppm})(300 \text{ Hz/ppm}) = 1281 \text{ Hz}$$

(We could measure your height from sea level, or we could measure your height from the floor.)

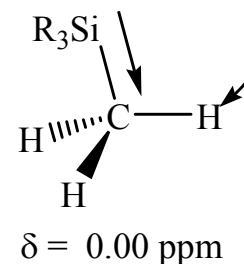
These protons are least shielded because of the inductive pull of fluorine (deshielded)



These are typical methyl protons in a simple alkane.

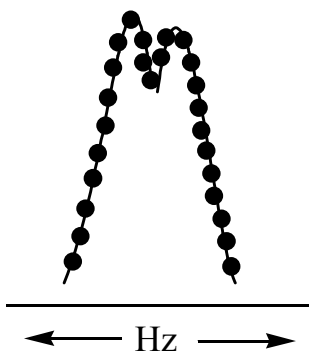


These protons are most shielded because of the inductive push of silicon.

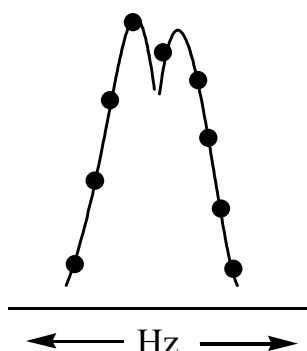


Two important ratios that are important to NMR (resolution and signal to noise)

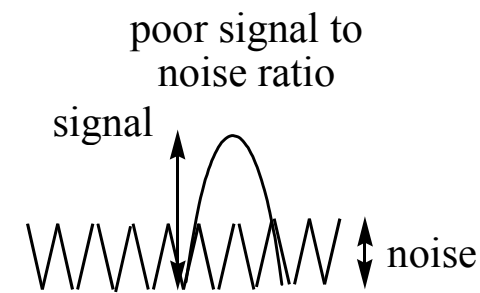
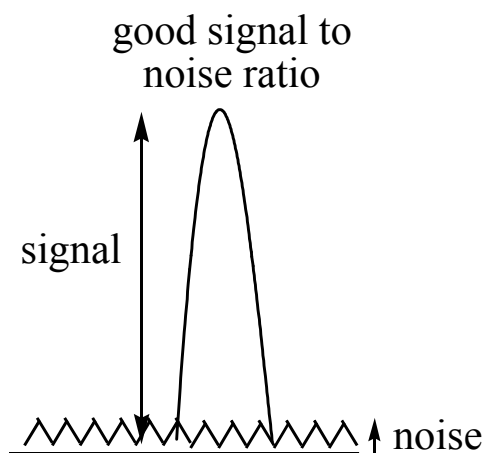
$$\text{resolution} = (\# \text{ points} / \text{Hz})$$



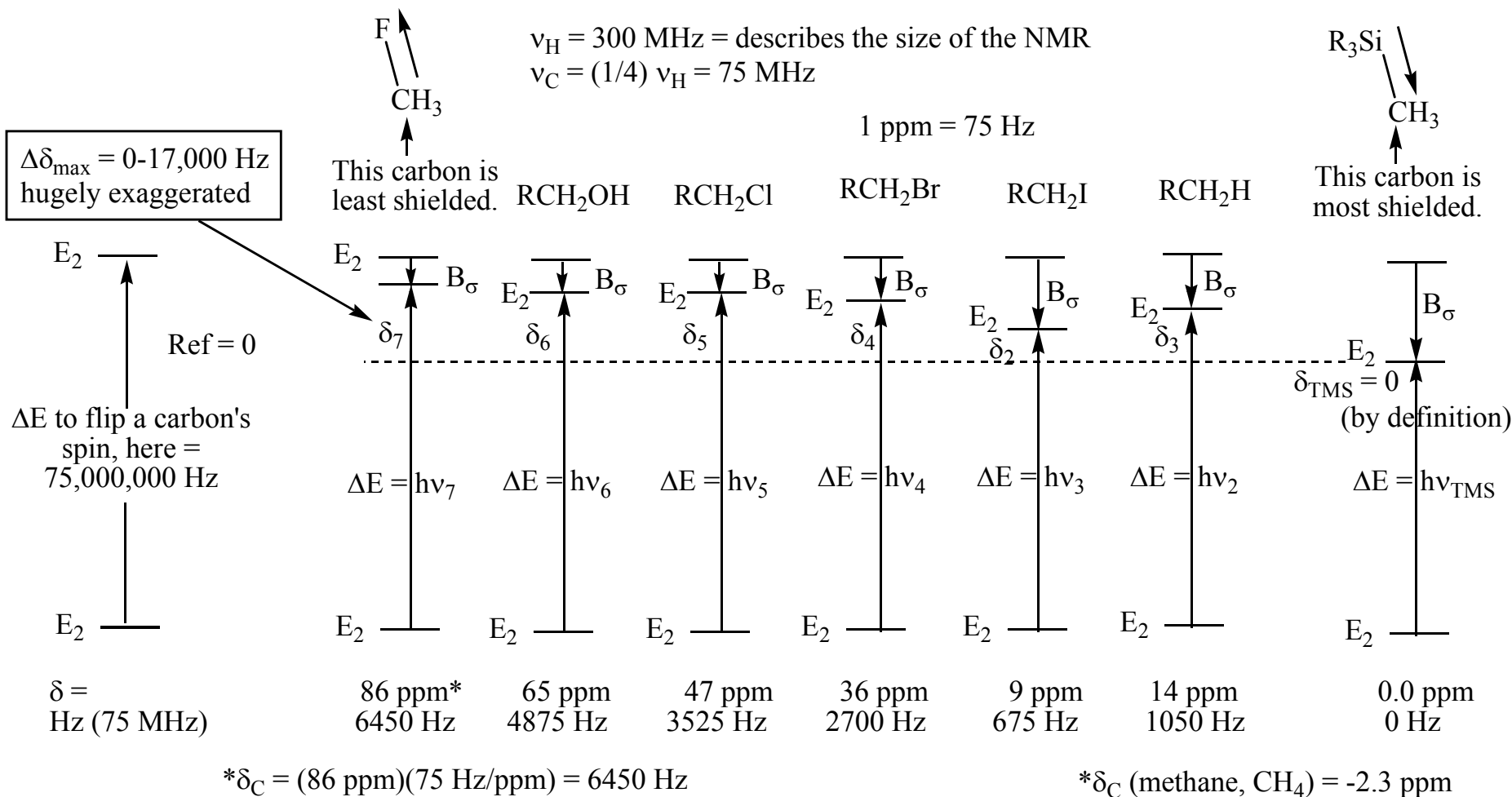
Good resolution because there are plenty of points to see each peak

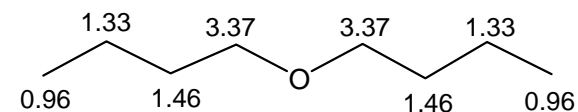
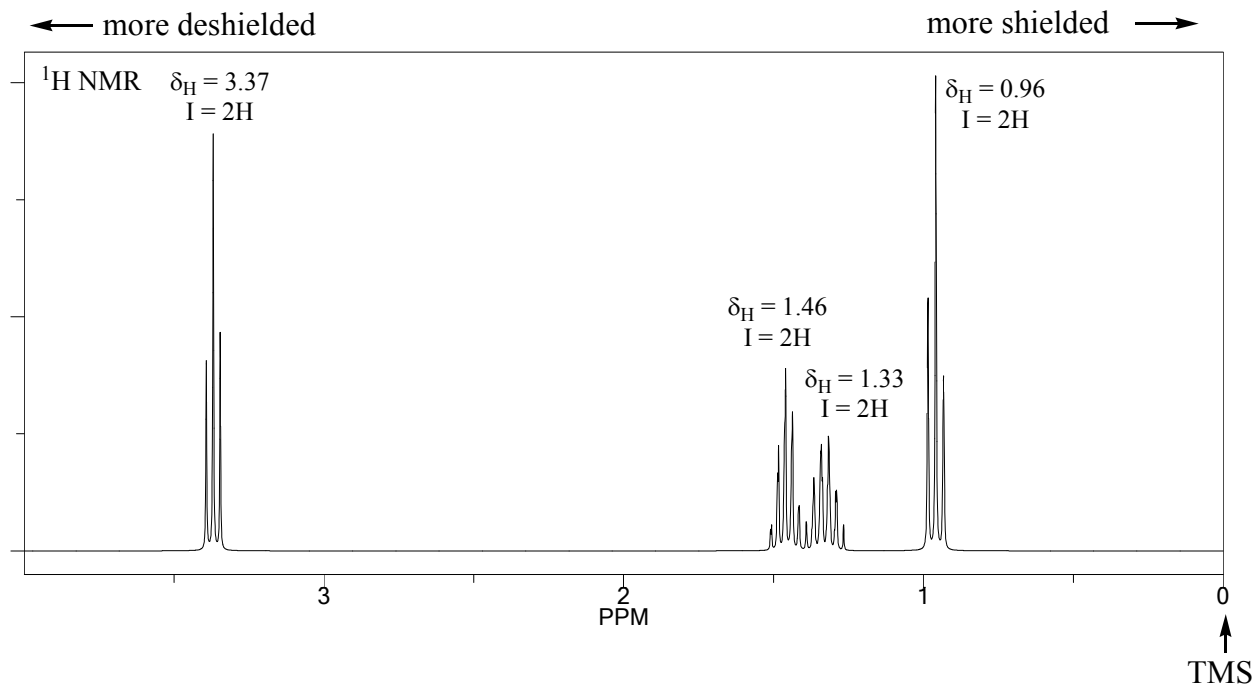


Poor resolution because there are too few points to see each peak

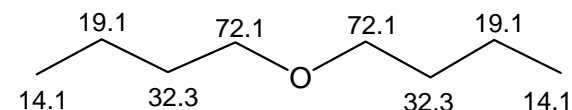
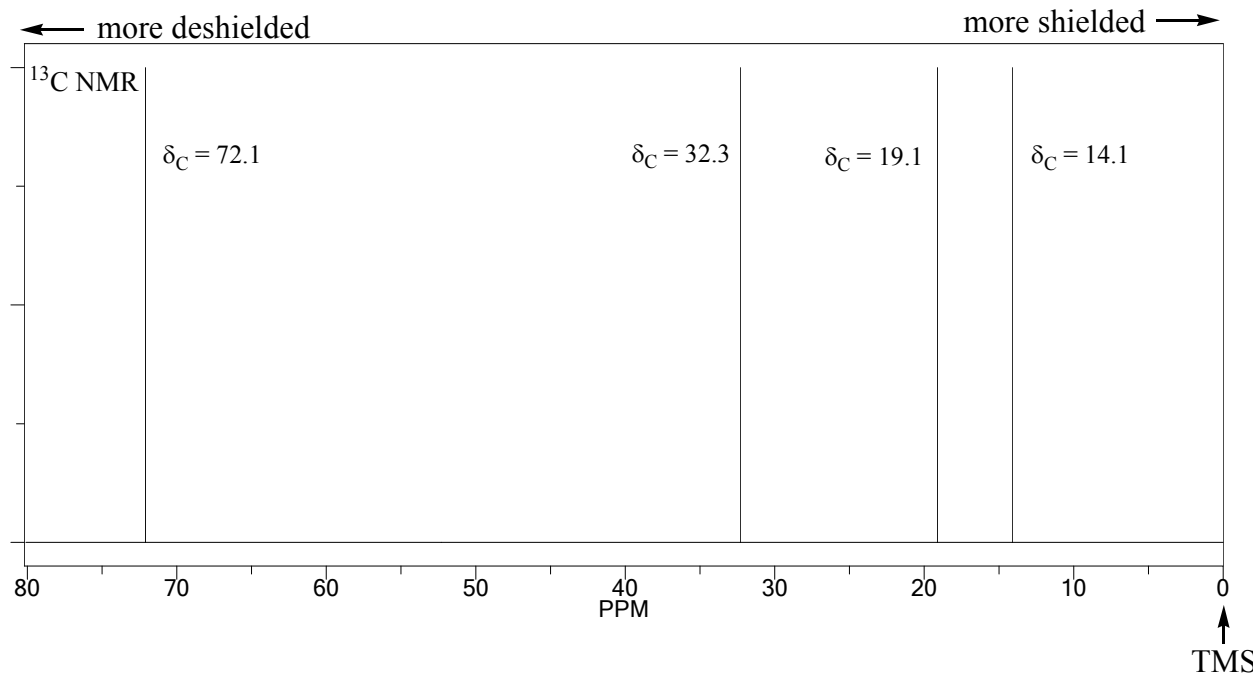


Similar information for ^{13}C shifts on a 300 MHz NMR ($^{13}\text{C} = 75 \text{ MHz}$)



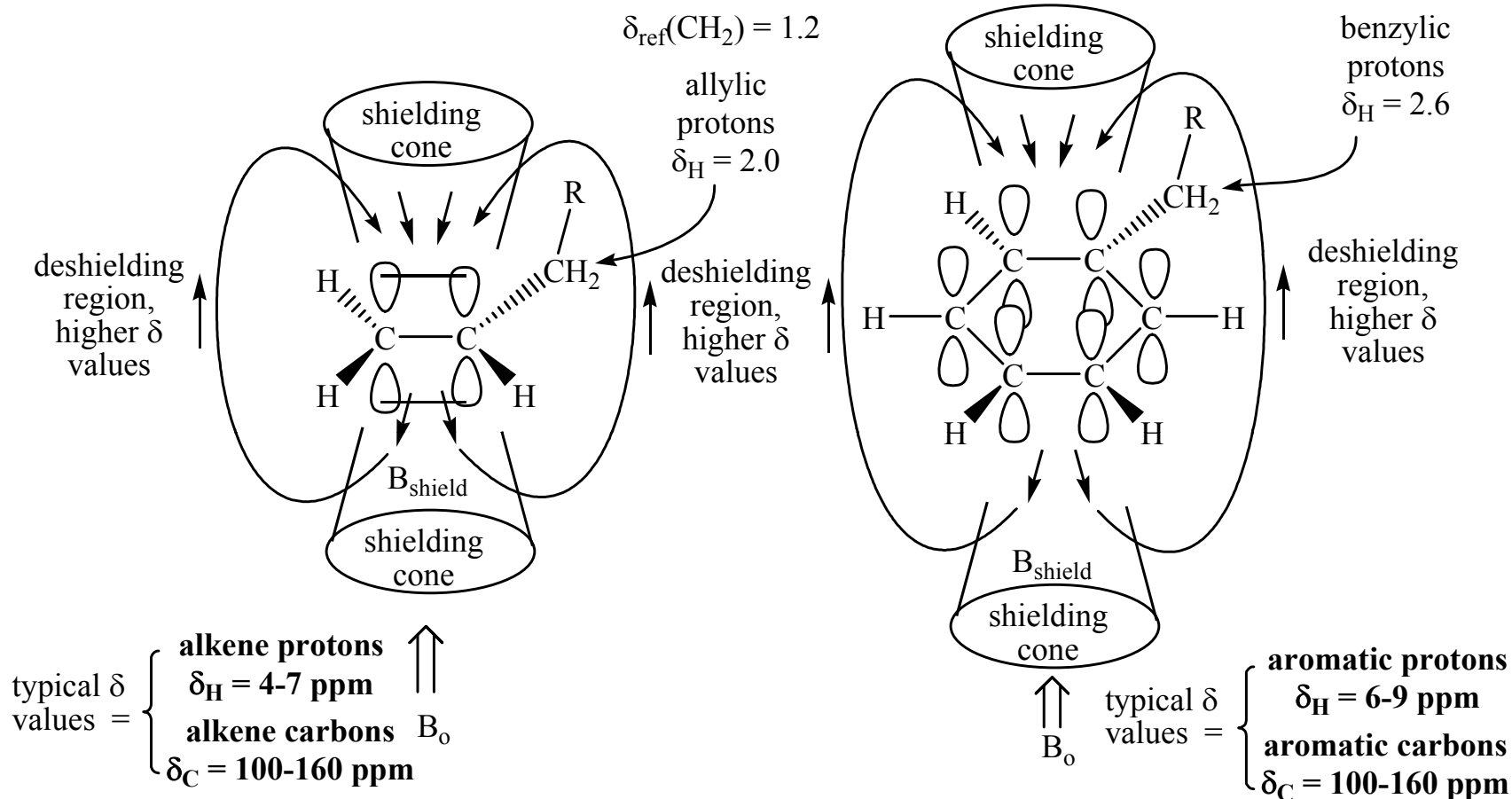


Each type of proton looks more complicated than expected due to interactions (coupling) with the neighbor protons. Coupling will be a later topic and even though it is complicated, it provides the necessary information to solve our structures. (I = integration = area proportional to the number of H.



Each type of carbon appears as a single peak because their attached protons have been decoupled. Decoupled atoms do not "see" each other. This simplifies the appearance of the spectrum but we lose valuable coupling information which tells how many protons are on each carbon. This will also be a later topic where we learn how we can get this information back.

Pi bond anisotropy: certain orientations of the molecule (relative to B_0) add to the external magnetic field and others cancel with a net contribution of what is shown below in the following figures.



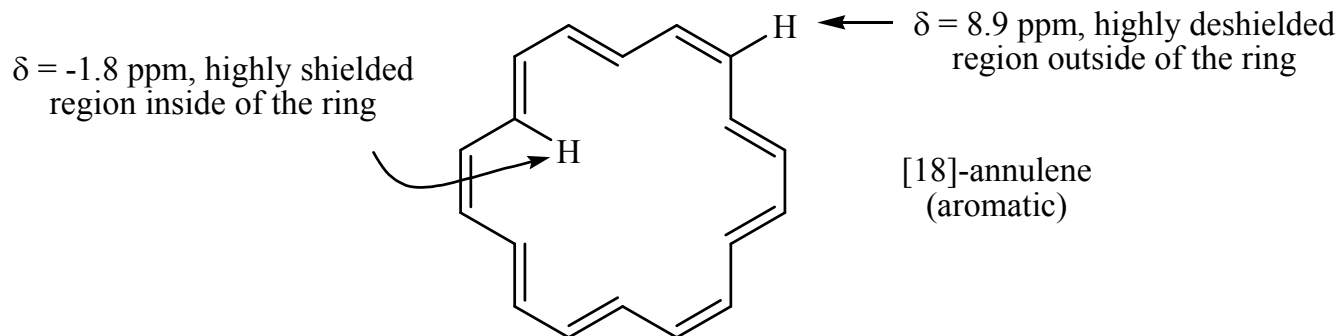
Protons to the side of an alkene pi bond are deshielded and shifted to a larger chemical shift = δ . Allylic protons are shifted in a similar direction but by a smaller amount because they are farther away from the pi bond.

Ring current in aromatics has a larger effect than a single pi bond in a typical alkene. Aromatic protons usually have a larger chemical shift than alkene protons. Benzylic protons are shifted in a similar direction but by a smaller amount because they are farther away from the pi bonds.

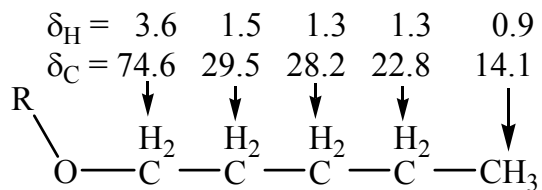
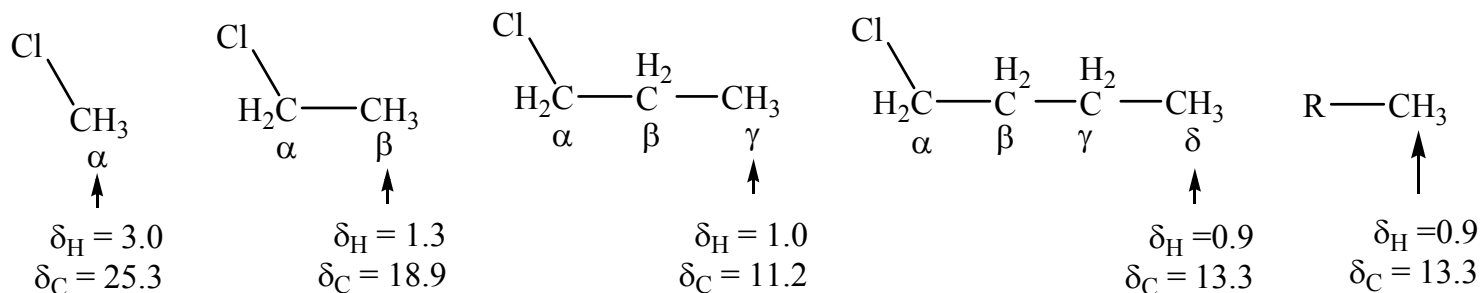
B_{pi} = induced magnetic field due to pi bond electrons

a. B_{shield} opposes B_0 in shielding cone; B_0 is effectively made smaller and a smaller δ is the result

b. $B_{\text{deshielded}}$ adds to B_0 in the deshielding region; B_0 is effectively made larger and a larger δ is the result. 21



Electronegative substituent and distance from protons

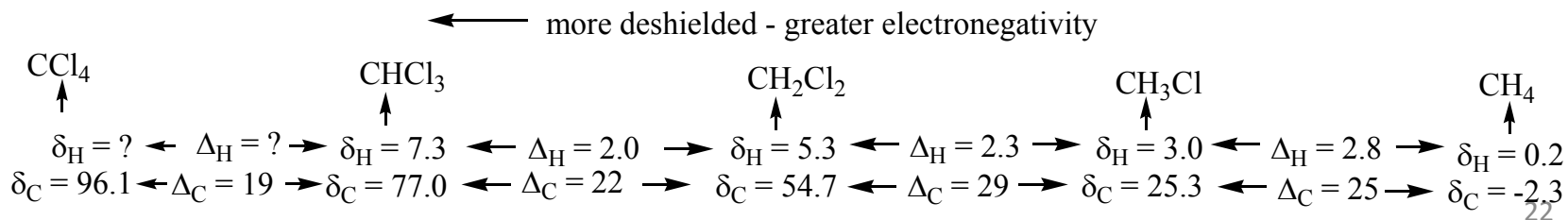


falls off with distance

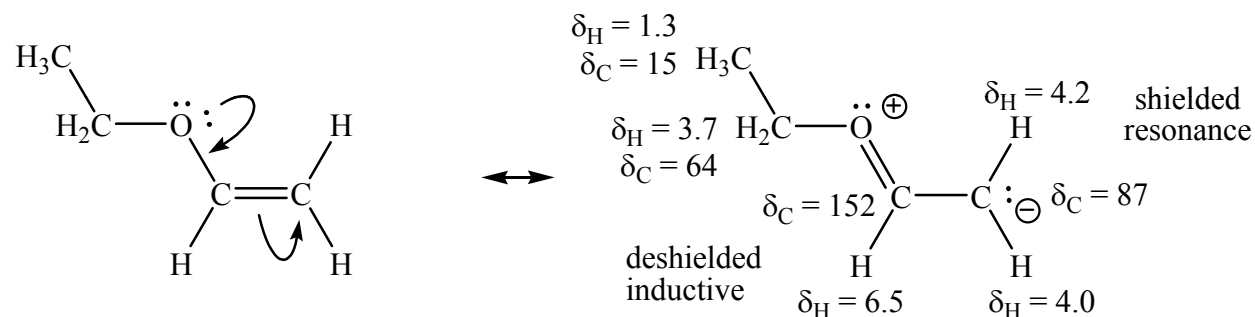
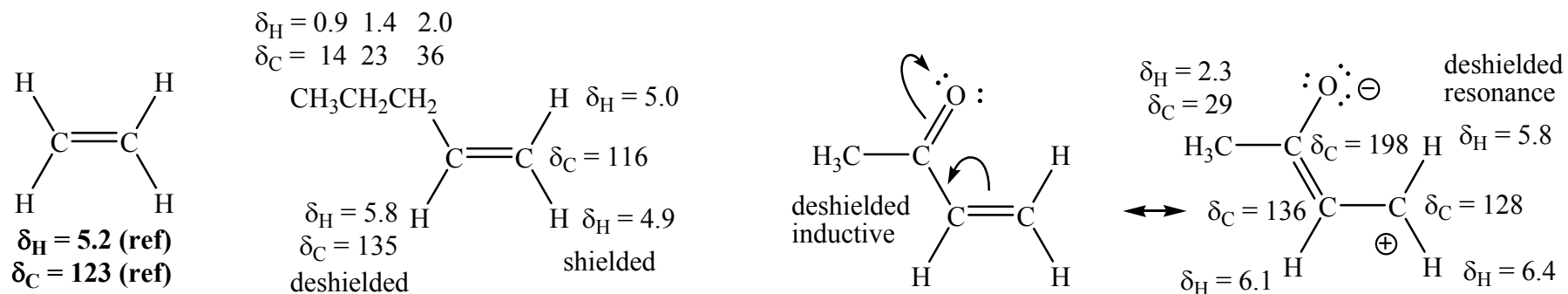
δ_{H} reference values	
CH ₃	0.9 ppm
CH ₂	1.2 ppm
CH	1.5 ppm

← deshielded - electronegativity

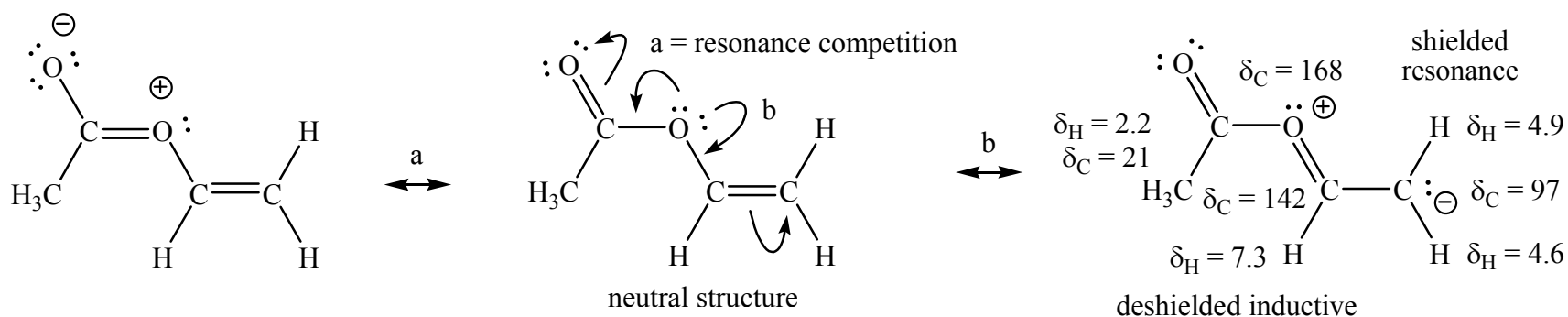
Multiple substituents (often each additional substituent has a smaller effect)



Alkene substituents - pi bond anisotropy, resonance and inductive effects

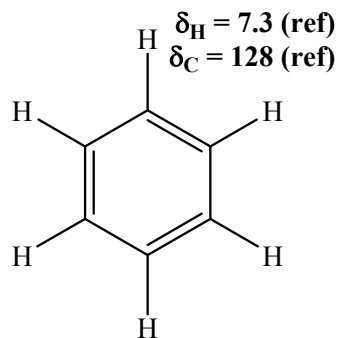


Look at the range of possible values, from 7+ ppm to 4 ppm !



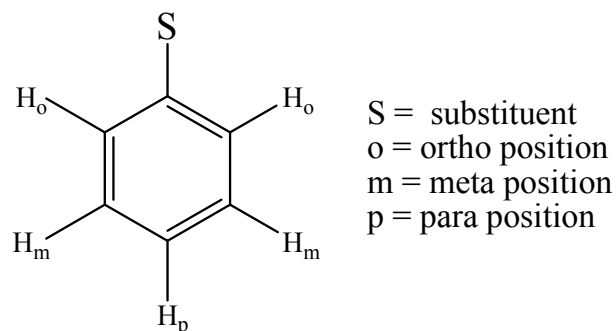
Resonance effects are helpful at providing insight into chemical shift changes (if you know how to draw them). Inductive effects overlay the resonance effects and are more intuitive (push or pull electron density).

Aromatics - pi bond anisotropy, resonance and inductive effects

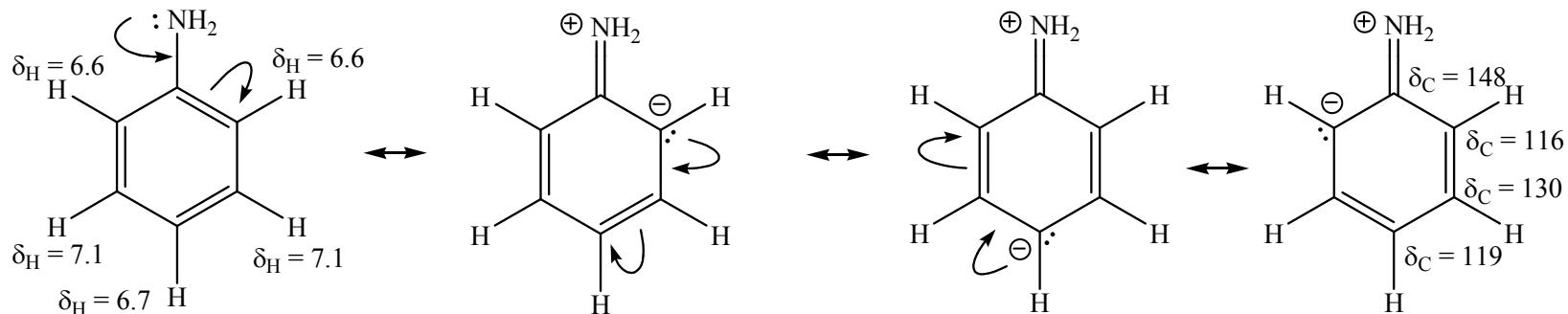


Pi bond anisotropy produces deshielding effect on aromatic protons.

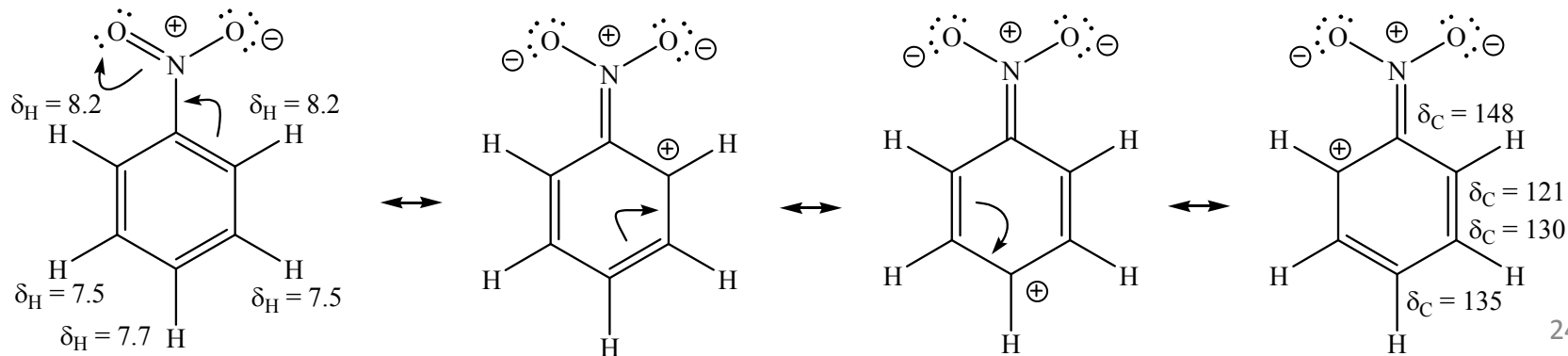
Look at the range of possible values, from 8+ ppm to 6.6 ppm !



Extra electron density pushed into ring via resonance donation produces shielding effect on aromatic protons, especially at the ortho and para positions



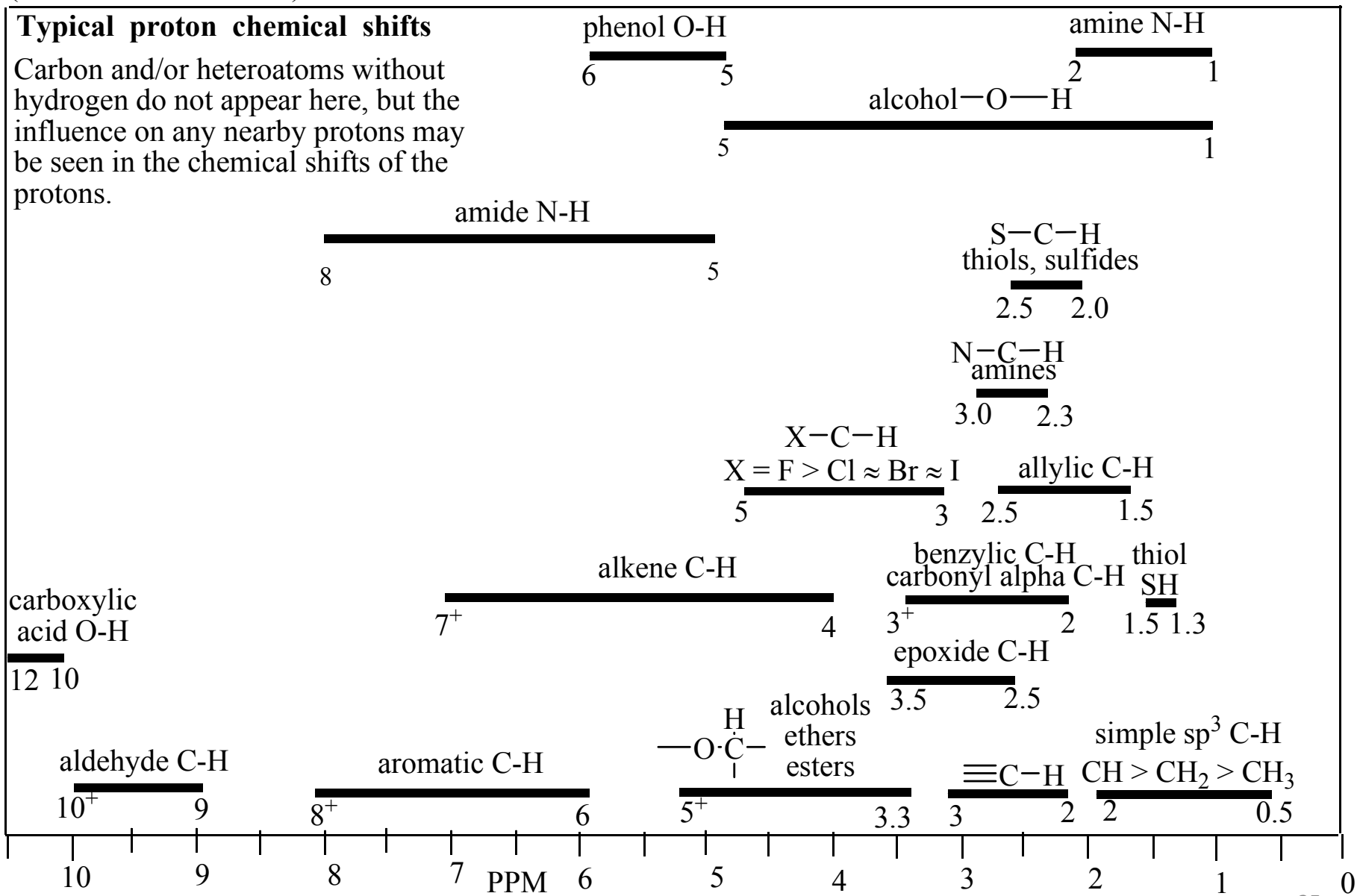
Withdrawal of electron density from ring via resonance and a large inductive effect produces deshielding effect on aromatic protons, especially at the ortho and para positions



deshielding side
less electron rich
(inductive & resonance)

Typical ^1H NMR chemical shift values

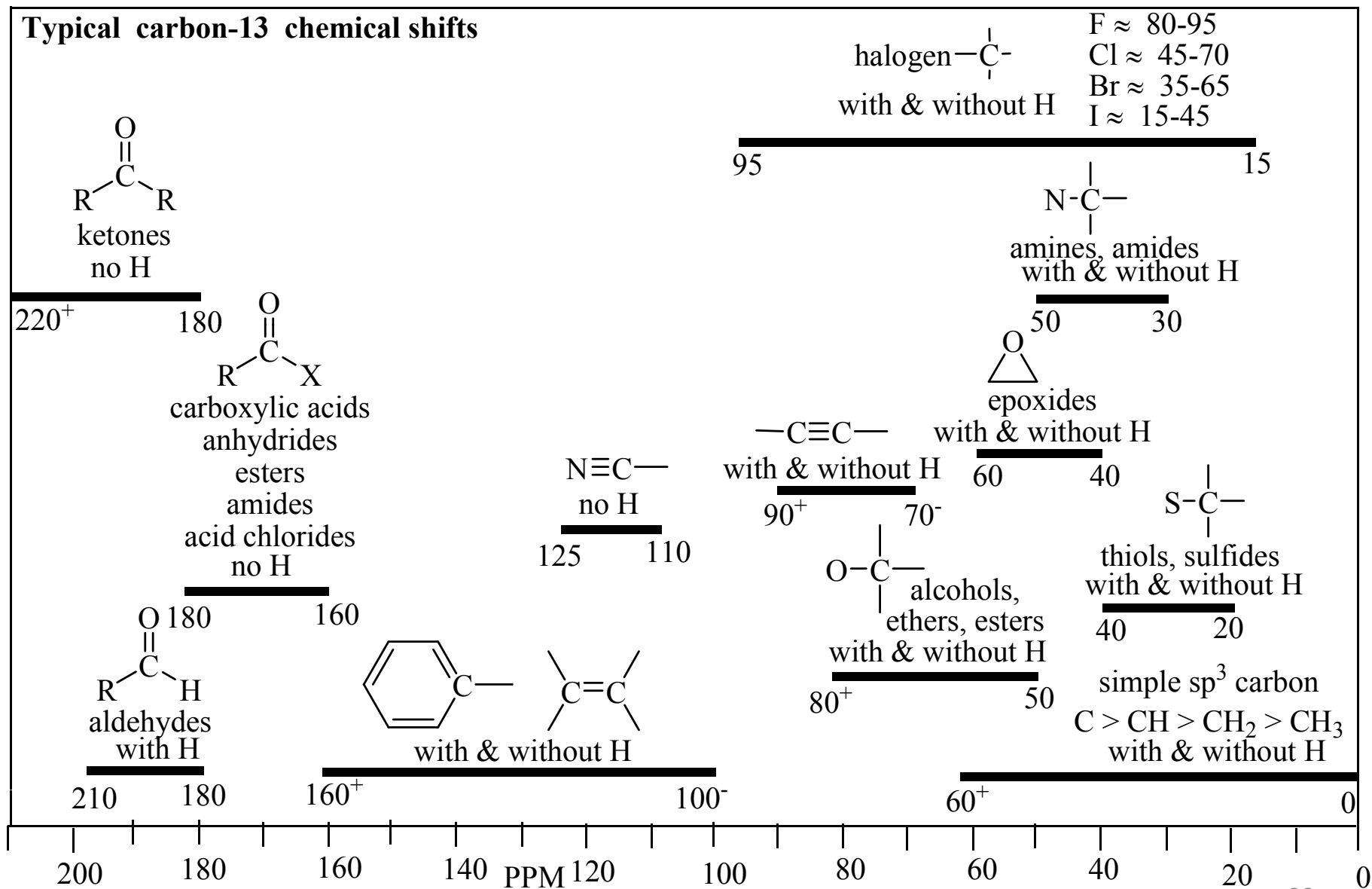
shielding side
more electron rich
(inductive & resonance)



deshielding side
less electron rich
(inductive & resonance)

Typical ^{13}C NMR chemical shift values

shielding side
more electron rich
(inductive & resonance)



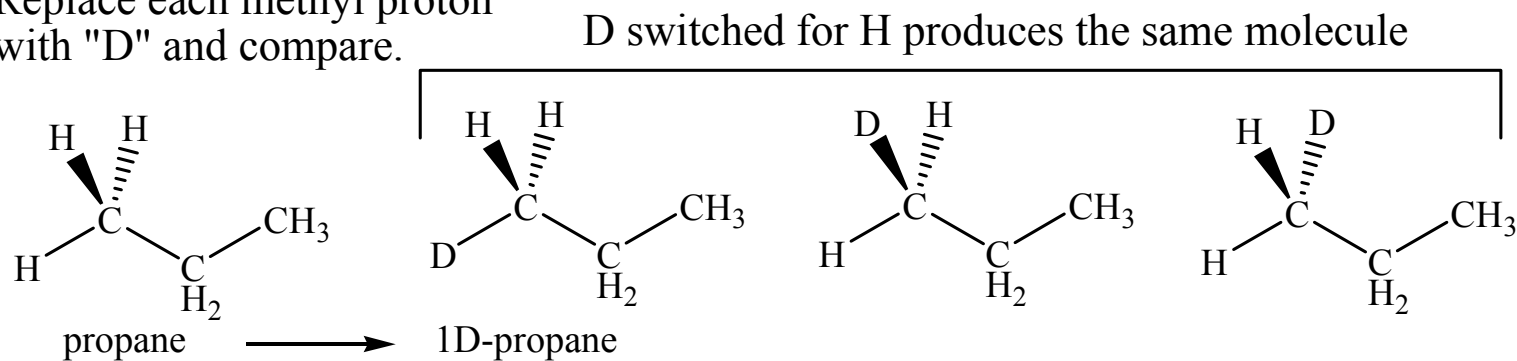
Recognizing different types of protons and carbons (necessary vocabulary)

Replace each proton being compared with "D", as a different group, and evaluate the new structures obtained with D at each position according to the following guidelines. When comparing C, replace all of the attached "H" for attached "D" and compare.

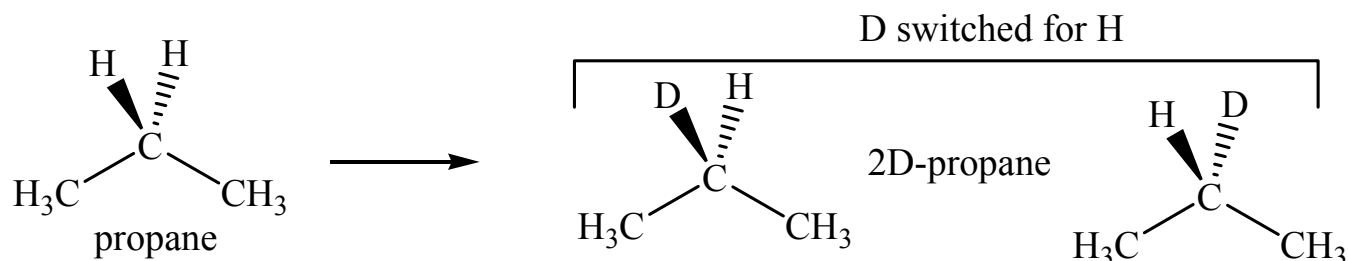
Classification of Protons (and Carbons) by Group Topology

1. □ homotopic groups - Do the switches produce the same end result? If so, the protons are homotopic protons and have the same chemical shift and do not split one another. This generally produces straight forward splitting patterns based on the simple N+1 rule (explained later).

Replace each methyl proton with "D" and compare.

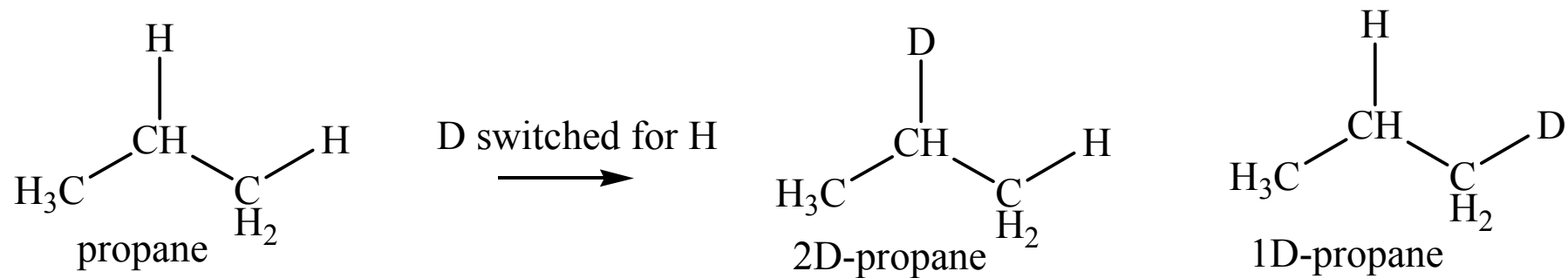


Replace each methylene proton with "D" and compare. In propane this produces the same molecule.



2. □ heterotopic groups - When substitution of each atom produces structural or positional isomers, the atoms are heterotopic. Such groups do not generally have the same chemical shifts, but may coincidentally have the same chemical shifts (accidental equivalence).

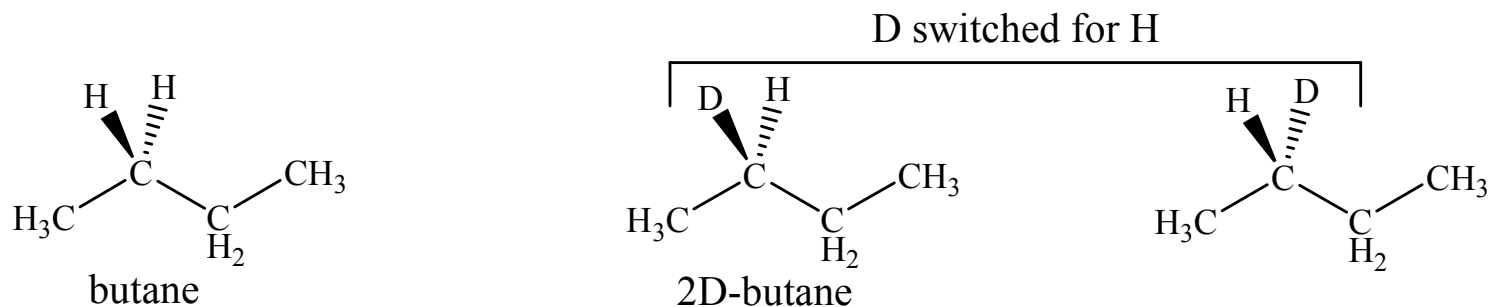
Replace methylene proton with "D" and compare to replacing methyl proton with "D".



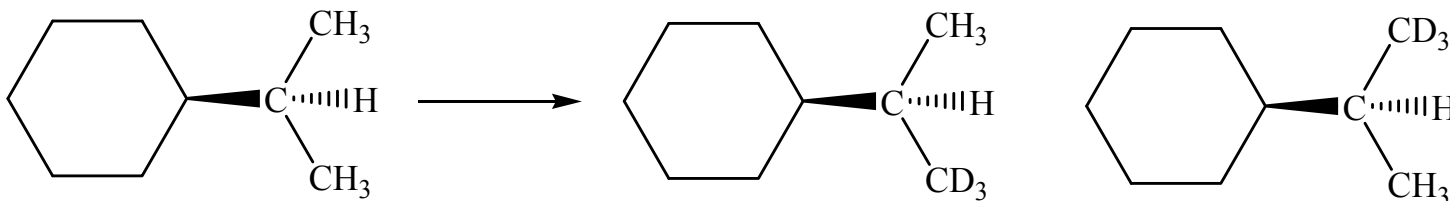
These two molecules are isomers, but the methylene hydrogen is completely different from the methyl hydrogen. Those protons (and carbons) are heterotopic and will very likely have different chemical shifts and split one another when neighbors.

3. **enantiotopic groups** - Do the switches produce different molecules, as enantiomers (different mirror images)? If so, the protons are enantiotopic protons. In the absence of a chiral environment these protons still have identical chemical shifts and will not split one another. However in the presence of a chiral environment (an adjacent chiral center or another molecule that is chiral such as a reagent or a solvent molecule), they will become nonequivalent (diastereotopic) and may or may not have different chemical shifts (they could coincidentally have the same chemical shift, but probably not). If their chemical shifts are different, they may split one another (couple) and make the spectrum appear more complicated.

The methyl protons are all homotopic, as in propane, and simple to consider. Next, replace each methylene proton with "D" and compare. These two molecules are enantiomers and, in this example the methylene hydrogen atoms are enantiotopic. In the absence of any chiral environment they would not split one another because they have the same chemical shift. In the presence of any other chiral center they would become diastereotopic and could split one another and split their neighboring hydrogen atoms differently. However in this example that is not the case.



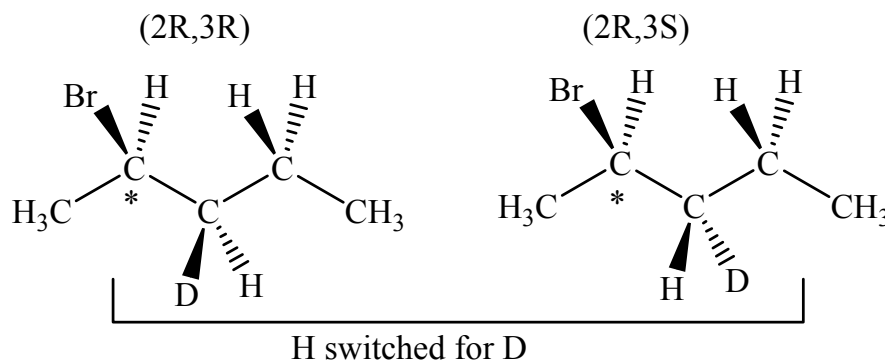
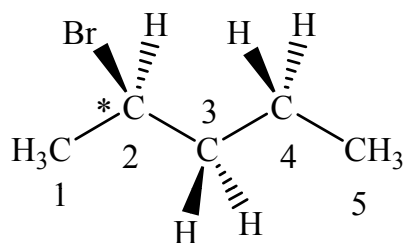
In a similar way the two methyl groups in isopropylcyclohexane are also enantiotopic (both the methyl protons and the methyl carbons).



4. □ diastereotopic groups - Do the switches produce different molecules, as diastereomers? If so, the protons are diastereotopic protons, and will be different and quite likely have different chemical shifts. This would cause them to split one another and to possibly split neighboring protons differently, leading to a more complicated spectrum than expected. Of course, there is always the possibility that there exist coincidental (or accidental) equivalence, and then they would not split one another.

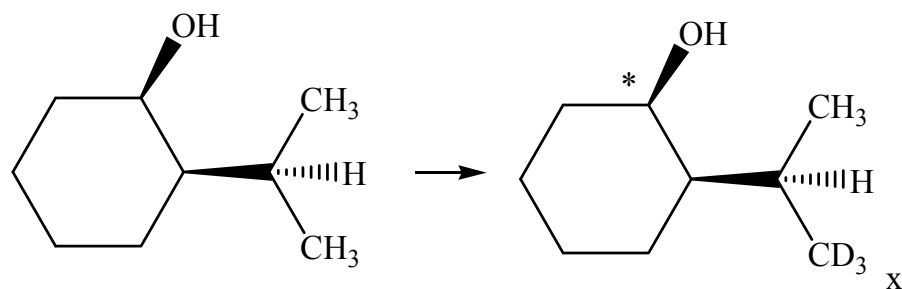
2R-bromopentane * = chiral center

Replace the C3 methylene protons with "D" and compare.



This 3D stereoisomer is 2R-bromopentane. \longrightarrow 3D,2R-bromopentane

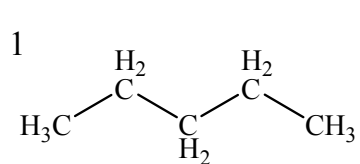
Because of the chiral center at C2, switching H for D at C3 forms diastereomers and, in this example the C3 methylene hydrogen atoms are diastereotopic. They could split one another if they have different chemical shifts and they could split their neighboring hydrogen atoms differently. This would make the spectrum more complicated. A similar result would be obtained with 2S-bromopentane. A similar result occurs with the C4 protons. This means there are seven different kinds of hydrogen in 2-bromopentane! Each of the methyl groups has a different type of proton, the methine hydrogen is different and all four methylene hydrogens are different.



These two methyl groups are diastereotopic because of the chiral alcohol carbon. They would likely have different proton and carbon chemical shifts.

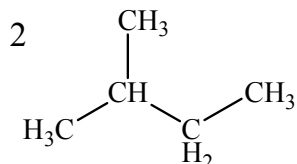
Problem - (11 simple examples?): How many different protons and carbons are in each of the C_5H_{12} isomers and $C_5H_{11}Br$ isomers?

There are three C_5H_{12} isomers



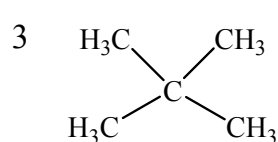
#H =

#C =



#H =

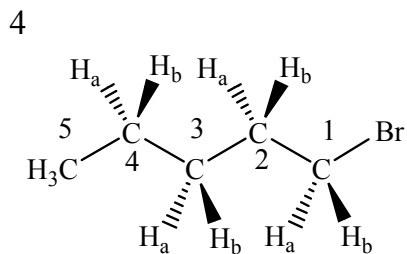
#C =



#H =

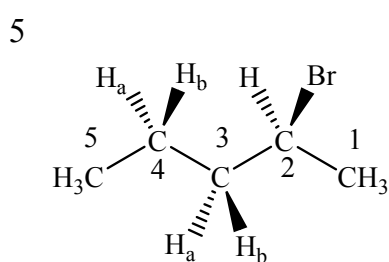
#C =

There are eight $C_5H_{11}Br$ isomers. If you switch H_b for "D", does it make enantiomers or diastereomers?



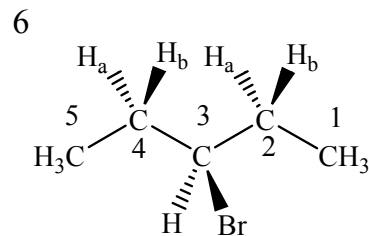
#H =

#C =



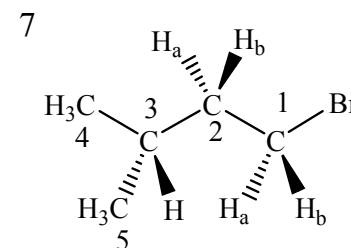
#H =

#C =



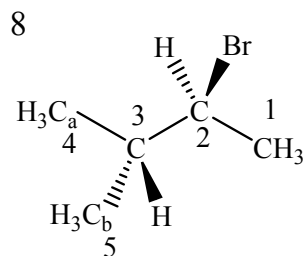
#H =

#C =



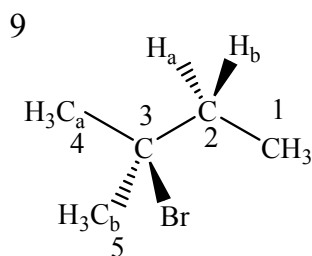
#H =

#C =



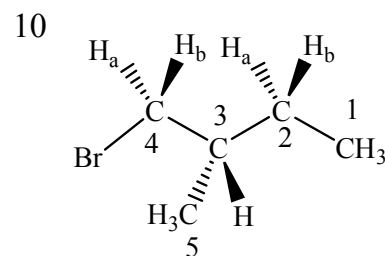
#H =

#C =



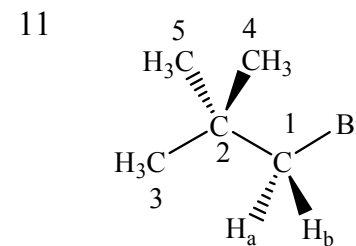
#H =

#C =



#H =

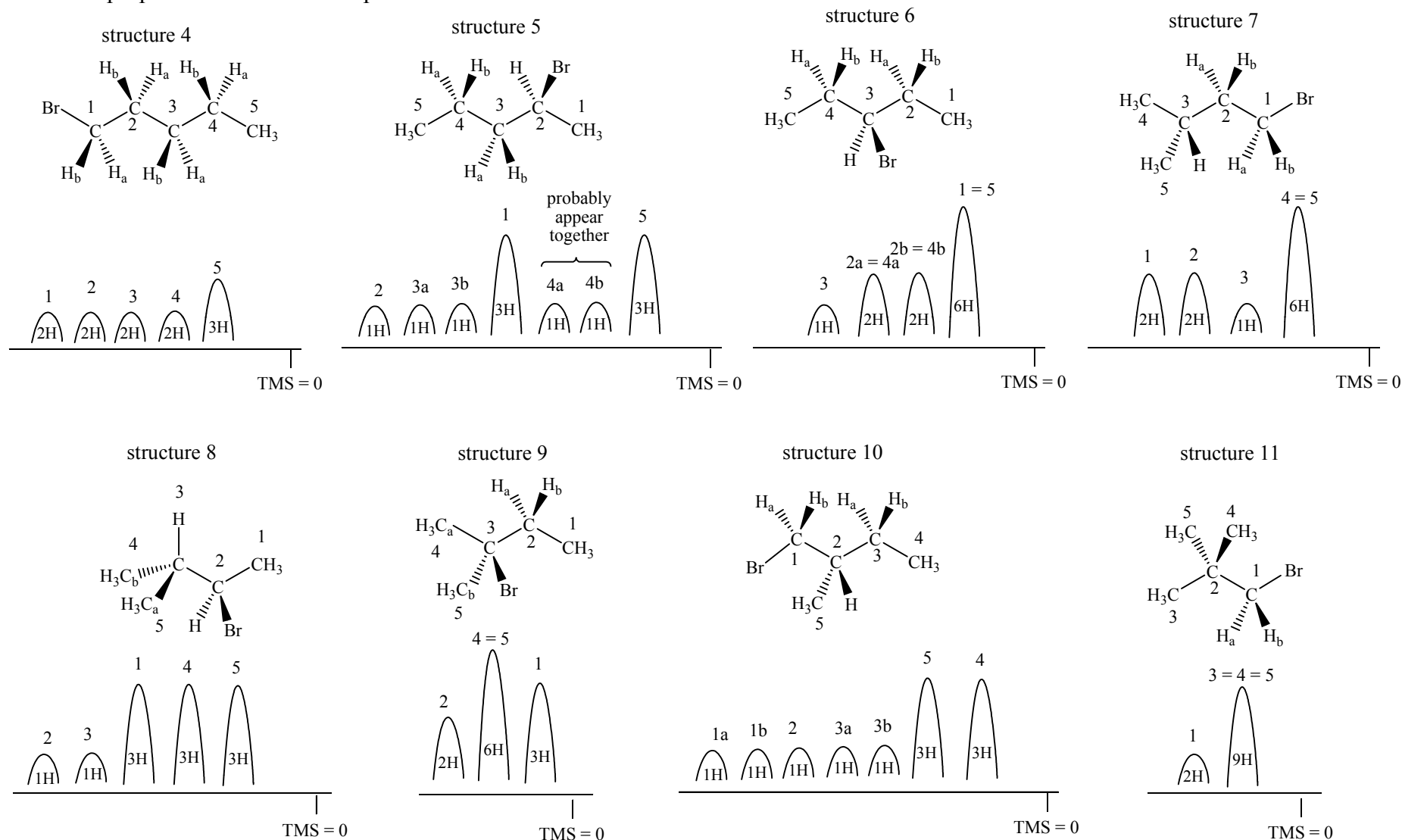
#C =



#H =

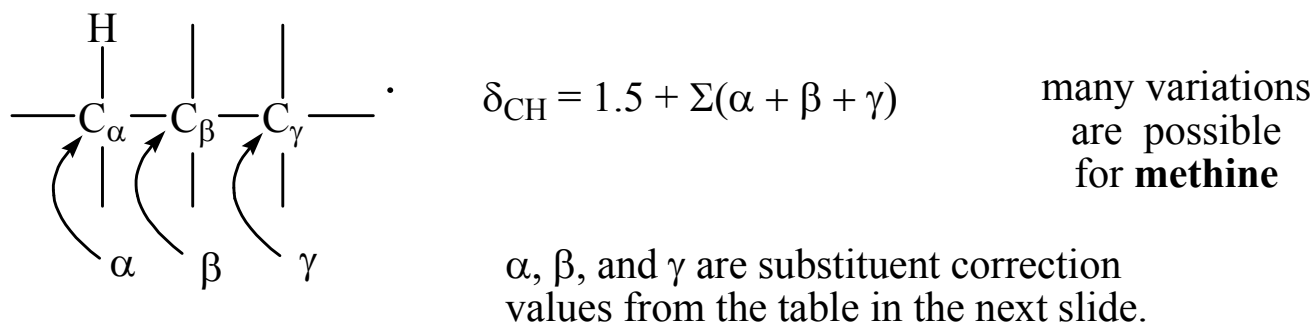
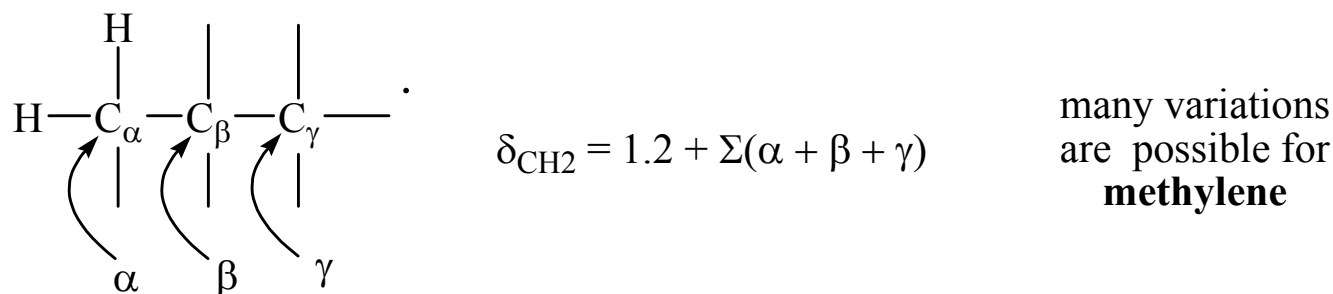
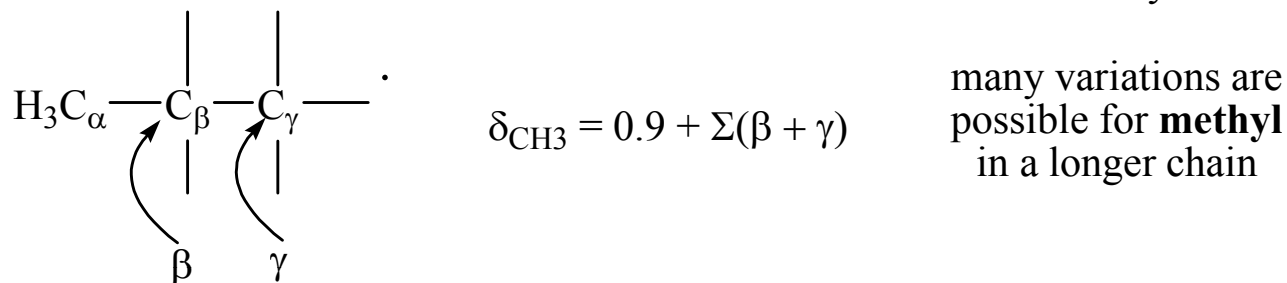
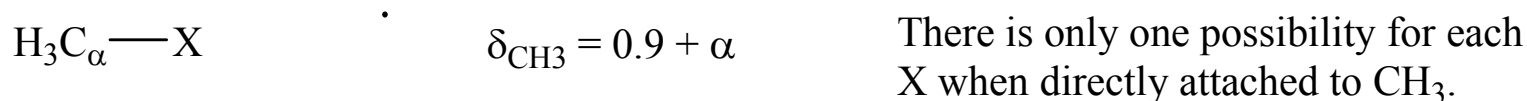
#C =

There are eight $C_5H_{11}Br$ isomers. The largest chemical shifts are protons closest to the Br. Integration measures the area under the peaks, which is proportional to number of protons at each chemical shift.



Calculating Proton Chemical Shifts (alkane sp^3 C-H, alkene and aromatic sp^2 C-H protons)

Σ is the summation symbol for all substituents used to estimate sp^3 proton chemical shifts (δ_H).

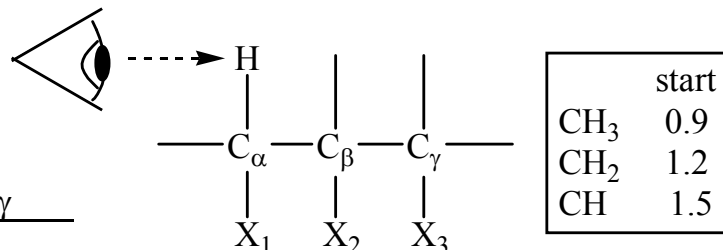


Chemical Shifts Correction Factors for Protons on sp^3 carbon atoms

Estimation of sp^3 C-H chemical shifts for one to multiple substituent parameters for protons within 3 Cs of consideration.

Relative position of calculated proton and substituent(s)

- α = hydrogen and substituent are attached to the same carbon
- β = hydrogen and substituent are on adjacent (vicinal) carbons
- γ = hydrogen and substituent have a 1,3 substitution pattern

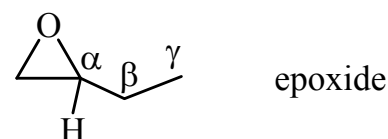


X = substituent	α	β	γ
substituent atom is a carbon			
R- (alkyl substituent)	0.0	0.0	0.0
R ₂ C=CR- (alkene)	0.7	0.2	0.1
RCC- (alkyne)	0.8	0.3	0.1
Ar- (aromatic)	1.4	0.5	0.1
substituent atom is a halogen			
F-	2.9	0.3	0.1
Cl-	2.2	0.4	0.1
Br-	2.1	0.6	0.1
I-	1.9	0.7	0.1
substituent atom is an oxygen			
HO- (alcohol, hydroxy)	2.3	0.3	0.1
RO- (simple ether, alkoxy)	2.2	0.3	0.1
R ₂ C=CRO- (enol ether)	2.8	0.5	0.1
ArO- (aromatic ether)	2.7	0.6	0.1
epoxide	1.5	0.4	0.1
RCO ₂ - (simple ester, oxygen side)	2.9	0.4	0.1
ArCO ₂ - (aromatic ester, oxygen side)	3.1	0.6	0.1
ArSO ₃ - (sulfonate, oxygen side)	2.3	0.3	0.1

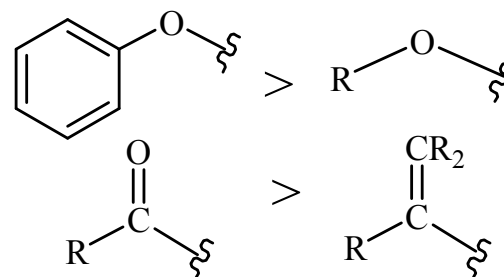
values from ChemDraw

Substituent's positions relative to calculated proton chemical shift.
X = substituent from table.

In general, multiple substituents do not add their entire values. Each additional substituent adds a smaller portion of its listed increment. Even so, the calculated values are typically close to the experimental values.



Notice ! F > Cl > Br > I



Additional parameters on the next slide.

Chemical Shifts Correction Factors for Protons on sp^3 carbon atoms

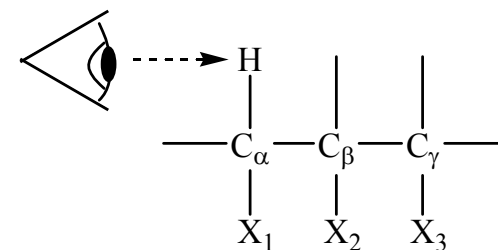
Estimation of sp^3 C-H chemical shifts for one to multiple substituent parameters for protons within 3 Cs of consideration.

Relative position of calculated proton and substituent(s)

α = hydrogen and substituent are attached to the same carbon

β = hydrogen and substituent are on adjacent (vicinal) carbons

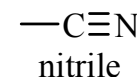
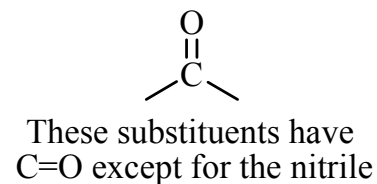
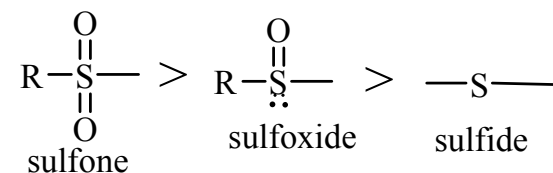
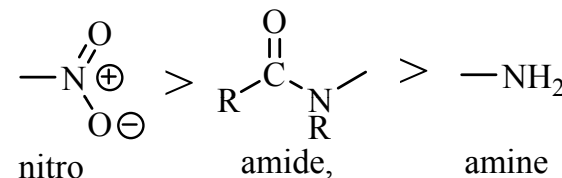
γ = hydrogen and substituent have a 1,3 substitution pattern



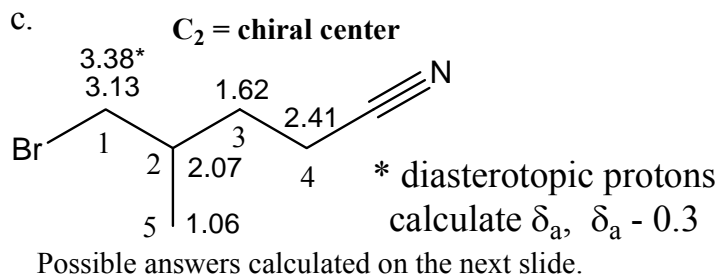
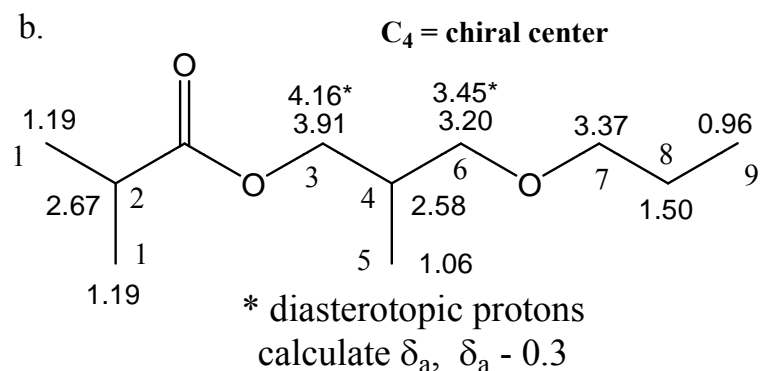
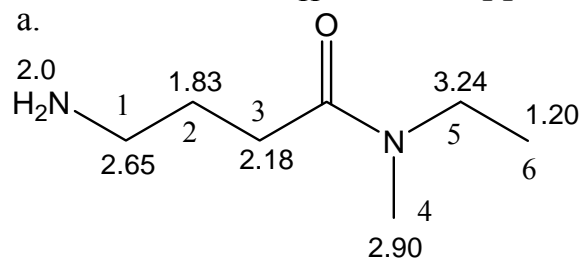
Substituent's positions relative to calculated proton chemical shift.
X = substituent from table.

X = substituent	α	β	γ
substituent atom is a nitrogen			
R ₂ N- (amine, R = H or C)	1.4	0.4	0.1
ArRN- (aromatic amine, R = H or C)	1.9	0.4	0.1
R'CONR- (amide, nitrogen side)	2.0	0.4	0.1
ArCONR- (aromatic amide, nitrogen side)	2.0	0.4	0.1
O ₂ N- (nitro)	3.2	0.8	0.1
substituent atom is a sulfur			
HS- (thiol)	1.4	0.4	0.1
RS- (sulfide)	1.2	0.5	0.1
ArS- (aromatic sulfide)	1.5	0.4	0.1
RSO- (sulfoxide)	1.6	0.5	0.1
ArSO- (aromatic sulfoxide)	1.7	0.5	0.1
RSO ₂ - (sulfone)	2.2	0.7	0.1
ArSO ₂ - (aromatic sulfone)	2.2	0.7	0.1
substituent atom is a carbonyl group or nitrile			
OHC- (aldehyde)	1.2	0.5	0.1
RCO- (ketone)	1.2	0.4	0.1
ArCO- (aromatic ketone)	1.4	0.3	0.1
HO ₂ C- (carboxylic acid)	1.0	0.4	0.1
RO ₂ C- (ester, carbon side)	1.1	0.5	0.1
R ₂ NOC- (amide carbon side)	1.0	0.4	0.1
ClOC- (acid chloride)	1.6	0.5	0.1
NC- (nitrile)	1.2	0.5	0.1

values from ChemDraw



Chemical shifts are calculated values from ChemDraw. All δ_H values in ppm.

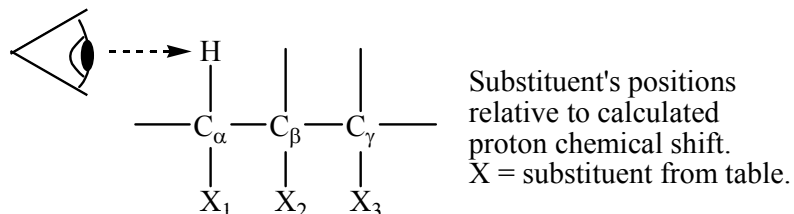


Chemical Shifts Correction Factors for Protons on sp^3 carbon atoms

Estimation of sp^3 C-H chemical shifts for one to multiple substituent parameters for protons within 3 Cs of consideration.

Relative position of calculated proton and substituent(s)

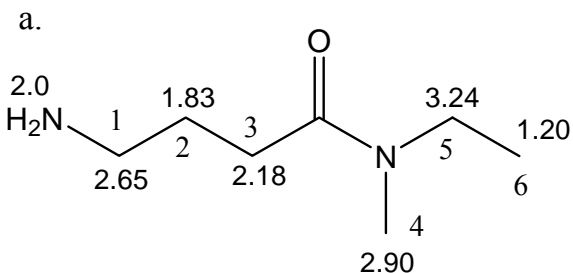
- α = hydrogen and substituent are attached to the same carbon
- β = hydrogen and substituent are on adjacent (vicinal) carbons
- γ = hydrogen and substituent have a 1,3 substitution pattern



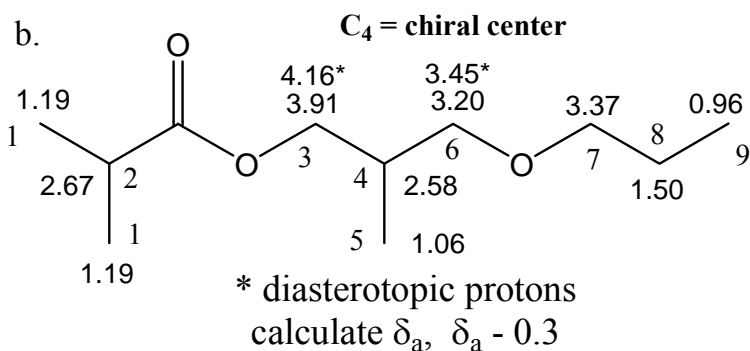
X = substituent	α	β	γ
substituent atom is a halogen			
Br-	2.1	0.6	0.1
substituent atom is an oxygen			
RO- (simple ether)	2.2	0.3	0.1
RCO ₂ - (simple ester, oxygen side)	2.9	0.4	0.1
substituent atom is a nitrogen			
R ₂ N- (amine, R = H or C)	1.4	0.4	0.1
R'CONR- (amide, nitrogen side)	2.0	0.4	0.1
substituent atom is a carbonyl group or nitrile			
RO ₂ C- (ester, carbon side)	1.1	0.5	0.1
R ₂ NOC- (amide carbon side)	1.0	0.4	0.1
NC- (nitrile)	1.2	0.5	0.1

values from ChemDraw

Possible Answers (If you get a different answer, double check my work, in case I made an error.)

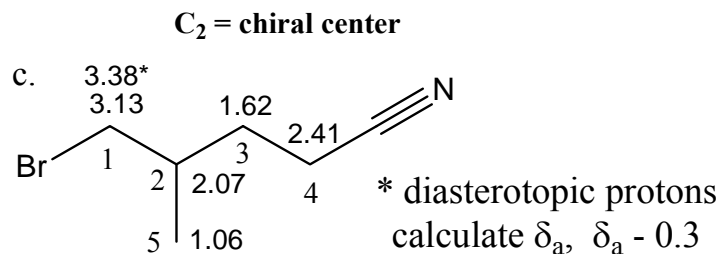


	1	2	3	4	5	6
	0.9	1.2	1.2	0.9	1.2	0.9
amine =	1.4	0.4	0.1			
amide-C =	0.1	0.4	1.0			
amide-N =				2.0	2.0	0.4
	<u>2.5</u>	<u>2.0</u>	<u>2.3</u>	<u>2.9</u>	<u>3.2</u>	<u>1.3</u>



	1	2	3a	3b *	4	5	6a	6b *	7	8	9
	0.9	1.5	1.2		1.5	0.9	1.2		1.2	1.2	0.9
ester-C =	0.5	1.1									
ester-O =			2.9	4.2	0.4	0.1	0.1	3.5			
ether-O =			0.1	-0.3	0.3	0.1	2.2	-0.3	2.2	0.3	0.1
	<u>1.4</u>	<u>2.6</u>	<u>4.2</u>	<u>3.9</u>	<u>2.2</u>	<u>1.1</u>	<u>3.5</u>	<u>3.2</u>	<u>3.4</u>	<u>1.5</u>	<u>1.9</u>

* = diastereotopic H
 $\delta_b = \delta_{a,calc} - 0.3$ ppm

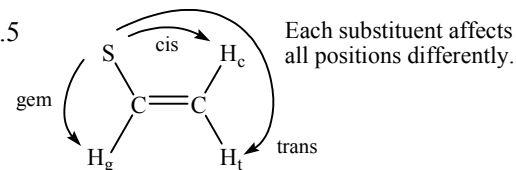
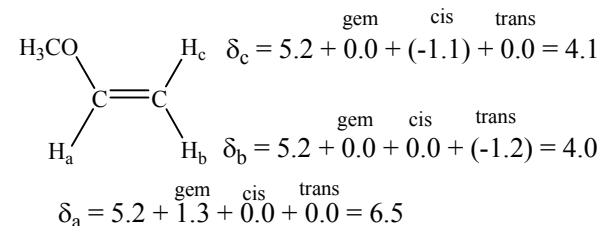
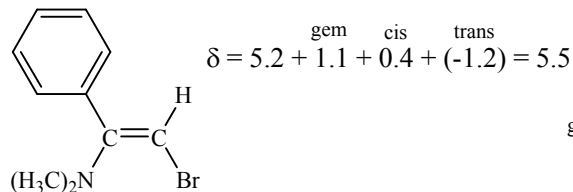
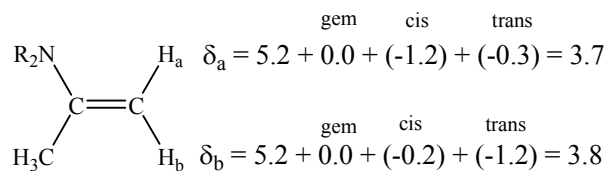
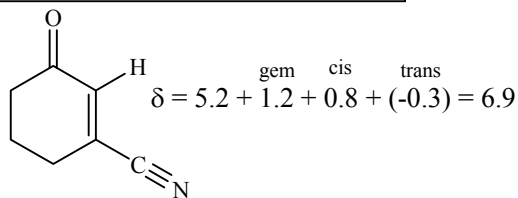
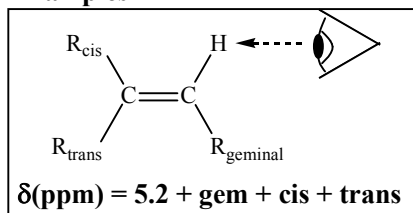


	1a	1b *	2	3a	3b *	4	5
	1.2		1.5	1.2		1.2	0.9
bromine =	2.1	3.3	0.6	0.1	1.8		0.1
nitrile =		-0.3	0.1	0.5	-0.3	1.2	
	<u>3.3</u>	<u>3.0</u>	<u>2.2</u>	<u>1.8</u>	<u>1.5</u>	<u>2.4</u>	<u>1.0</u>

Estimated Chemical Shifts for Protons on Alkene sp² Carbon Atoms

X = substituent	geminal	cis	trans
H-	0.0	0.0	0.0
hydrogen			
R-	0.5	-0.2	-0.3
alkyl			
C ₆ H ₅ CH ₂ -	1.1	-0.3	-0.3
benzyl			
X-CH ₂ -	0.8	0.1	-0.1
halomethyl (X = F, Cl, Br, I)			
(H)/ROCH ₂ -	0.7	0.0	0.0
hydroxy/alkoxy methyl			
(H ₂)/R ₂ NCH ₂ -	0.6	0.1	0.1
aminomethyl			
RCOCH ₂ -	0.7	0.1	0.1
carbonyl methyl			
NCCH ₂ -	0.7	0.1	0.1
cyanomethyl			
R ₂ C=CR-	1.0	0.1	-0.2
alkenyl			
RCC-	0.5	0.4	0.1
alkynyl			
C ₆ H ₅ -	1.4	0.4	0.0
phenyl			
F-	1.6	-0.4	-1.0
fluoro			
Cl-	1.1	0.2	0.2
chloro			
Br-	1.1	0.5	0.6
bromo			
I-	1.2	0.9	0.9
iodo			

Examples



Estimated Chemical Shifts for Protons on Alkene sp² Carbon Atoms

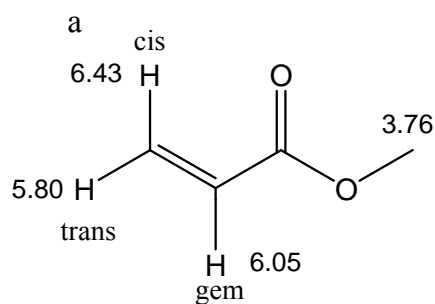
X = substituent	geminal	cis	trans
RO-	1.3	-1.0	-1.2
alkoxy			
RCO ₂ -	2.1	-0.3	-0.6
ester, oxygen side			
R ₂ N-	0.8	-1.2	-1.2
amino			
RCONH-	2.1	-0.5	-0.7
amide, nitrogen side			
O ₂ N-	1.9	1.3	0.6
nitro			
RS-	1.2	-0.4	-0.1
sulfide			
RSO-	1.3	0.7	0.5
sulfoxide			
RSO ₂ -	1.6	1.2	1.0
sulfone			
OHC-	1.1	1.0	1.2
aldehyde			
ROC-	1.2	1.2	0.9
ketone			
HO ₂ C-	1.0	1.5	0.8
carboxylic acid			
RO ₂ C-	0.8	1.2	0.6
ester, carbon side			
H ₂ NOC-	1.3	1.0	0.5
amide, carbon side			
ClOC-	1.2	1.5	1.1
acid chloride			
NC-	0.3	0.8	0.6
nitrile			

Estimated Chemical Shifts for Protons on Alkene sp^2 Carbon Atoms

X = substituent	geminal	cis	trans
RO- alkoxy	1.2	-1.0	-1.2
RCO ₂ - ester, oxygen side	2.1	-0.3	-0.6
RO ₂ C- ester, carbon side	0.8	1.2	0.6

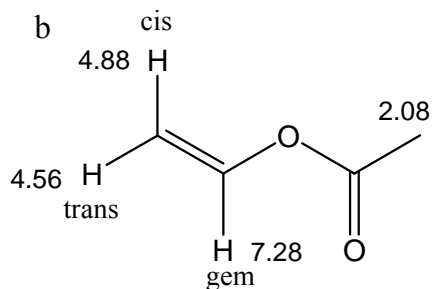
Notice δ_H ranges from 4 ppm to 7+ ppm.

Calculate chemical shifts for the following alkene sp^2 protons (and compare to the values given).

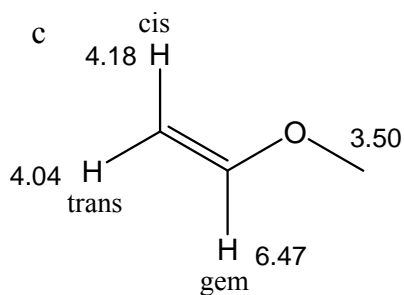


$$\text{alkene } sp^2 \delta_H = 5.2 + \text{correction terms}$$

	geminal	cis	trans	methyl
ester, C side =	5.2	5.2	5.2	0.9
	_____	_____	_____	_____



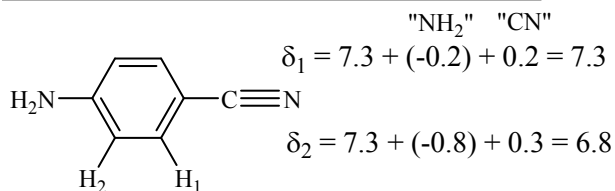
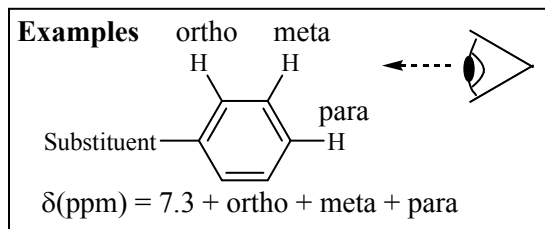
	geminal	cis	trans	methyl
ester, O side =	5.2	5.2	5.2	0.9
	_____	_____	_____	_____



	geminal	cis	trans	methyl
ether =	5.2	5.2	5.2	0.9
	_____	_____	_____	_____

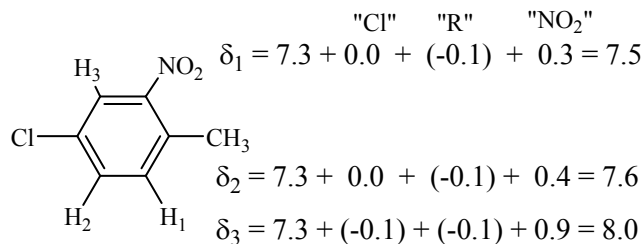
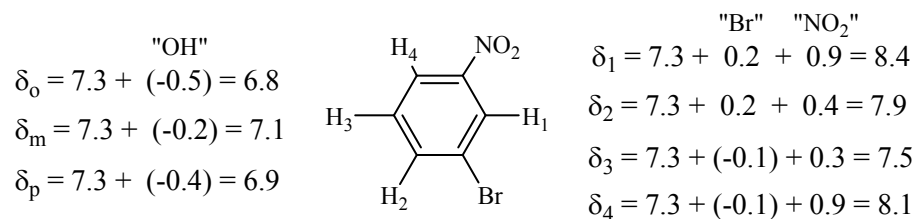
Estimated chemical shifts for protons at aromatic sp^2 carbon atoms

X = substituent	ortho	meta	para
H- hydrogen	0.0	0.0	0.0
R- alkyl	-0.1	-0.1	-0.2
XCH ₂ - halomethyl (X = F,Cl,Br,I)	0.3	0.1	-0.1
(H)/ROCH ₂ - hydroxy/alkoxy methyl	-0.1	-0.1	-0.1
R ₂ C=CR- alkenyl	0.0	0.0	-0.2
RCC- alkynyl	0.5	0.4	-0.1
C ₆ H ₅ - phenyl	0.2	0.0	0.0
F- fluoro	-0.3	0.0	-0.2
Cl- chloro	0.0	-0.1	-0.1
Br- bromo	0.2	-0.1	-0.1
I- iodo	0.4	-0.2	0.0
RO- alkoxy	-0.5	-0.1	-0.4
HO- hydroxy	-0.5	-0.2	-0.4
RCO ₂ - ester, oxygen side	-0.2	0.0	-0.2



Estimated chemical shifts for protons at aromatic sp^2 carbon atoms

X = substituent	ortho	meta	para
(H ₂ N)R ₂ N- amino	-0.8	-0.2	-0.7
RCONH- amide, nitrogen side	0.4	0.0	-0.3
ON- nitroso	0.6	0.3	0.4
O ₂ N- nitro	0.9	0.3	0.4
RS-/HS- sulfide / thiol	-0.1	-0.2	-0.2
XO ₂ S- sulfonyl X (R,HO,RO,H ₂ N)	0.7	0.3	0.4
OHC- aldehyde	0.6	0.2	0.4
ROC- ketone	0.6	0.1	0.2
HO ₂ C- carboxylic acid	0.9	0.2	0.3
RO ₂ C- ester, carbon side	0.7	0.1	0.2
H ₂ NOC- amide, carbon side	0.7	0.2	0.2
ClOC- acid chloride	0.8	0.2	0.4
NC- nitrile	0.3	0.2	0.3



Estimated chemical shifts for protons at aromatic sp^2 carbon atoms

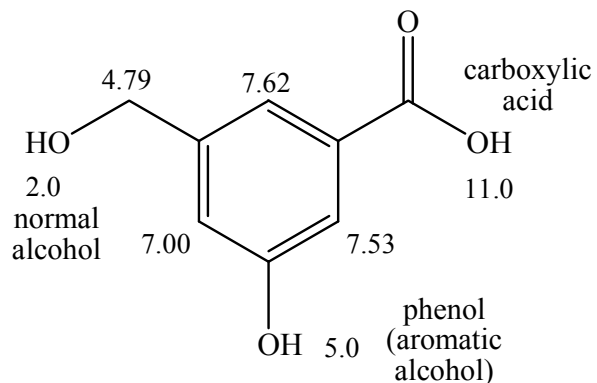
X = substituent	ortho	meta	para
(H ₂ N)R ₂ N- amino	-0.8	-0.2	-0.7
RCONH- amide, nitrogen side	0.4	0.0	-0.3
O ₂ N- nitro	0.9	0.3	0.4
H ₂ NOC- amide, carbon side	0.7	0.2	0.2

Calculate chemical shifts for the following aromatic sp^2 protons (and compare to the values given).

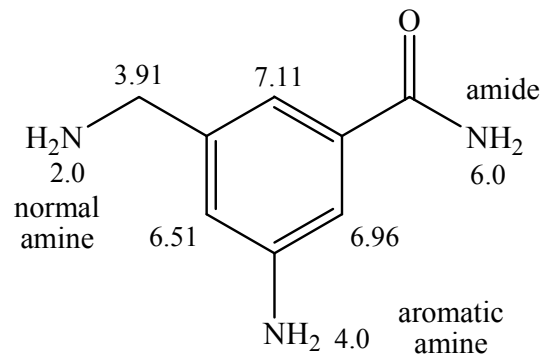
<p>a</p>	aromatic sp^2 $\delta_H = 7.3 + \text{correction terms}$												
<p>b</p>	<table border="0"> <thead> <tr> <th></th> <th>ortho</th> <th>meta</th> <th>para</th> </tr> </thead> <tbody> <tr> <td>amide, C side =</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> </tr> <tr> <td></td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> </tr> </tbody> </table>		ortho	meta	para	amide, C side =	7.3	7.3	7.3		_____	_____	_____
	ortho	meta	para										
amide, C side =	7.3	7.3	7.3										
	_____	_____	_____										
<p>c</p>	<table border="0"> <thead> <tr> <th></th> <th>ortho</th> <th>meta</th> <th>para</th> </tr> </thead> <tbody> <tr> <td>amine =</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> </tr> <tr> <td></td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> </tr> </tbody> </table>		ortho	meta	para	amine =	7.3	7.3	7.3		_____	_____	_____
	ortho	meta	para										
amine =	7.3	7.3	7.3										
	_____	_____	_____										
<p>d</p>	<table border="0"> <thead> <tr> <th></th> <th>ortho</th> <th>meta</th> <th>para</th> </tr> </thead> <tbody> <tr> <td>nitro =</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> <td style="text-align: center;">7.3</td> </tr> <tr> <td></td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> <td style="text-align: center;">_____</td> </tr> </tbody> </table>		ortho	meta	para	nitro =	7.3	7.3	7.3		_____	_____	_____
	ortho	meta	para										
nitro =	7.3	7.3	7.3										
	_____	_____	_____										

The following examples show generic proton shifts based on the ChemDraw program that is used to generate structures in these notes. We don't have a formula to calculate these proton shifts.

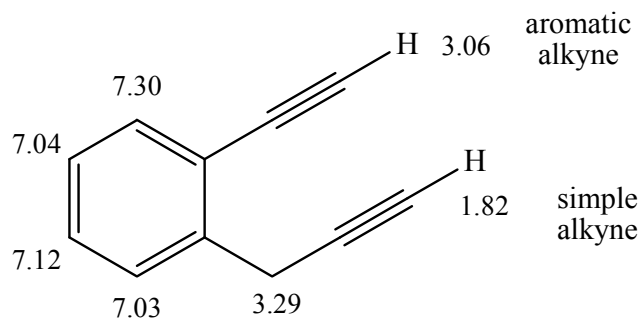
Different types of "OH" (alcohols, phenols, carboxylic acids)



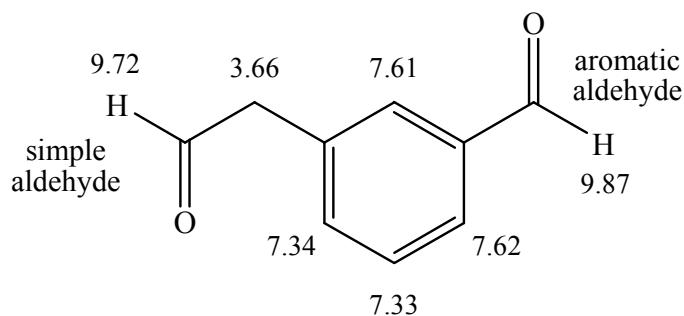
Different types of "NH" (amines, amides)



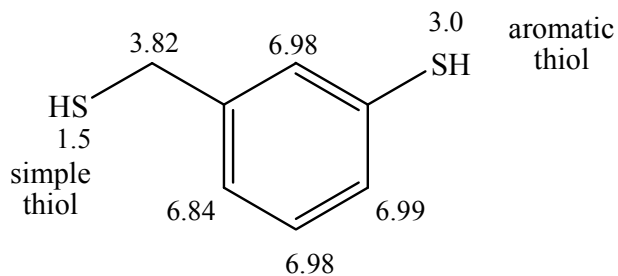
Different types of "sp H" (alkynes)



Different types of "aldehyde H"

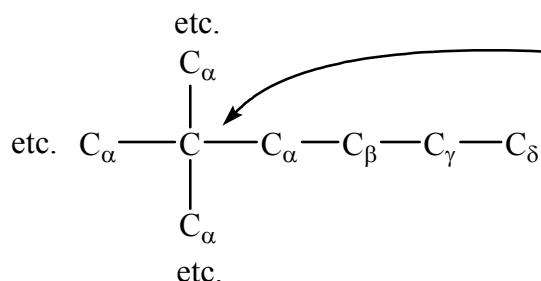


Different types of "SH" (thiols)



sp³ Carbon Chemical Shift Calculations, Method 1: starting from scratch (-2 ppm)

Calculations of the individual ¹³C shifts of any alkane can be estimated starting from the chemical shift of methane (approximately -2 ppm). Approximate correction factors are included for every directly attached carbon atom (C_α = +9), every once removed carbon atom (C_β = +9) and every twice removed carbon atom (C_γ = -2). There are even some corrections for C_δ carbons, but they are generally smaller than the uncertainties in our estimations so we will ignore those. Steric corrections are also necessary, have been simplified to integer values below.



There can be 0 to 4 branches on any carbon atom.

Corrections for attached carbon atoms.

$$C_{\alpha} \approx 9 \text{ ppm}$$

$$C_{\beta} \approx 9 \text{ ppm}$$

$$C_{\gamma} \approx -2 \text{ ppm}$$

$$C_{\delta} \approx 0 \text{ ppm}$$

The simplified equation for calculating a chemical shift for an sp³ carbon looks as follows.

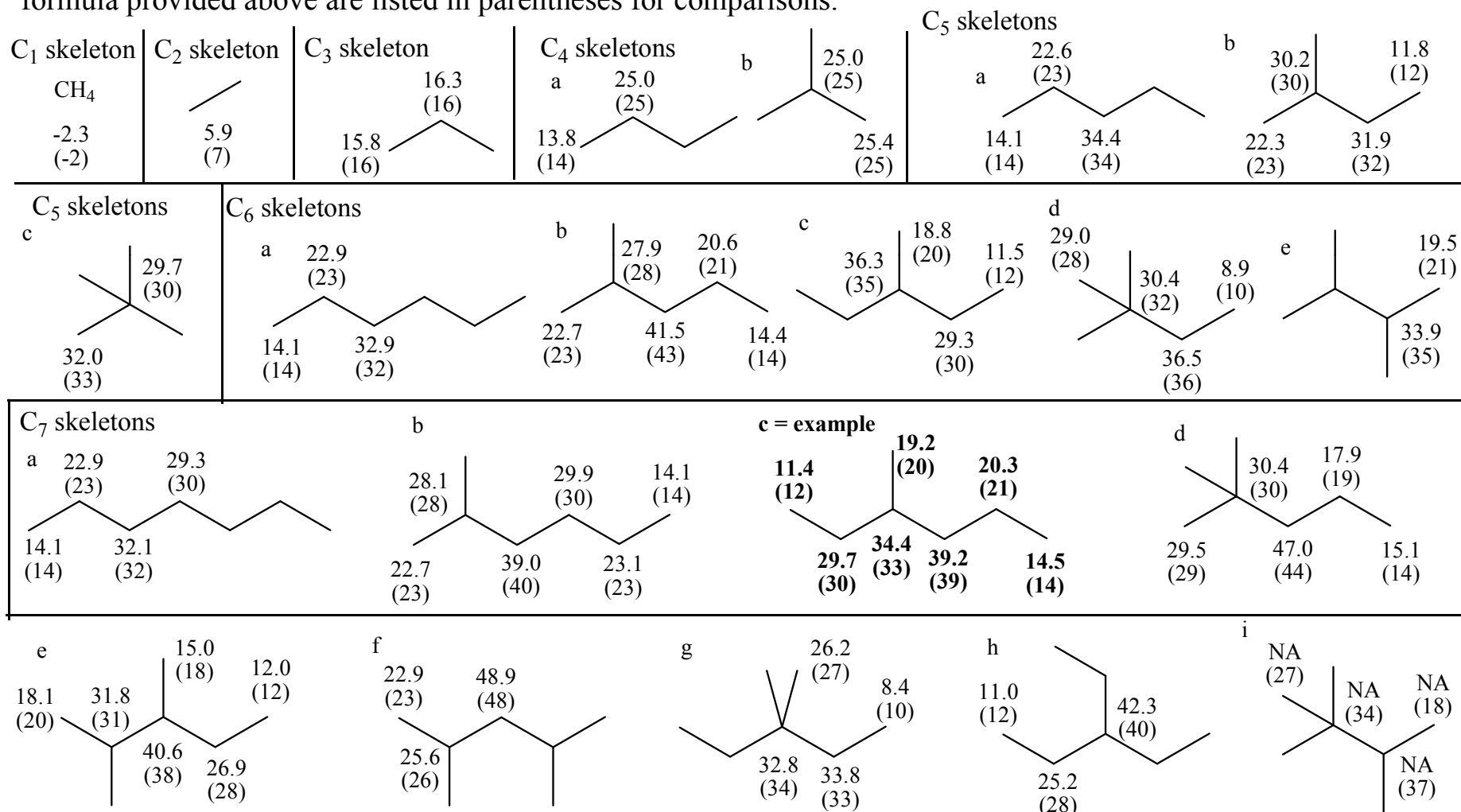
$$\delta_C = (-2) + (9)(\#C_{\alpha} + \#C_{\beta}) + (\#C_{\gamma})(-2) + (\text{simplified steric corrections}) \text{ ppm}$$

Simplified steric corrections:

The calculated carbon atom is: ↓	The attached C _α carbons are: (make a correction for each attached carbon)			
	primary	secondary	tertiary	quaternary
primary	0	0	-1	-3
secondary	0	0	-2	-8
tertiary	0	-4	-10	-15
quaternary	-1	-8	-15	-25

Method 2: sp³ Carbon Chemical Shift Calculations starting from a known carbon skeleton

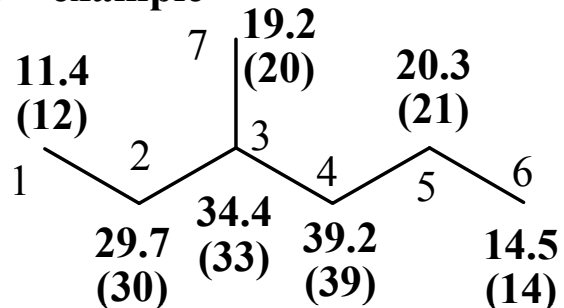
Examples of real carbon chemical shifts in C₁ - C₇ alkanes are listed as possible starting points for calculation of carbon chemical shifts in substituted molecules (all ¹³C shifts in ppm). Estimated values using the simplified formula provided above are listed in parentheses for comparisons.



Ref. experimental values from: http://sdfs.db.aist.go.jp/sdfs/cgi-bin/cre_index.cgi

$$\delta_C = (-2) + (9)(\#C_\alpha + \#C_\beta) + (\#C_\gamma)(-2) + (\text{simplified steric corrections}) \text{ ppm}$$

c = example

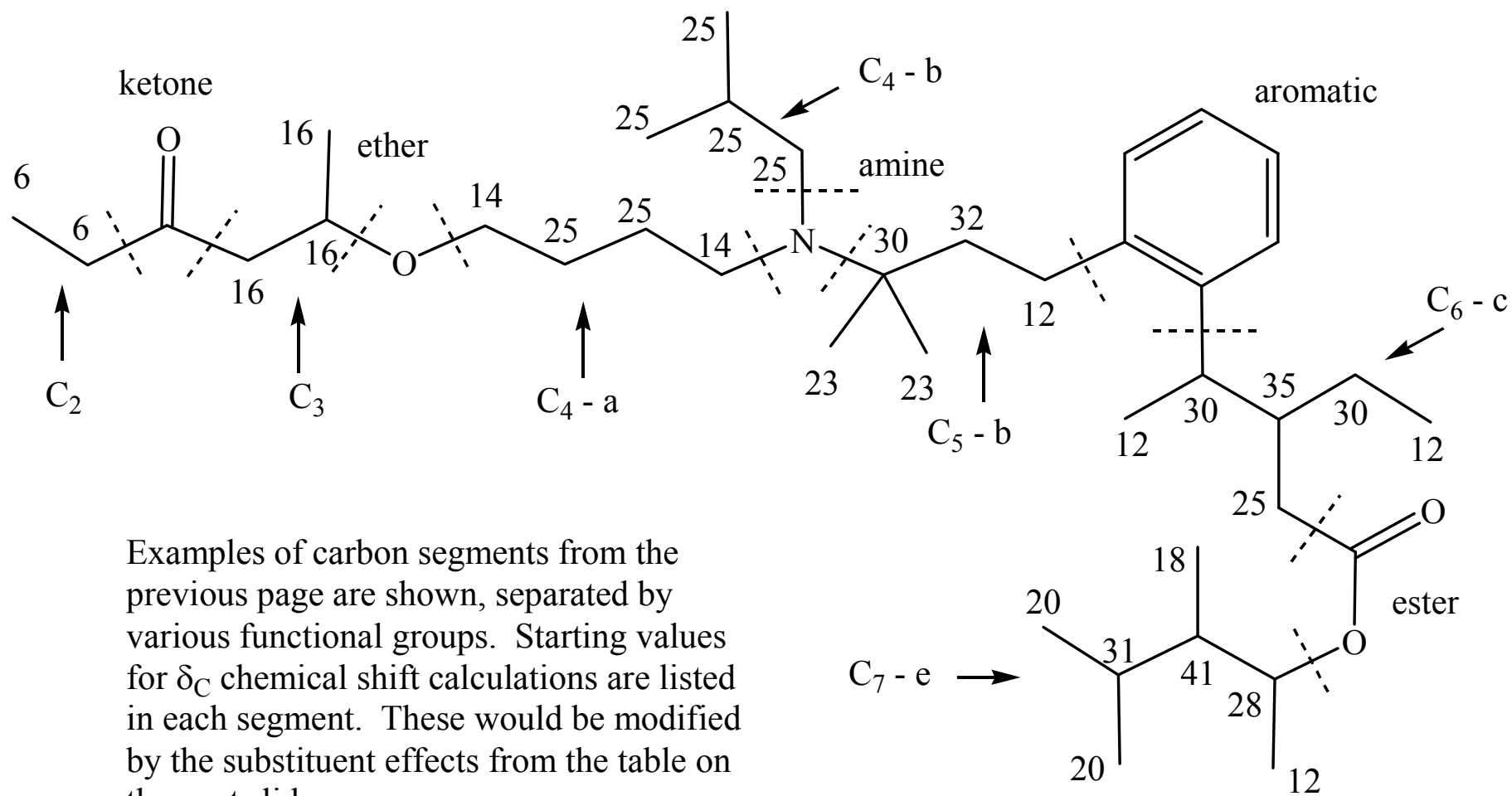


	C1	C2	C3	C4	C5	C6	C7
start =	-2	-2	-2	-2	-2	-2	-2
$\alpha + \beta =$	18	36	45	45	27	18	27
$\gamma =$	-4	-2	-2	-2	-4	-2	-4
steric =	0	-2	-8	-2	0	0	-1
calc. $\delta =$	12	30	33	39	21	14	20
exp. $\delta =$	11.4	29.7	34.4	39.2	20.3	14.5	19.2

Simplified steric corrections:

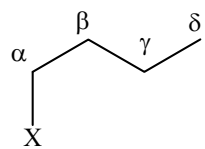
The attached C_α carbons are:
(make a correction for each attached carbon)

The calculated carbon atom is: ↓	primary	secondary	tertiary	quaternary
primary	0	0	-1	-3
secondary	0	0	-2	-8
tertiary	0	-4	-10	-15
quaternary	-1	-8	-15	-25



Examples of carbon segments from the previous page are shown, separated by various functional groups. Starting values for δ_C chemical shift calculations are listed in each segment. These would be modified by the substituent effects from the table on the next slide.

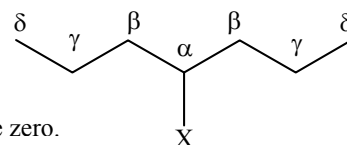
The following table presents many functional group correction factors. These will be applied to the carbon atoms in the appropriate skeletons presented above that are near each functional group. Two sets of correction values are provided for each substituent, depending on whether a substituent is at the end of a chain (terminal) or in the middle of a chain (internal). These are provided in side-by-side tables that follow ($\alpha > \beta > \gamma$). With only a couple of exceptions, the α and β corrections are deshielding (positive) and the γ corrections are shielding (negative). The correction factors are only reported to whole number values because estimated chemical shifts are not generally reliable to more than a few ppm.



terminal substituent

X = a substituent

δ values are assumed to be zero.



internal substituent

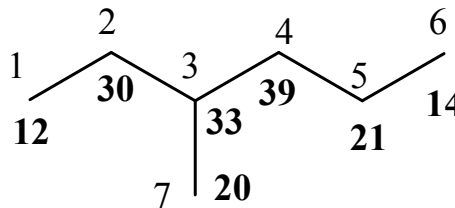
Substituent = X	X is attached to a terminal carbon atom (ppm)			X is attached to an internal carbon atom (ppm)		
	C_α correction	C_β correction	C_γ correction	C_α correction	C_β correction	C_γ correction
-CH=CH ₂ alkenes	20	7	-2	14	5	-2
-CCH alkynes	7	6	-3	-1	4	-3
-C ₆ H ₅ aromatic	22	9	-3	15	7	-2
-OH alcohol	49	10	-6	42	8	-5
-OCH ₃ ether	58	7	-6	57	6	-5
-O ₂ CR ester,oxygen side	51	6	-6	47	5	-5
-NH ₂ 1° amine	28	10	-5	21	8	-4
-NH(CH ₃) 2° amine	38	8	-5	32	6	-4
-N(CH ₃) ₂ 3° amine	45	5	-5	41	3	-4
-RNOCR amide,nitrogen side	26	7	-5	18	6	-5
-NO ₂ nitro	61	5	-5	55	1	-5

* Chemical shift values based on ChemDraw calculations.

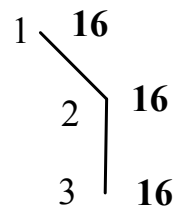
Substituent = X	X is attached to a terminal carbon atom (ppm)			X is attached to an internal carbon atom (ppm)		
	C _α correction	C _β correction	C _γ correction	C _α correction	C _β correction	C _γ correction
-F fluoro	70	8	-7	62	3	-7
-Cl chloro	31	10	-5	38	10	-5
-Br bromo	21	10	-4	29	10	-4
-I iodo	-7	11	-2	9	1	-2
-CH=O aldehyde	30	1	-3	21	-2	-2
-CR=O ketone	31	1	-3	23	1	-3
-C(OH)=O acid	22	2	-3	17	1	-3
-C(OR)=O ester, carbon side	20	2	-3	15	1	-3
-C(NR ₂)=O amide, carbon side	25	3	-4	17	1	-3
-CN nitrile	3	3	-3	1	1	-3
-C(Cl)=O acid chloride	33	2	-4	26	1	-3
-SH thiol	11	10	-4	5	6	-4
-SR sulfide	21	8	-3	15	4	-3

* Chemical shift values based on ChemDraw calculations.

carbon chemical shifts of 2-methylhexane and propane used in the example structure

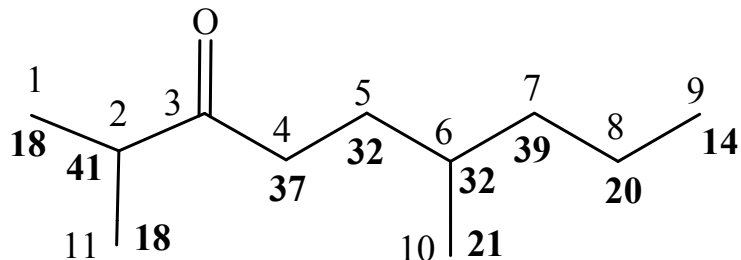


We either calculate these carbon shifts from scratch or the ^{13}C shifts are experimentally available.

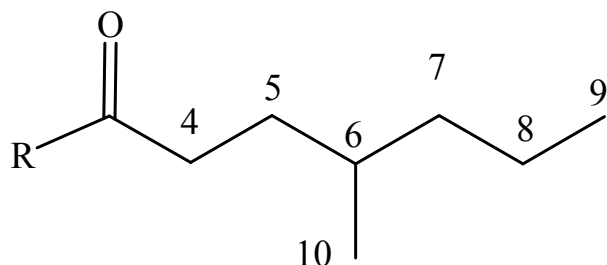


We either calculate these carbon shifts from scratch or the ^{13}C shifts are experimentally available.

example structure

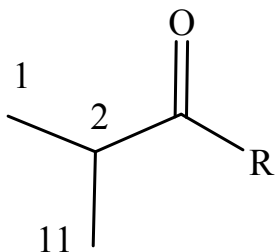


substituent on the end



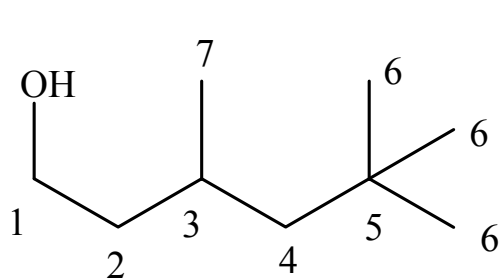
	C4	C5	C6	C7	C8	C9	C10
start =	12	30	33	39	21	14	20
"ketone" =	31	1	-3	0	0	0	0
calculated δ =	43	31	30	39	21	14	20
ChemDraw. δ =	37	32	32	39	20	14	21

substituent in the middle



	C1	C2	C11
start =	16	16	16
"ketone" =	1	23	1
calculated δ =	17	39	17
ChemDraw. δ =	18	41	18

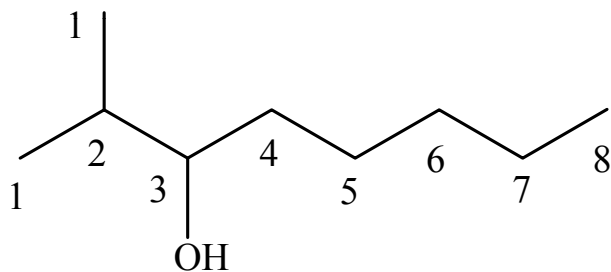
$$\delta_C = (-2) + (9)(\#C_\alpha + \#C_\beta) + (\#C_\gamma)(-2) + (\text{simplified steric corrections}) \text{ ppm}$$



	C1	C2	C3	C4	C5	C6	C7
start =	-2	-2	-2	-2	-2	-2	-2
$\alpha + \beta =$	18	36	45	63	45	36	27
$\gamma =$	-2	-2	-6	-2	-4	-2	-4
steric =	0	-2	-8	-10	-11	-3	-1
subst. =	48	10	-6	0	0	0	0
calc. $\delta =$	62	40	23	49	28	29	20

"OH" at the end

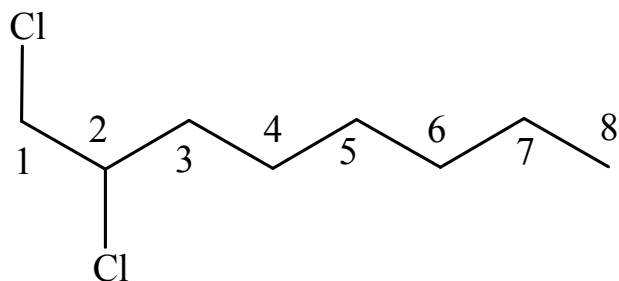
exp. $\delta =$ 61.0 42.4 26.0 51.5 31.1 30.0 22.7



	C1	C2	C3	C4	C5	C6	C7	C8
start =	-2	-2	-2	-2	-2	-2	-2	-2
$\alpha + \beta =$	27	36	45	36	36	36	27	18
$\gamma =$	-2	-2	-2	-6	-4	-2	-2	-2
steric =	-1	-4	-2	0	0	0	0	0
subst. =	-4	7	42	7	-4	0	0	0
calc. $\delta =$	18	35	81	35	26	32	23	14

"OH" in the middle

exp. $\delta =$ 17.2 33.6 76.8 34.3 25.9 32.1 22.8 14.1



experimental $\delta_C =$

	1	2	3	4	5	6	7	8
$\delta_C =$	48	61	35	26	29	32	23	14

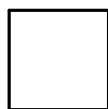
octane = starting values, modified by 2 chlorine

	1	2	3	4	5	6	7	8
octane	14	23	32	30	30	32	23	14
1-Cl =	31	10	-5					
2-Cl =	10	29	10	-4				
total	55	62	35	28	30	32	23	14

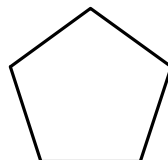
Here are some possible starting values for C_n cycloalkanes (ppm). Use the internal correction factors from the table when calculating rings with substituents.



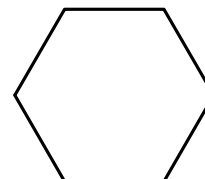
$$\delta_C = -3$$



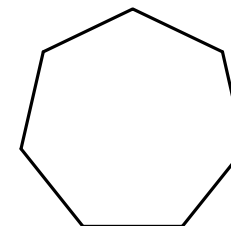
$$\delta_C = 22$$



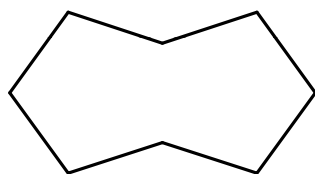
$$\delta_C = 30$$



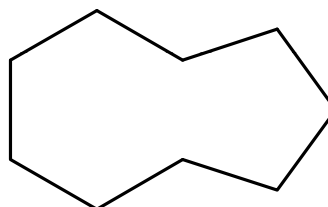
$$\delta_C = 28$$



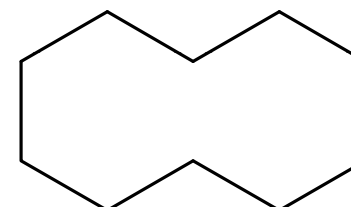
$$\delta_C = 29$$



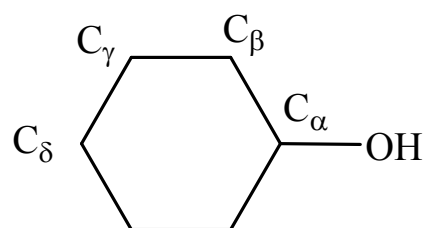
$$\delta_C = 27$$



$$\delta_C = 26$$

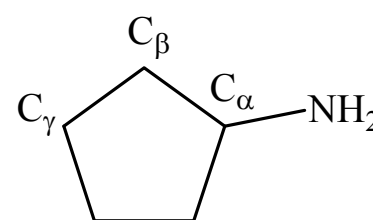


$$\delta_C = 26$$



cyclohexane value
28 ppm (ChemDraw)
27.1 ppm (experimental)

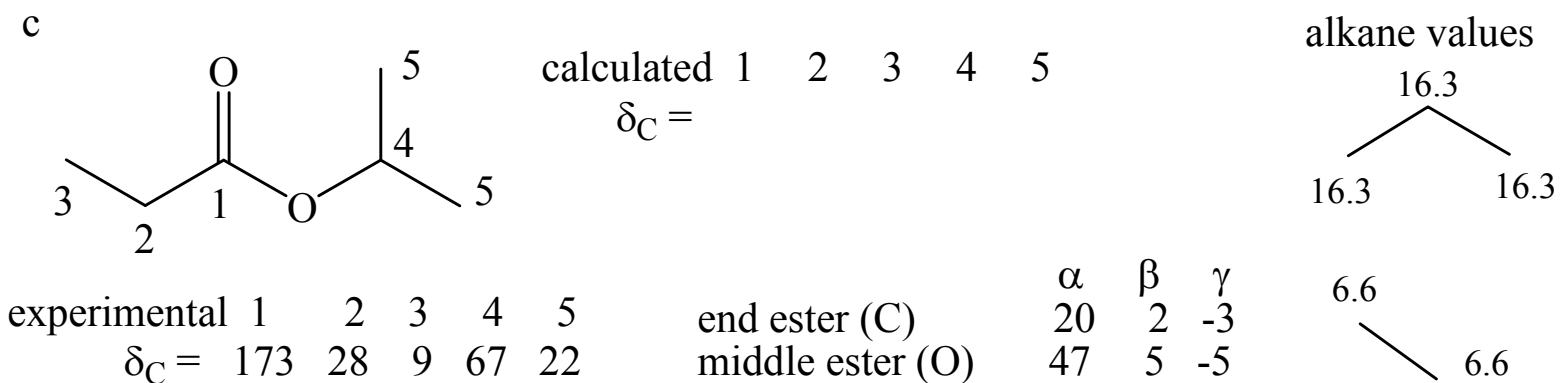
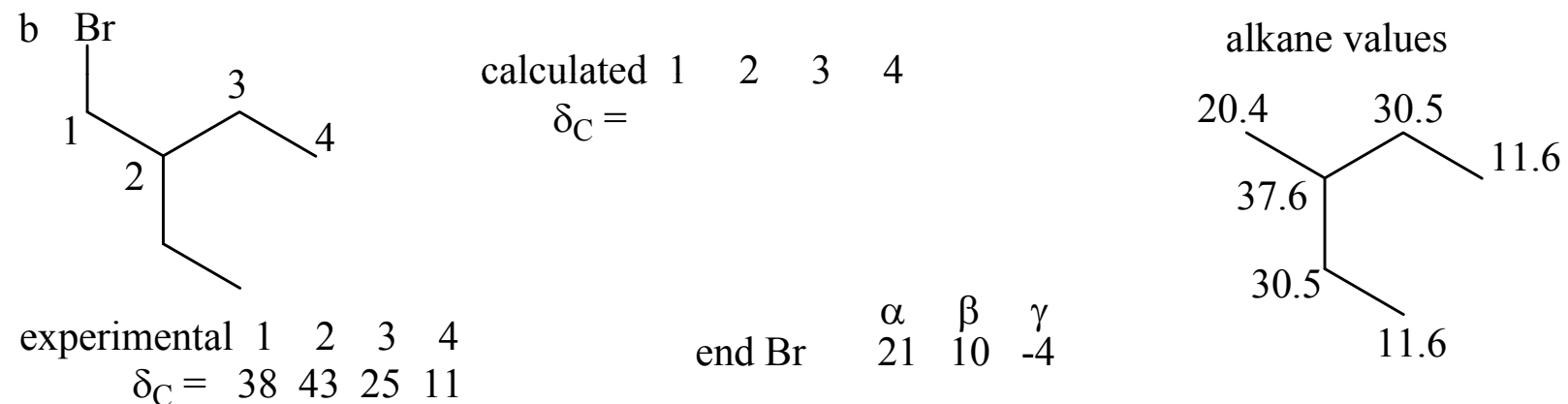
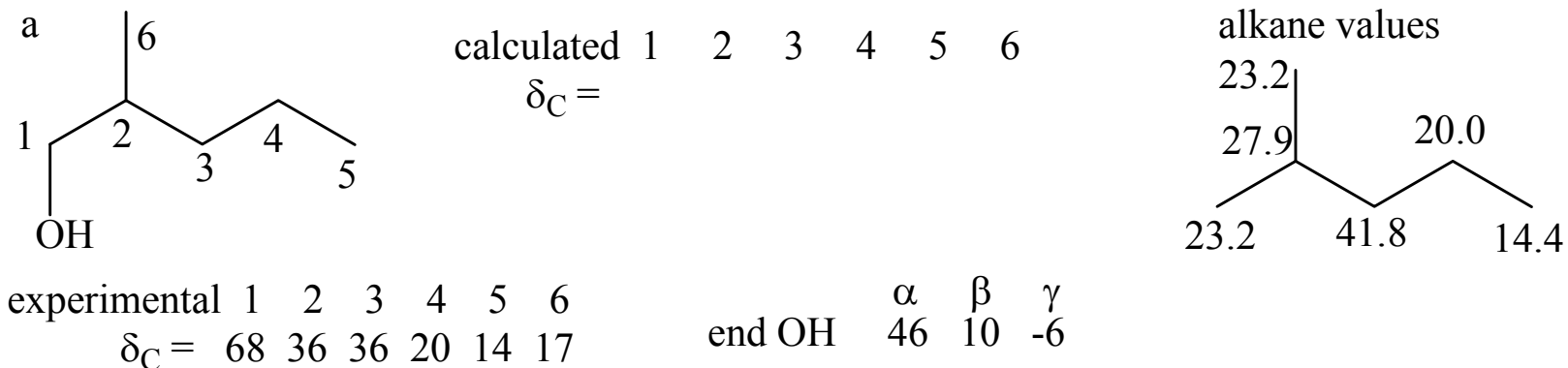
calc δ_C (ppm)	exp δ_C
$C_\alpha = 28 + 42 = 70$	70
$C_\beta = 28 + 8 = 36$	36
$C_\gamma = 28 - 5 = 23$	24
$C_\delta = 28 + 0 = 28$	26



cyclopentane value
30 ppm (ChemDraw)
26.0 ppm (experimental)

calc δ_C (ppm)	exp δ_C
$C_\alpha = 30 + 21 = 51$	53
$C_\beta = 30 + 8 = 38$	36
$C_\gamma = 30 - 4 = 26$	24

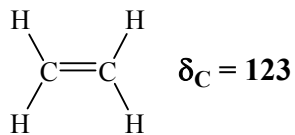
Estimate δ_C for substituted structures using the starting alkane chemical shifts



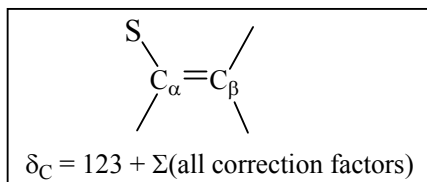
Calculating Alkene ¹³C Chemical Shifts (ppm)

To calculate alkene carbon chemical shifts, there are two types of substituent corrections. The alpha values are used when a substituent is directly attached to the carbon and the beta values are used when a substituent is attached to the other carbon of the double bond. Since there are four bonding positions at any alkene it is possible that 1-4 corrections might be needed.

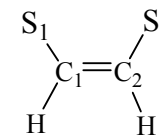
Correction factors for sp² alkene shifts



alkene starting point = ethene



S = is attached to an alkene carbon (ppm)



$$\delta_{C1} = 123 + S_1(\alpha) + S_2(\beta)$$

$$\delta_{C2} = 123 + S_1(\beta) + S_2(\alpha)$$

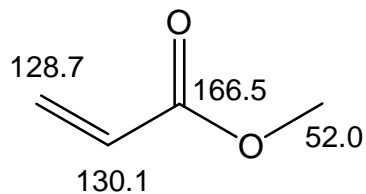
Substituent = X	C _α correction	C _β correction	Substituent = X	C _α correction	C _β correction
H ₃ C- methyl	12	-6	-OR ether, alkoxy	29	-38
CH ₃ CH ₂ - ethyl	11	-7	-O ₂ CR ester, O side	19	-26
CH ₃ CH ₂ CH ₂ - propyl	12	-7	-NR ₂ enamine	24	-30
(H ₃ C) ₂ CH- isopropyl	16	-10	-NO ₂ nitro	20	-1
(H ₃ C) ₃ C- t-butyl	22	-13	-SR sulfide	19	-8
-CH=CH ₂ alkenes	12	-7	-CH=O aldehyde	16	15
-CCH alkynes	-6	6	-CR=O ketone	14	5
-C ₆ H ₅ aromatic	12	-9	-C(OH)=O acid	5	10
* X-CH ₂ - allylic X	≈12	≈ -6	-C(OR)=O ester, C side	7	6
-F fluoro	25	-34	-C(NR ₂)=O amide, C side	8	6
-Cl chloro	2	-7	-C(Cl)=O acid chloride	7	14
-Br bromo	-8	-2	-CN nitrile	-16	13
-I iodo	-38	7			

*X = Cl, Br, I, OH, OR

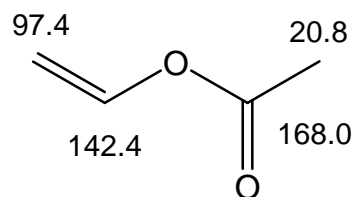
* Chemical shift values based on ChemDraw calculations.

ChemDraw values

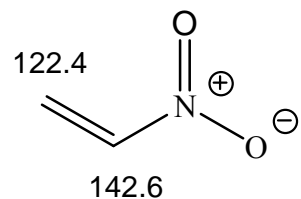
a



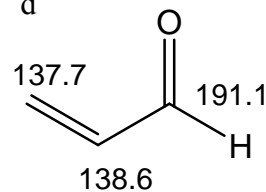
b



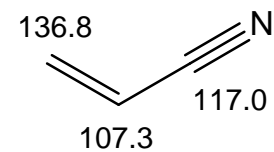
c



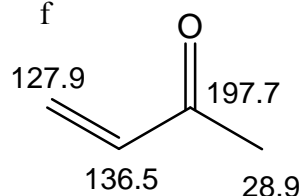
d



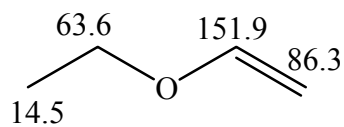
e



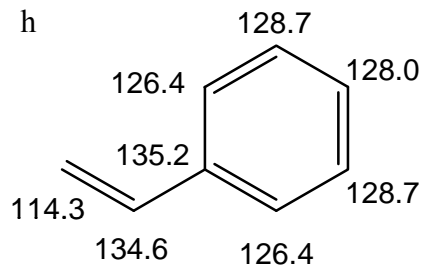
f



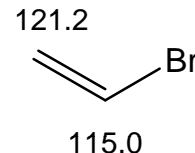
g



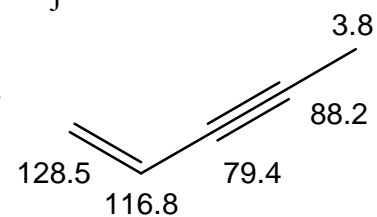
h



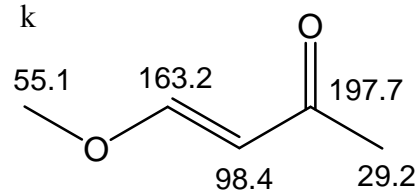
i



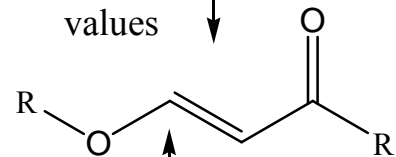
j



k

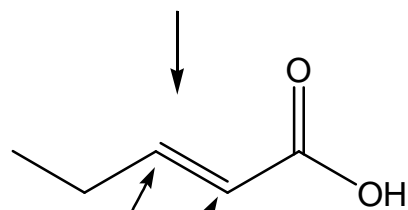
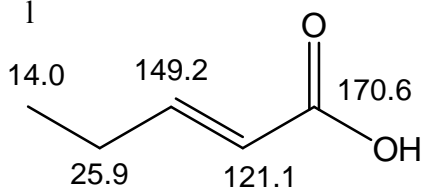


calculated values



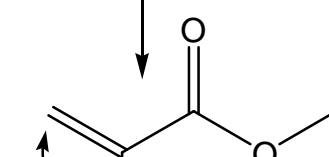
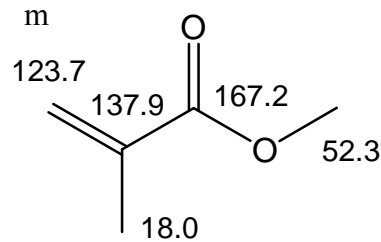
	123	123
ether =	29	-38
ketone =	5	14
total =	157	99

l



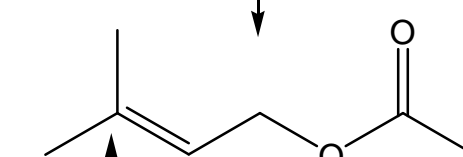
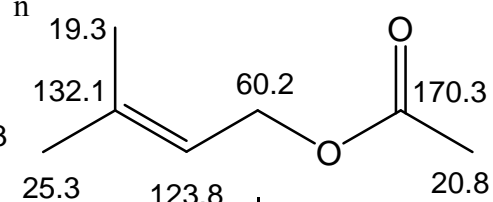
	123	123
ethyl =	11	-7
acid =	5	10
total =	139	126

m



	123	123
methyl =	-6	12
ester, C side =	6	7
total =	123	142

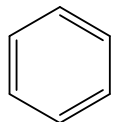
n



	123	123
methyl =	12	-6
methyl =	12	-6
allyl X =	-6	12
total =	141	123

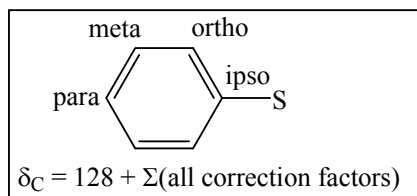
Correction factors for sp^2 aromatic shifts

aromatic starting point = benzene



$$\delta_C = 128.5$$

Substituent = S	ipso	ortho	meta	para
H ₃ C- methyl	10	1	0	-3
CH ₃ CH ₂ - ethyl	11	-1	0	-3
CH ₃ CH ₂ CH ₂ - propyl	10	0	0	-2
(H ₃ C) ₂ CH- isopropyl	20	-2	0	-3
(H ₃ C) ₃ C- t-butyl	22	-3	0	-3
-CH=CH ₂ alkenes	7	-2	0	-1
-CCH alkynes	-6	4	0	0
-C ₆ H ₅ aromatic	8	-1	1	-1
* X-CH ₂ - benzylic X	≈10	≈0	1	0
-F fluoro	39	-13	2	-4
-Cl chloro	6	0	2	-2
-Br bromo	-5	3	2	-1
-I iodo	-34	9	2	-1
-OH phenol	30	-13	2	-7
-OR ether	32	-14	1	-7
-O ₂ CR ester,oxygen side	23	-7	1	-3



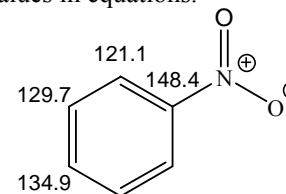
X is attached to an aromatic carbon atom (ppm)

Substituent = S	ipso	ortho	meta	para
-NR ₂ amines	16	-15	1	-10
-RNOCR amide,nitrogen side	10	-7	0	-4
-NO ₂ nitro	20	-7	1	6
-NO nitroso	40	-7	1	7
-SH thiol	2	1	1	-3
-SR sulfide	8	-2	0	-3
-SOR sulfoxide	17	-3	1	3
-SO ₂ R sulfone	10	0	1	5
-CH=O aldehyde	8	1	1	6
-CR=O ketone	8	0	0	4
-C(OH)=O acid	2	2	0	6
-C(OR)=O ester,carbon side	2	1	0	5
-C(NR ₂)=O amide,carbon side	5	-1	0	3
-C(Cl)=O acid chloride	5	3	1	7
-CN nitrile	-16	4	1	5

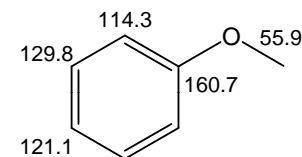
*X = Cl, Br, I, OH, OR

* Chemical shift values based on ChemDraw calculations.

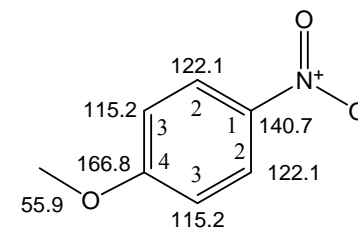
Experimental values in parentheses.
CD values by structures. Calculated
values in equations.



$$\begin{aligned}\delta_{\text{ipso}} &= 128 + 20 = 148 \text{ (148.3)} \\ \delta_{\text{ortho}} &= 128 - 7 = 121 \text{ (123.5)} \\ \delta_{\text{meta}} &= 128 + 1 = 129 \text{ (129.4)} \\ \delta_{\text{para}} &= 128 + 6 = 134 \text{ (134.7)}\end{aligned}$$

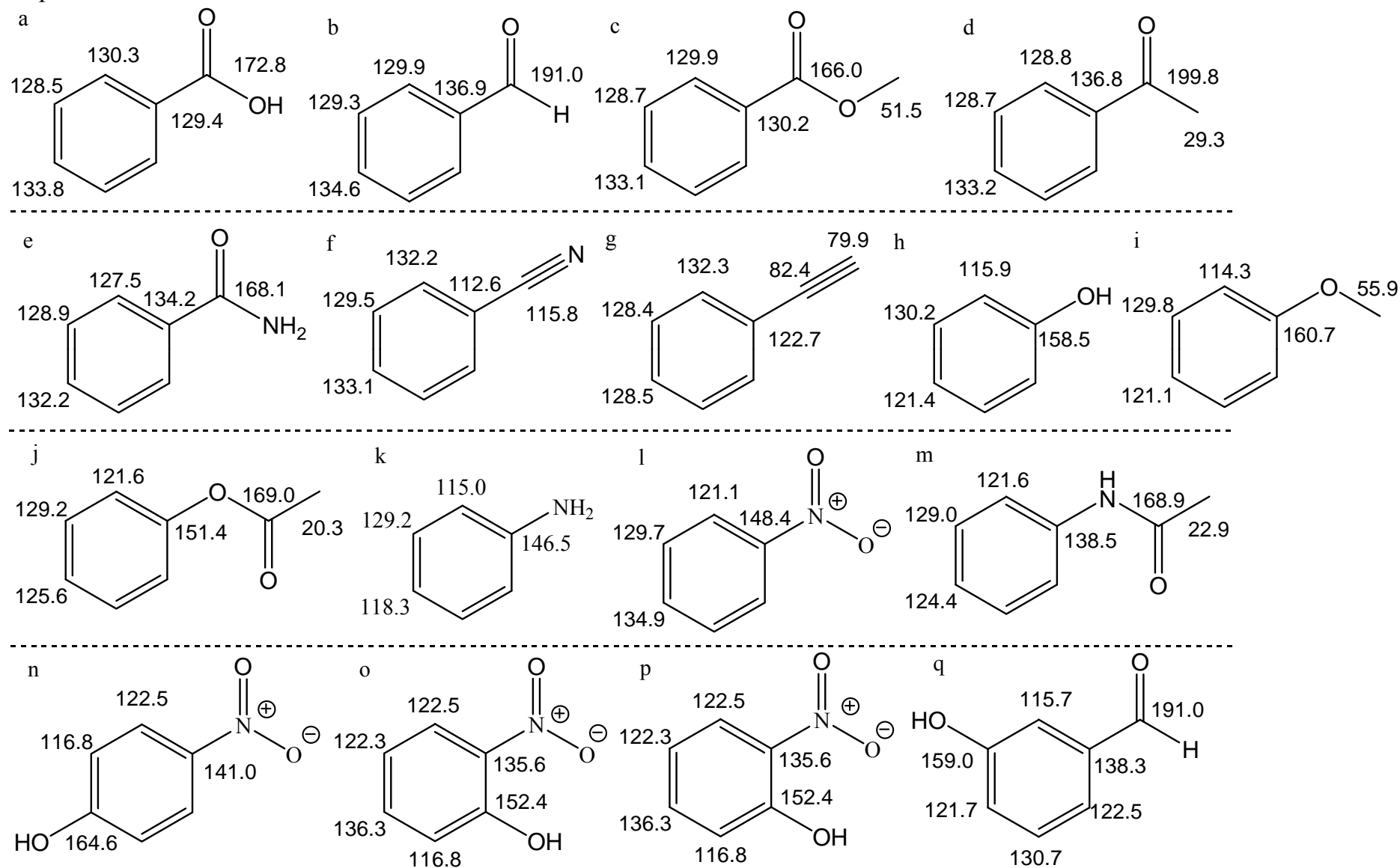


$$\begin{aligned}\delta_{\text{ipso}} &= 128 + 32 = 160 \text{ (159.7)} \\ \delta_{\text{ortho}} &= 128 - 14 = 114 \text{ (114.0)} \\ \delta_{\text{meta}} &= 128 + 1 = 129 \text{ (129.5)} \\ \delta_{\text{para}} &= 128 - 7 = 121 \text{ (120.7)}\end{aligned}$$



$$\begin{aligned}\delta_1 &= 128 + 20 - 7 = 141 \text{ (141.6)} \\ \delta_2 &= 128 - 7 + 1 = 122 \text{ (125.9)} \\ \delta_3 &= 128 + 1 - 14 = 115 \text{ (114.1)} \\ \delta_4 &= 128 + 6 + 32 = 166 \text{ (164.8)}\end{aligned}$$

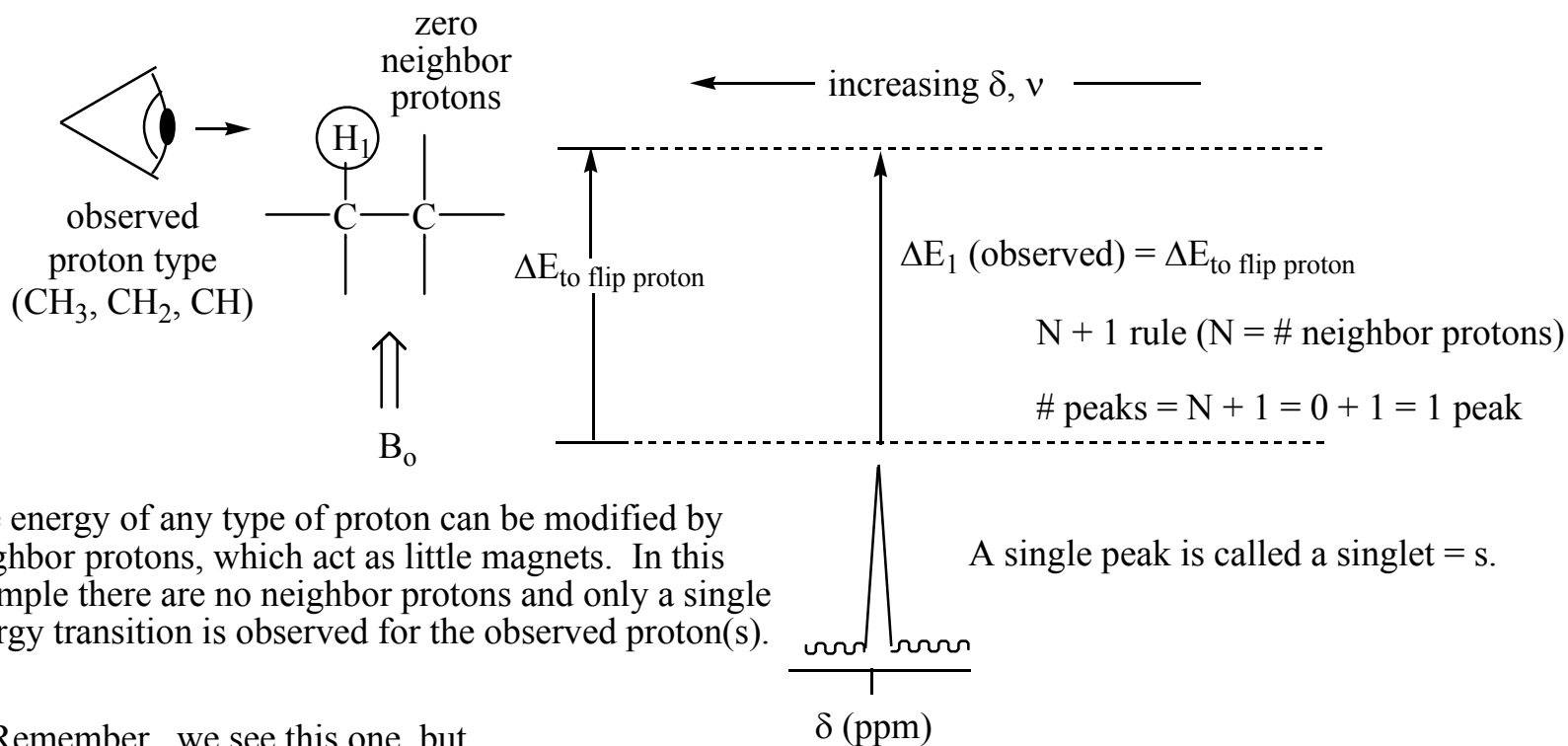
Experimental and ChemDraw values



Splitting patterns: H/H and H/C coupling

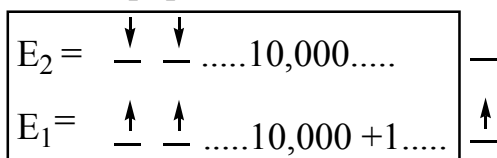
Zero neighbors

1. □ Proton(s) with zero different nearest neighbor protons do not have any perturbations of their special B_0 ($\Delta E_{\text{to flip}}$) due to their surrounding environment. Equivalent chemical shift protons (homotopic and enantiotopic) appear all together as a single peak. A special-case rule, where all the coupling constants are equal (usually $^3J_{\text{vicinal}} = 7\text{Hz}$) is called the N+1 rule, where N is the number of neighbor protons and N+1 is the number of peaks observed. With zero different neighbor protons, the N+1 rule correctly predicts there will be one peak.

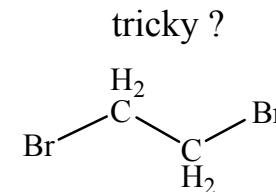
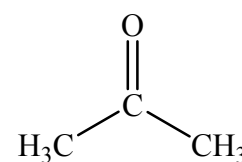
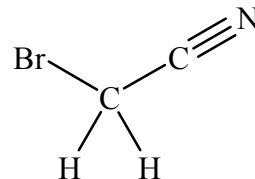
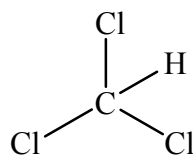


The energy of any type of proton can be modified by neighbor protons, which act as little magnets. In this example there are no neighbor protons and only a single energy transition is observed for the observed proton(s).

Remember., we see this one, but $\approx 50/50$ population distribution.

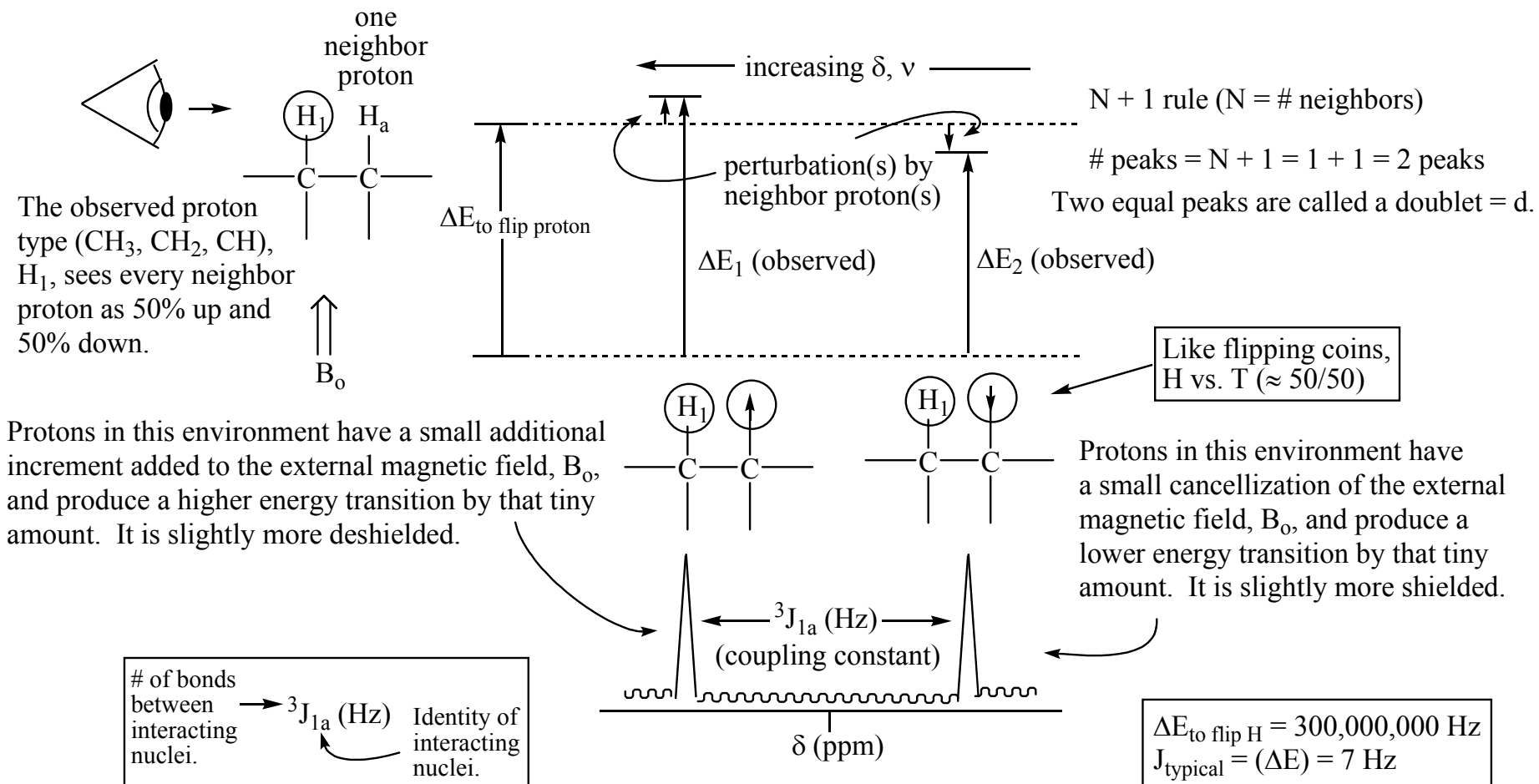


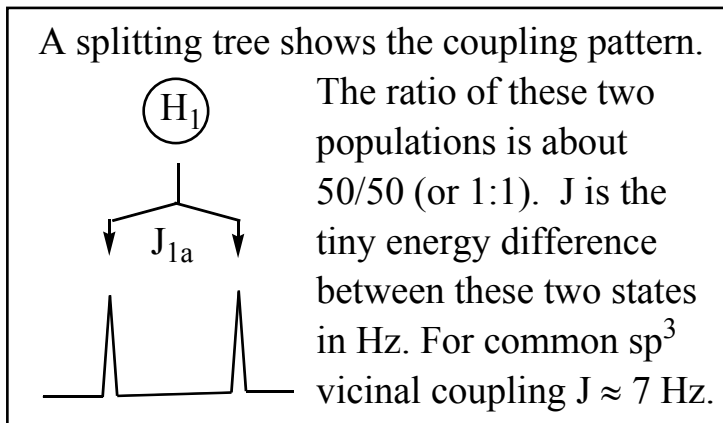
Some proton examples with zero proton neighbors:



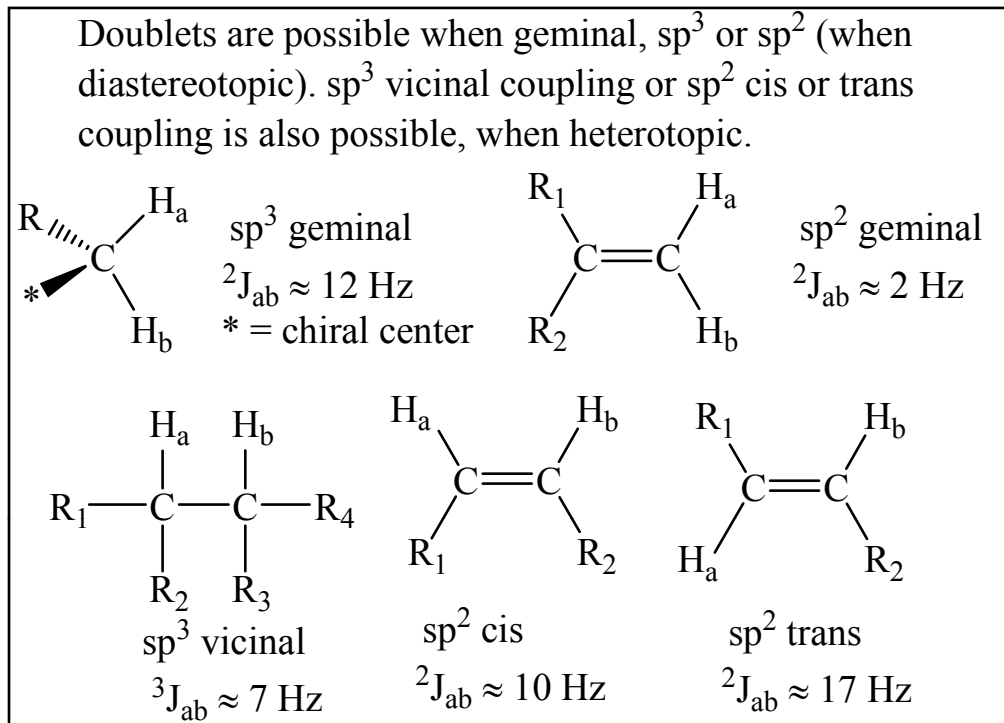
One Neighbor -

Proton(s) with one nearest neighbor proton are split into two equal populations (like flipping a coin, heads or tails). This can be vicinal ($^3J=7$ Hz) or geminal, when different ($^2J=12$ Hz). With one neighbor the N+1 rule correctly predicts there will be two equal area peaks separated by distance in Hz, called a J value or coupling constant.

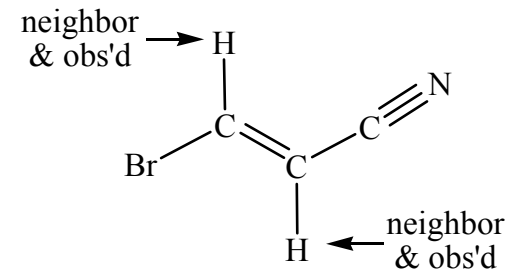
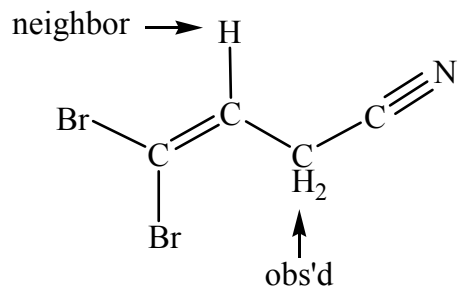
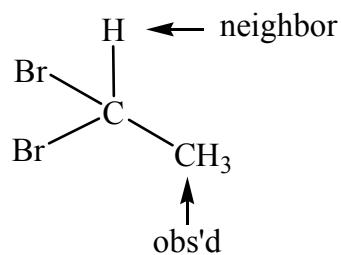
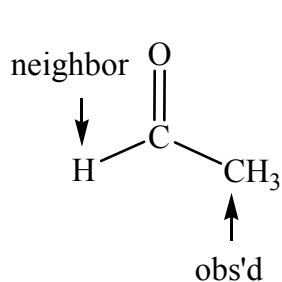




J values do not change when moving from instrument to instrument. The $\Delta\delta$ values in a multiplet only depend on the neighbor atom, as a very small magnet. Because J values are the same on all instruments (and very small) they are always reported in units of Hz.

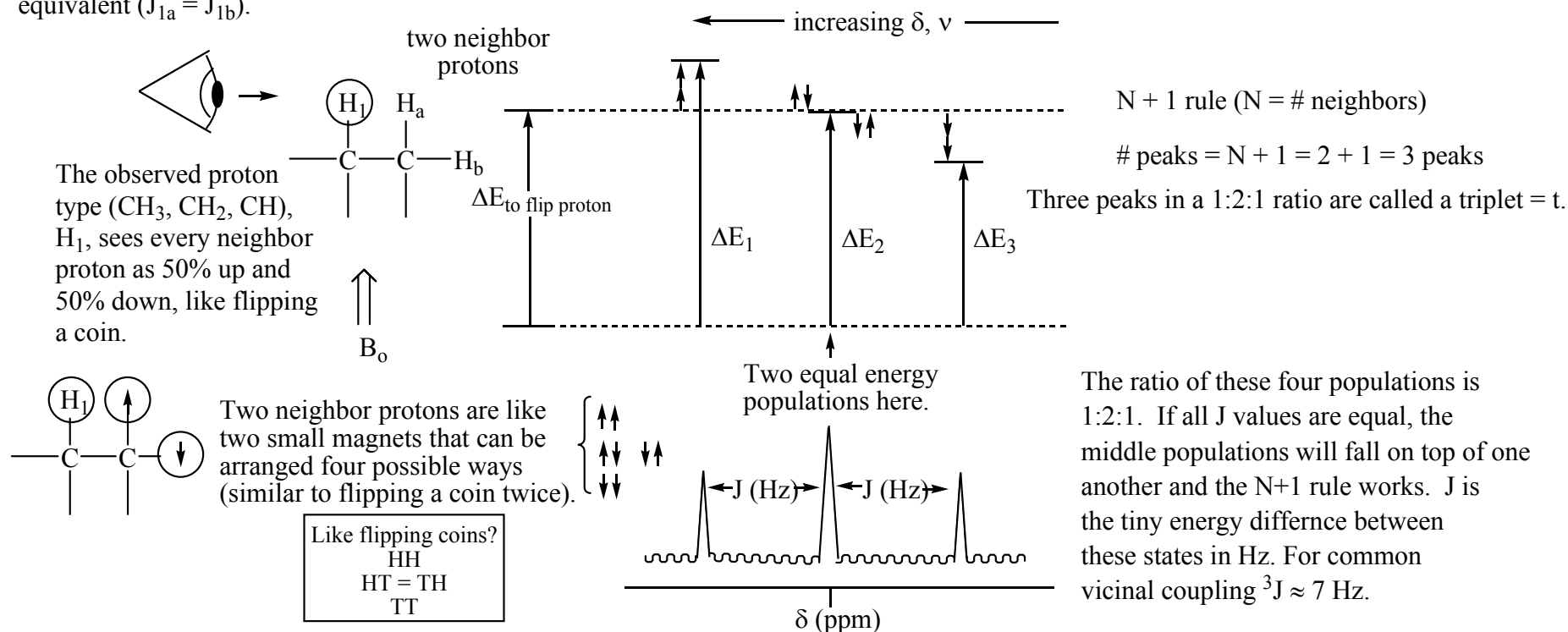


Some examples with one proton neighbor:

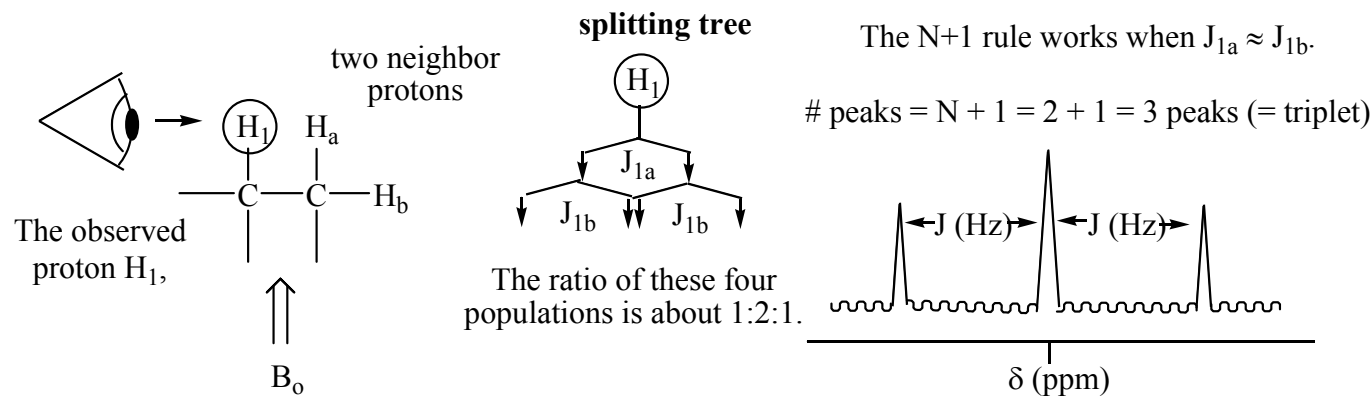


Two Neighbors Example

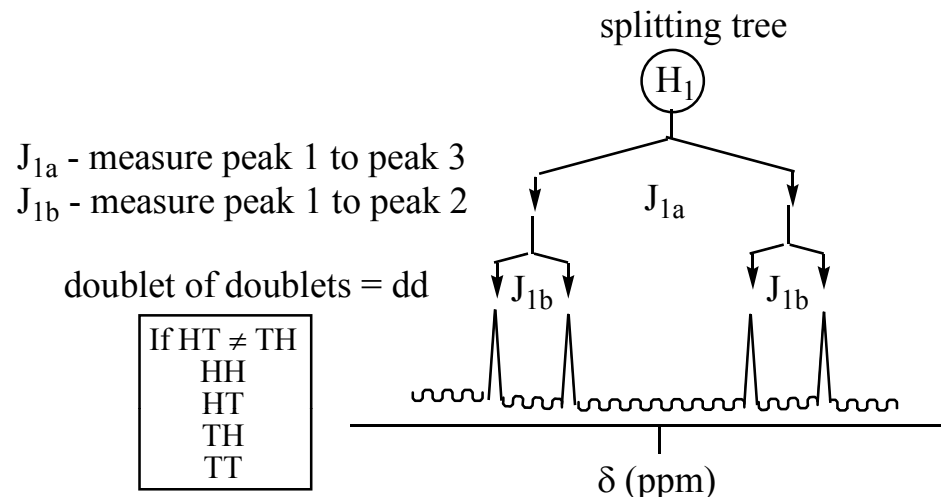
Protons with two nearest neighbor protons split into four populations (like two coin flips). The N+1 rule works when J values are equivalent ($J_{1a} = J_{1b}$).



Two nearest neighbor protons really produces a doublet of doublets = dd. (when $J_{1a} = J_{1b}$ we call this a triplet = t)



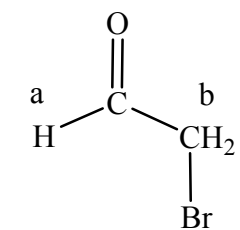
When the coupling constants are different ($J_{1a} \neq J_{1b}$), all four peaks will be observed as two sets of doublets called a doublet of doublets (dd), which are approximately equivalent in size.



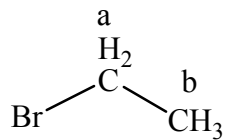
When the J values are not equal all four peaks are observed. The ratio of these four populations is 1:1:1:1. Draw splitting trees with the largest coupling at the top and the smallest coupling at the bottom. That way the lines don't overlap.

$$J_{1a} > J_{1b}$$

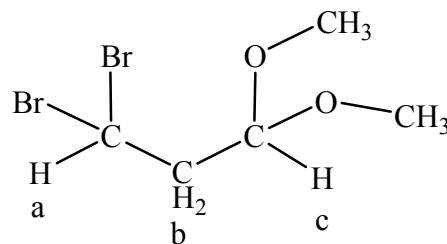
Some examples with two proton neighbors:



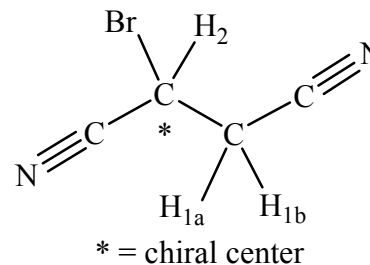
N+1 rule works
 $^3J_{ab} \approx 2 \text{ Hz}$



N+1 rule works
 $^3J_{ab} \approx 7 \text{ Hz}$

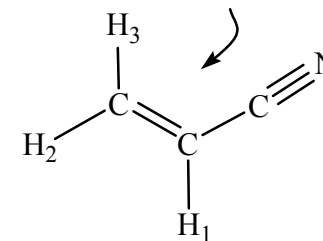


N+1 rule works
 $^3J_{ab} \approx ^3J_{bc} \approx 7 \text{ Hz}$
 $^3J_{ac} \approx 0 \text{ Hz}$
 (all are triplets)



N+1 rule does not work
 assumed
 $^2J_{1a,1b} \approx 12 \text{ Hz}$
 $^3J_{1a,2} \approx ^3J_{1b,2} \approx 7 \text{ Hz}$

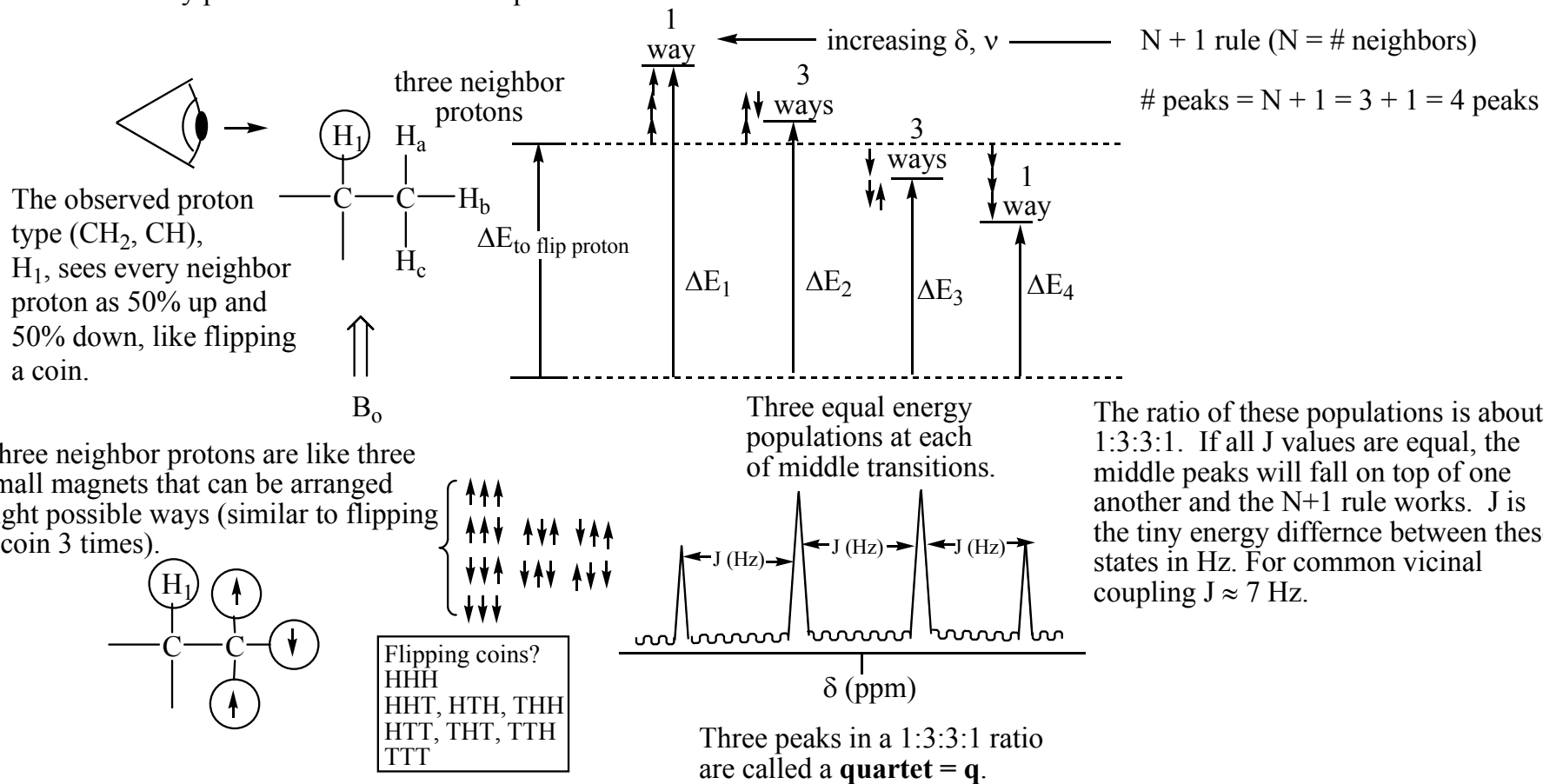
H_1 , H_2 and H_3 all have two different H neighbors.



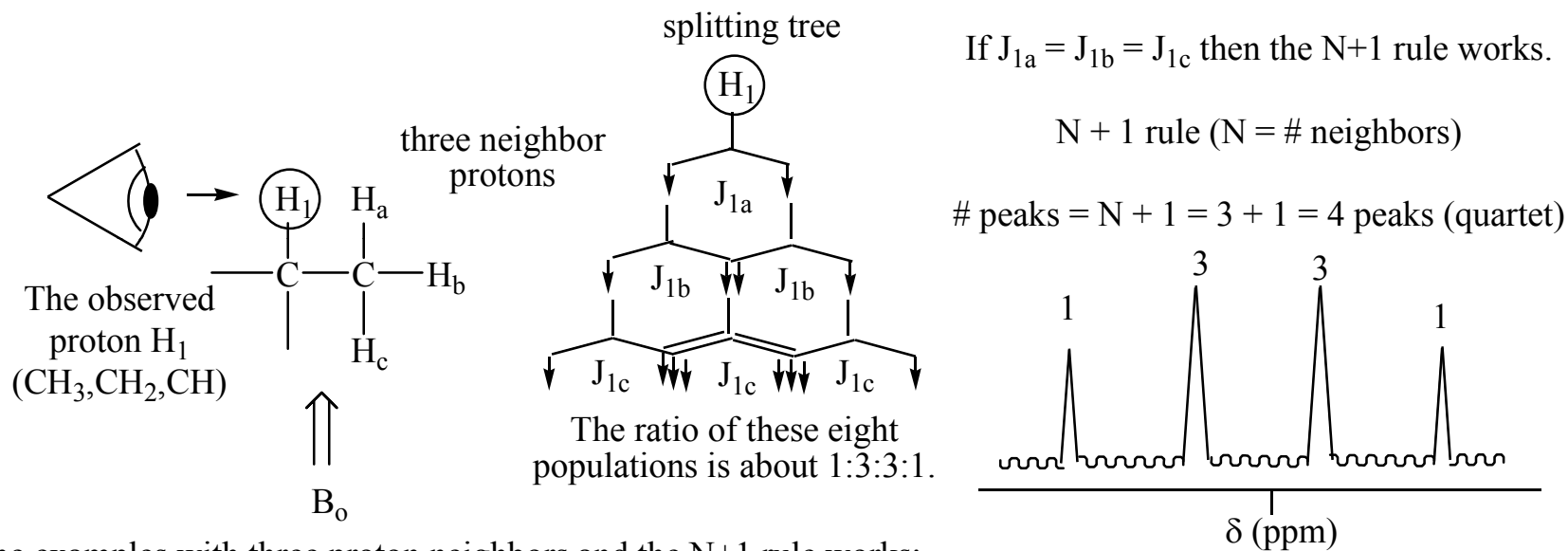
N+1 rule does not work
 $^3J_{1,2} \approx 10 \text{ Hz (cis)}$
 $^3J_{1,3} \approx 17 \text{ Hz (trans)}$
 $^2J_{2,3} \approx 2 \text{ Hz (geminal)}$

Three Neighbors

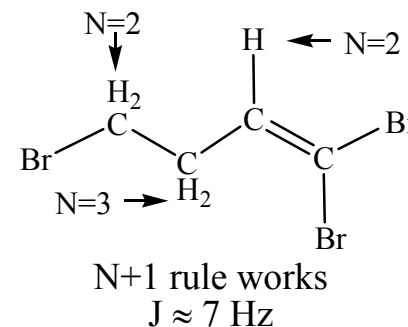
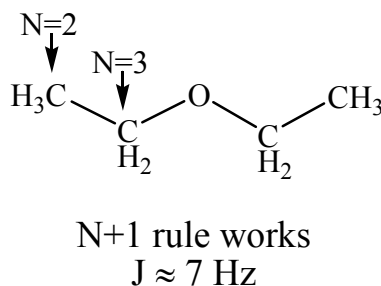
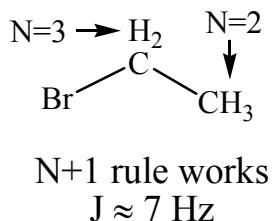
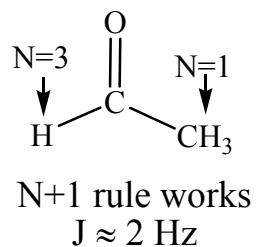
Protons with three nearest neighbor protons split into eight populations (like three coin flips). Neighbor protons can be on the same carbon, or two on one carbon and one on another carbon, or one each on three separate carbons. With three similar neighbors the N+1 rule correctly predicts there will be four peaks in a 1:3:3:1 ratio.



Three nearest neighbor protons to H_{observed} (H_1) really produce a doublet of doublet of doublets = ddd. Proton H_1 is split into two populations because of neighbor H_a and each of those populations is further split into two populations because of H_b and each of those populations is further split into two populations because of H_c ($2 \times 2 \times 2 = 8$ populations). The eight peaks look like four because the coupling constants are the same and the middle peaks continue to fall on top of one another. If it were not for the coincidence of identical coupling constants, we would be able to see all eight peaks (populations).

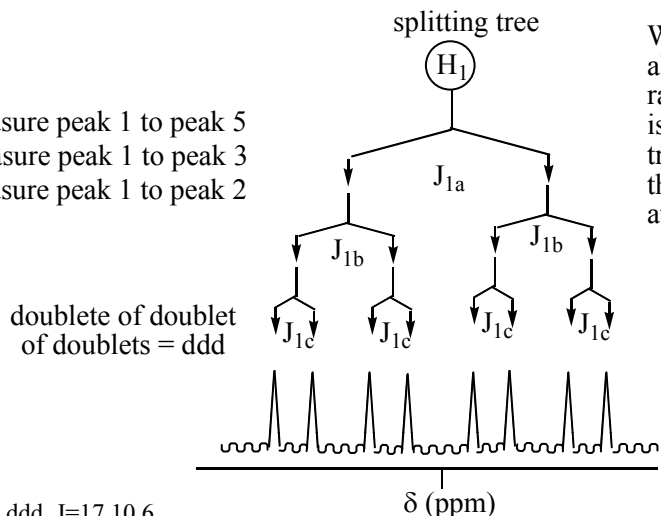


Some examples with three proton neighbors and the N+1 rule works:

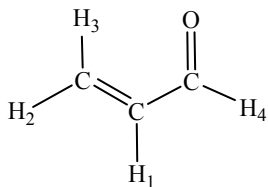


The splitting tree below shows what can happen when all of the coupling constants are different, called a doublet of doublets of doublets (ddd). Each peak will be approximately the same size (1/8 of the total area). The splitting tree is drawn using the largest coupling constant first and then the smaller coupling constant(s) so the lines don't overlap.

J_{1a} - measure peak 1 to peak 5
 J_{1b} - measure peak 1 to peak 3
 J_{1c} - measure peak 1 to peak 2

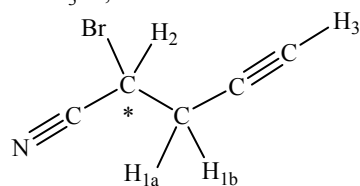


$H_1 = \text{ddd}, J=17,10,6$
 $H_2 = \text{dd}, J=10,2$
 $H_3 = \text{dd}, J=17,2$
 $H_4 = \text{d}, J=6$



N+1 rule does not work
 ${}^3J_{1,2} \approx 10$ Hz (cis)
 ${}^3J_{1,3} \approx 17$ Hz (trans)
 ${}^2J_{2,3} \approx 2$ Hz (geminal)
 ${}^3J_{1,4} \approx 6$ Hz

$H_{1a} = H_{1b} = \text{ddd}, J=12,7,2$
 $H_2 = \text{t}, J=7$
 $H_3 = \text{t}, J=2$



* = chiral center assumed

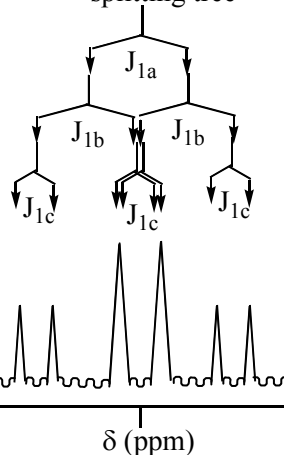
${}^2J_{1a,1b} \approx 12$ Hz
 ${}^3J_{1a,2} \approx {}^3J_{1b,2} \approx 7$ Hz
 ${}^4J_{1a,3} \approx J_{1b,3} \approx 2$ Hz

When the J values are not equal all eight peaks are observed. The ratio of these eight populations is 1:1:1:1:1:1:1:1. Draw splitting trees with the largest coupling at the top and the smallest coupling at the bottom.

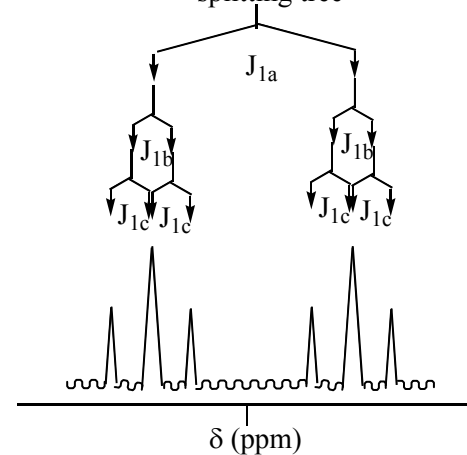
$$J_{1a} > J_{1b} > J_{1c}$$

Two additional variations of 8 peaks when two of the J values are equal to each other, but not equal to the third J value.

triplet of doublets = td
 $J_{1a} = J_{1b} > J_{1c}$
 splitting tree



doublet of triplets = dt
 $J_{1a} > J_{1b} = J_{1c}$
 splitting tree

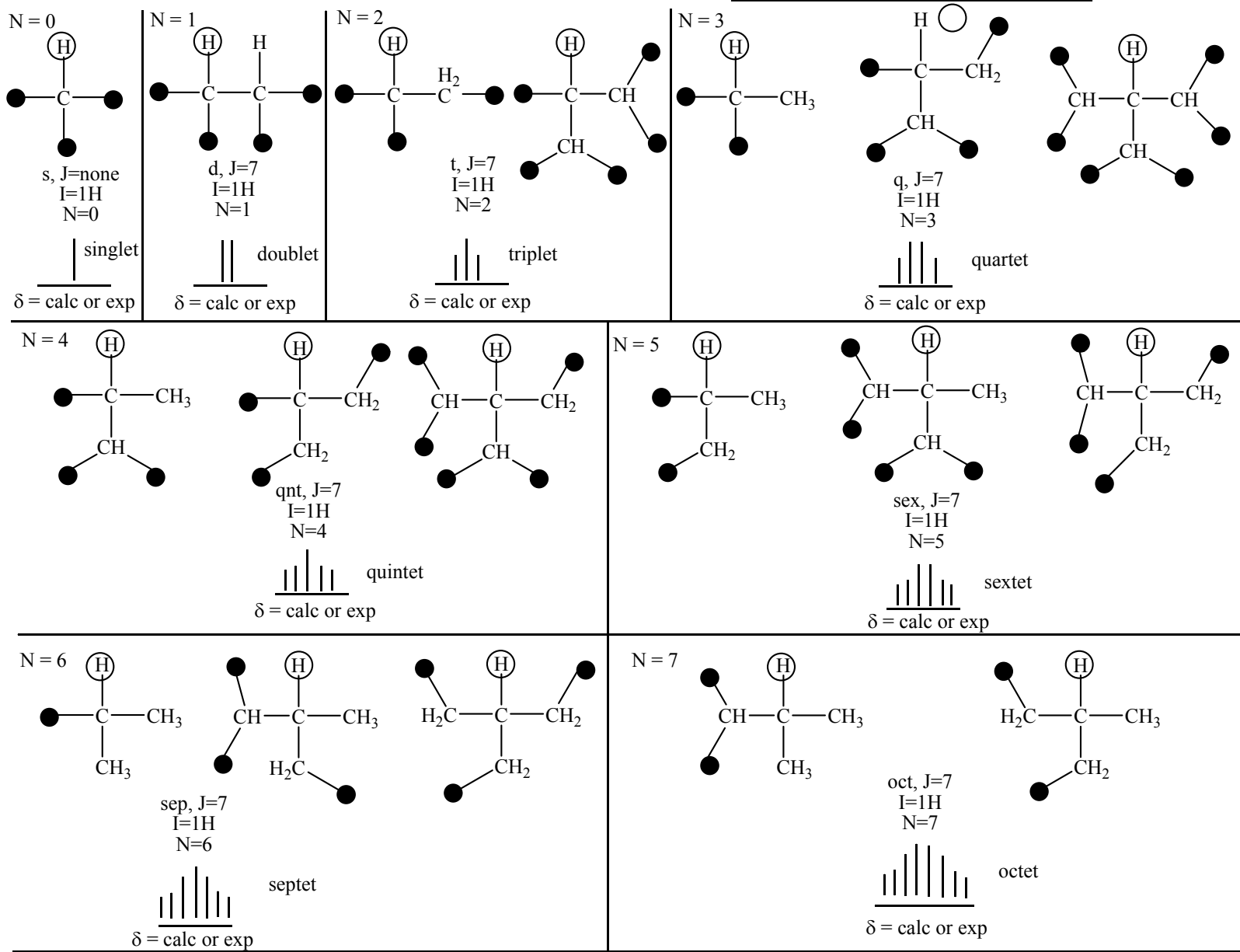


Examples where the N+1 rule works. (These are all the possibilities I can think of using typical vicinal coupling, $J=7$ Hz.)

● = group without any coupled proton(s)

⊕ = observed proton

I = integration (number of protons)
N = number of nearest neighbors



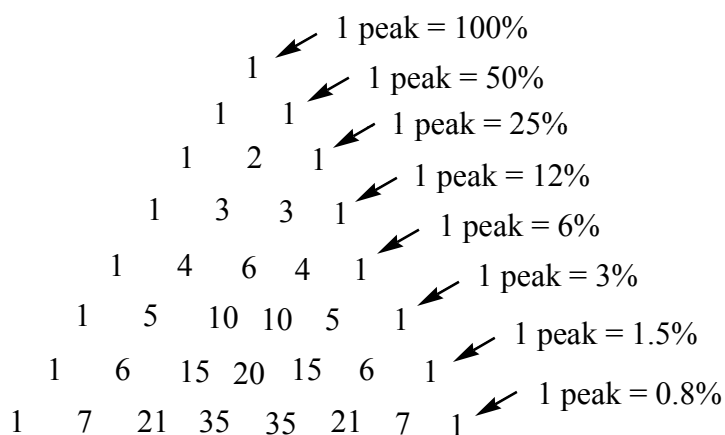
Pascal's triangle = coefficients of variable terms in binomial expansion $(x + y)^n$,
 $n = \text{integer}$

$$\begin{aligned} (x + y)^n, n = \text{integer} \\ (x + y)^0 &= 1 \\ (x + y)^1 &= 1x + 1y \\ (x + y)^2 &= 1x^2 + 2xy + 1y^2 \\ (x + y)^3 &= 1x^3 + 3x^2y + 3xy^2 + 1y^3 \\ \text{etc.} \end{aligned}$$

The coefficients of the polynomials appear in Pascal's triangle.

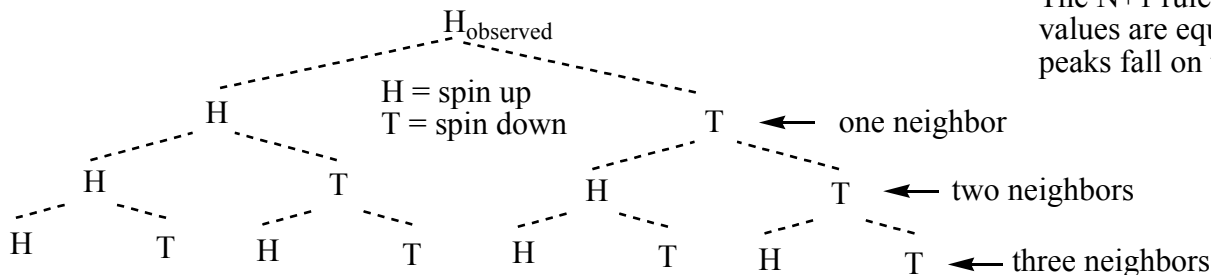
Multiplets when the N + 1 rule works (all J values are equal).

s = singlet
 d = doublet
 t = triplet
 q = quartet
 qnt = quintet
 sex = sextet
 sep = septet
 oct = octet



Relative sizes of the peaks in multiplets (% edge peak shown). As the multiplets get larger, it gets harder to see the edge peaks so you have to be careful interpreting large multiplets.

The N+1 rule works when the J values are equal and the middle peaks fall on top of one another.

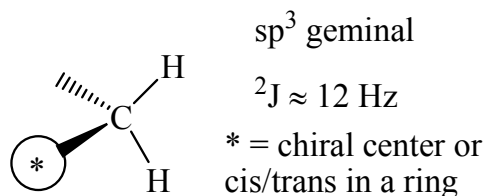


Protons spinning up and down is like flipping coins (H/T).

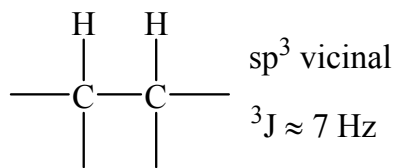
Combinations of these are possible.

dd = doublet of doublets; ddd = doublet of doublet of doublets;
 dddd = doublet of doublet of doublet of doublets;
 dt = doublet of triplets, td = triplet of doublets; etc.

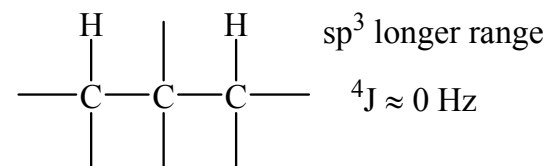
Examples where the N+1 rule works and where it does not work. Coupling constants have a range of values, however these are the only values used in our problems.



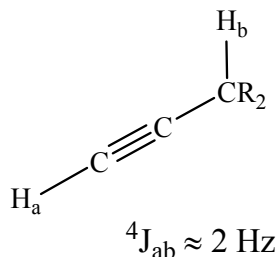
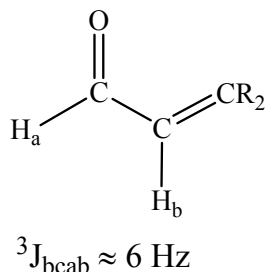
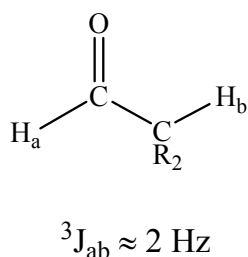
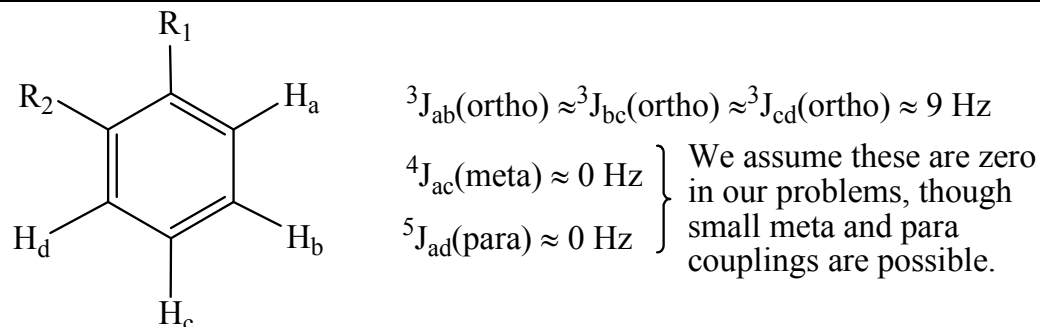
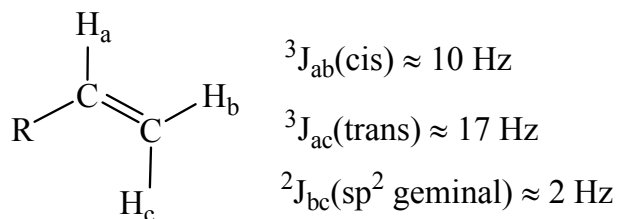
Geminal sp^3 protons, (twins), are on the same carbon, and 2J values can range from 0 Hz when equivalent to quite large, near 20 Hz, when diastereotopic. When present, we will use ${}^2J = J_{\text{gem}} = 12 \text{ Hz}$ as our typical value.



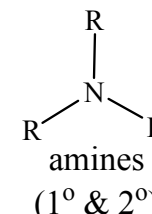
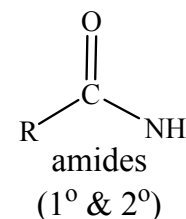
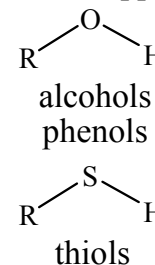
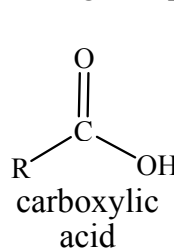
Vicinal protons (neighbors, Latin) are on adjacent carbons and 3J values for freely rotating neighbors are typically around 7 Hz. In more rigid systems 3J values can range from 0 Hz to over 12 Hz. We will use ${}^3J = J_{\text{vicinal}} = 7$ as our typical value.



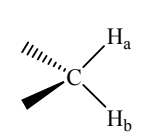
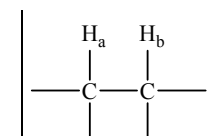
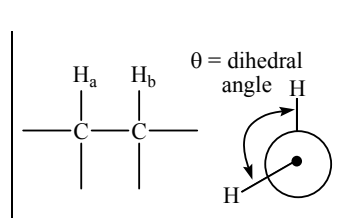
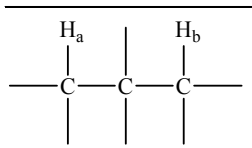
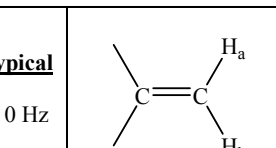
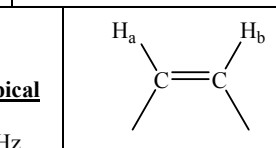
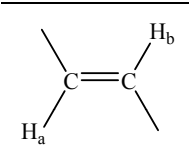
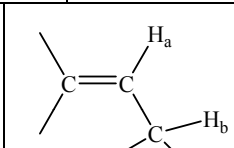
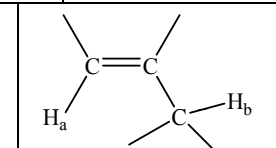
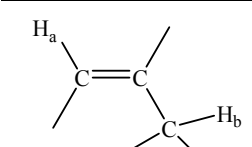
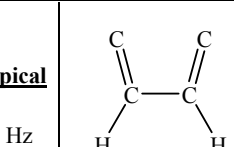
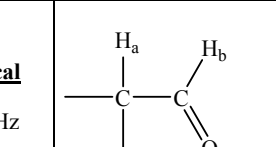
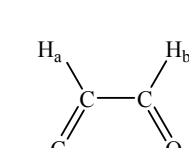
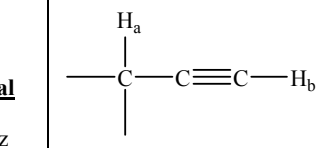
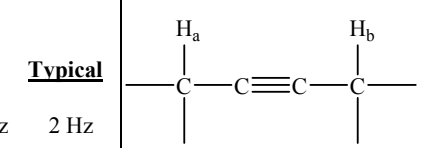
We can usually ignore 4 bond coupling (and higher) because any coupling is so small we can't see it. However, when special conformations are rigidly held (e.g. W coupling) there may be small J values of 1-2 Hz (very rarely can be as high as 7 Hz).



OH, NH and SH usually exchange too fast to couple to neighbor protons and appear as broad singlets.

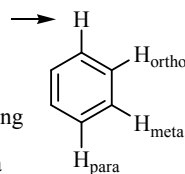


Consult the following table (p.67) for typical coupling constants (J values).

 <p>Range Typical 0-30 Hz 12 Hz</p> <p>Geminal protons can have different chemical shifts and split one another if they are diastereotopic.</p>	 <p>Range Typical 6-8 Hz 7 Hz</p> <p>Vicinal protons are on adjacent atoms, when freely rotating coupling averages out to about 7 Hz.</p>	 <p>Range Typical 0-12 Hz 7 Hz</p> <p>vicinal coupling depends on dihedral angle, see plot of Karplus equation, p 41</p>
 <p>Range Typical 0-7 Hz 0 Hz</p> <p>Protons rarely couple through 4 chemical bonds unless in a special, rigid shape (i.e. W coupling)</p>	 <p>Range Typical 0-3 Hz 2 Hz</p> <p>sp² geminal coupling</p>	 <p>Range Typical 5-11 Hz 10 Hz</p> <p>sp² cis (acyclic) coupling (always less than the trans isomer)</p>
 <p>Range Typical 11-19 Hz 17 Hz</p> <p>sp² trans coupling (always larger than the cis alkene)</p>	 <p>Range Typical 4-10 Hz 7 Hz</p> <p>sp² / sp³ vicinal coupling</p>	 <p>Range Typical 0-3 Hz 1 Hz</p> <p>cis / allylic coupling, notice through 4 bonds (not used in our simulated spectra)</p>
 <p>Range Typical 0-3 Hz 1 Hz</p> <p>trans / allylic coupling, notice through 4 bonds(not used in our simulated spectra)</p>	 <p>Range Typical 9-13 Hz 10 Hz</p> <p>sp² vicinal coupling (differen pi bonds)</p>	 <p>Range Typical 1-3 Hz 2 Hz</p> <p>sp³ vicinal aldehyde coupling</p>
 <p>Range Typical 5-8 Hz 6 Hz</p> <p>sp³ vicinal aldehyde coupling</p>	 <p>Range Typical 2-3 Hz 2 Hz</p> <p>sp / propargylic coupling, notice through 4 bonds</p>	 <p>Range Typical 2-3 Hz 3 Hz</p> <p>bis-propargylic coupling, notice through 5 bonds(not used in our simulated spectra)</p>

ortho,meta and para coupling to this proton,

only ortho coupling is used in our simulated spectra

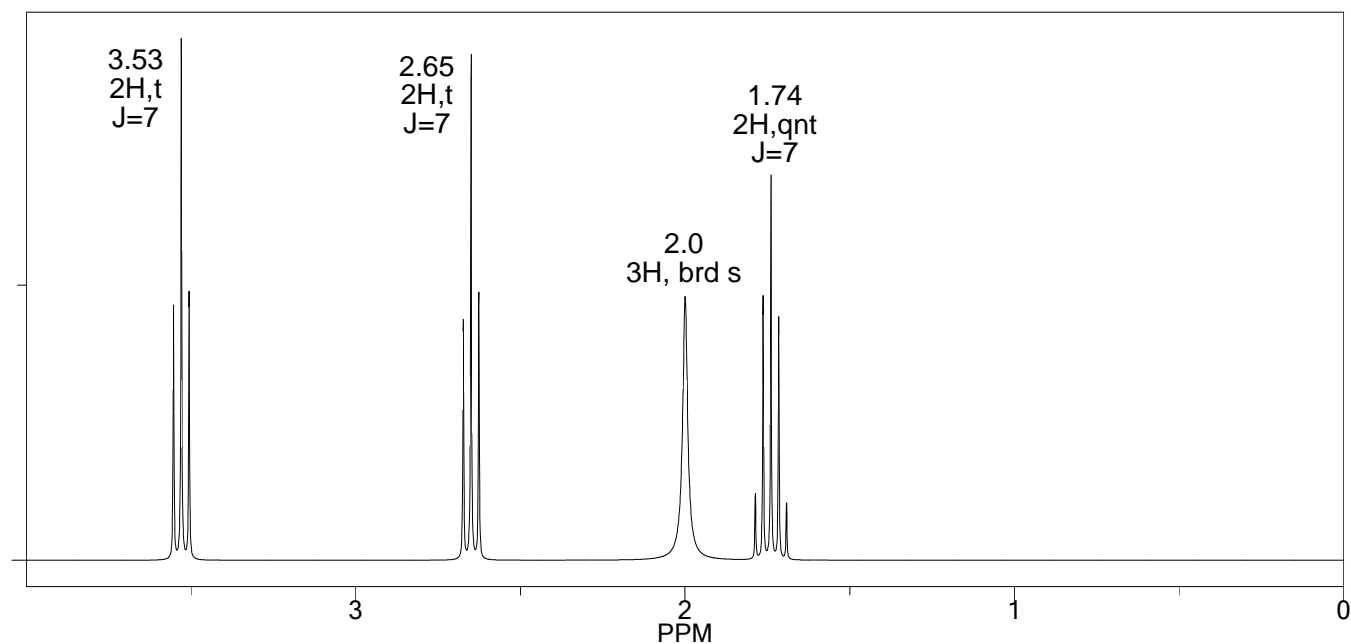
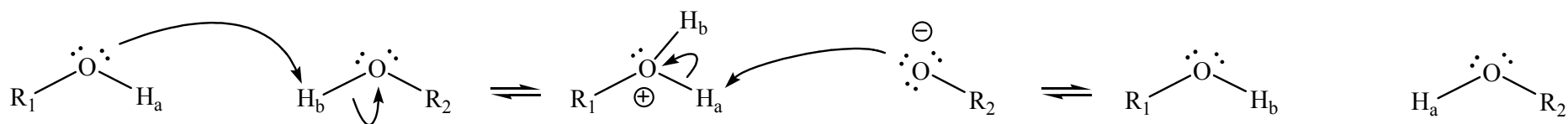


Range **Typical**

ortho 6-10 Hz 9 Hz
meta 2-3 Hz 2 Hz
para 0-1 Hz 0 Hz

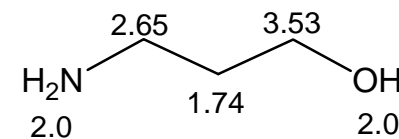
When J values are less than 1 Hz it is often difficult to resolve the peaks and a peak may merely appear wider and shorter.

Exchangeable protons appear as broad singlets (OH, NH and SH). H_a and H_b , below, see both R_1 and R_2 faster than the NMR sees each proton. R_1 and R_2 do not have time to couple with the exchangeable protons, so the signal is a blur of up and down spins, which appears as a broad singlet.



Exact Mass: 75.07

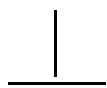
$M^+ = 75.07$ (100.0%),
 $M+1 = 76.07$ (3.8%)



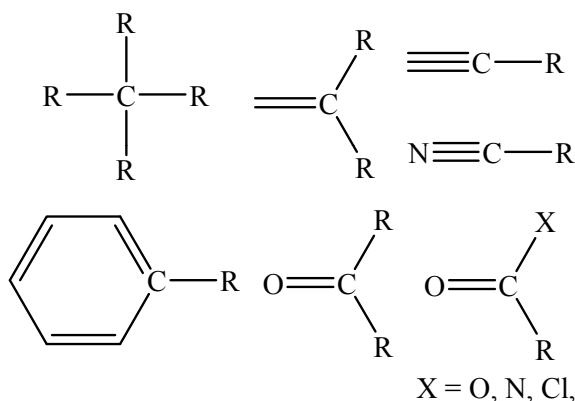
The N+1 rule works for C-H bonds when fully or partially coupled, but there is a more modern way to see the same information (called DEPT = distortionless enhancement by polarization transfer).

0 proton neighbors
carbon peak = singlet
(quaternary carbons)

singlet = s



No J_{CH} coupling

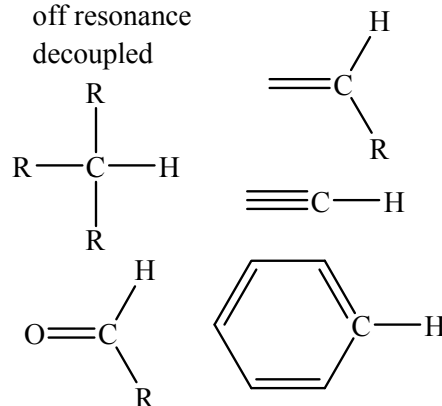


1 proton neighbor
carbon peak = doublet
(methine carbons)

doublet = d



$^1J_{CH} \approx$ small when
off resonance
decoupled

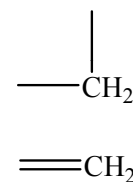


2 proton neighbors
carbon peak = triplet
(methylene carbons)

triplet = t



$^1J_{CH} \approx$ small when
off resonance
decoupled

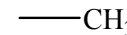


3 proton neighbors
carbon peak = quartet
(methyl carbons)

quartet = q

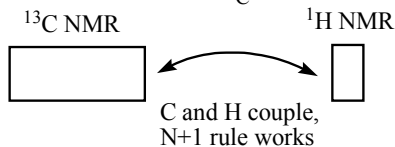
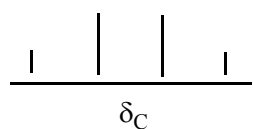


$^1J_{CH} \approx$ small when
off resonance
decoupled

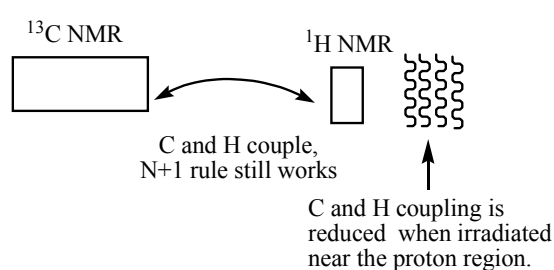
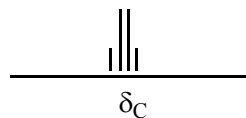


-CH₃ example

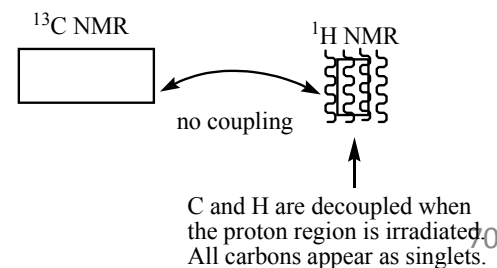
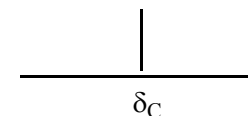
$^1J_{CH}$ (full) \approx 140 Hz



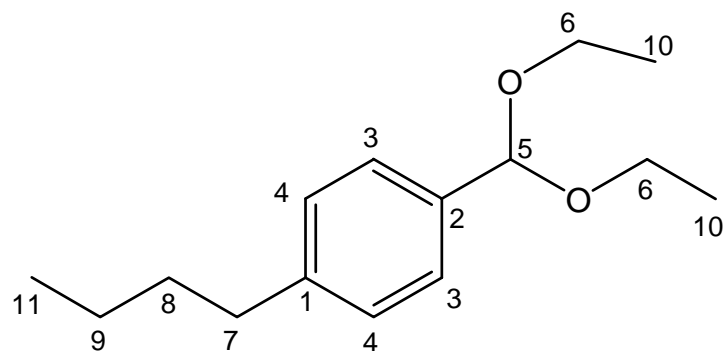
$^1J_{CH}$ (off resonance) \approx 10 Hz



$^1J_{CH}$ (decoupled) \approx 0 Hz



DEPT = distortionless enhancement by polarization transfer (all protonated Cs appear as single peaks)

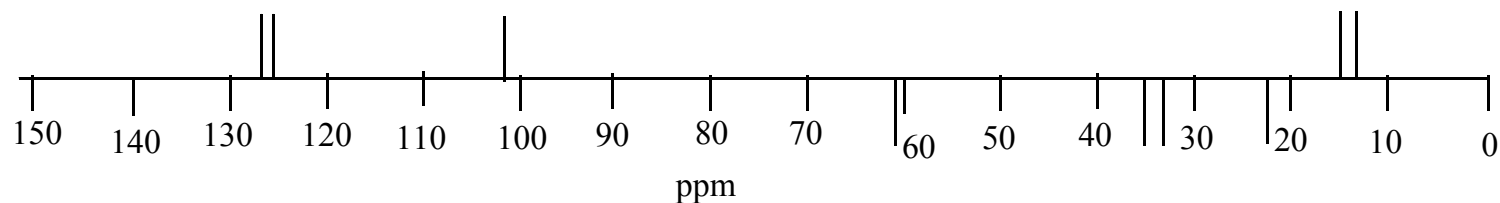


p-butylbenzaldehyde diethyl acetal

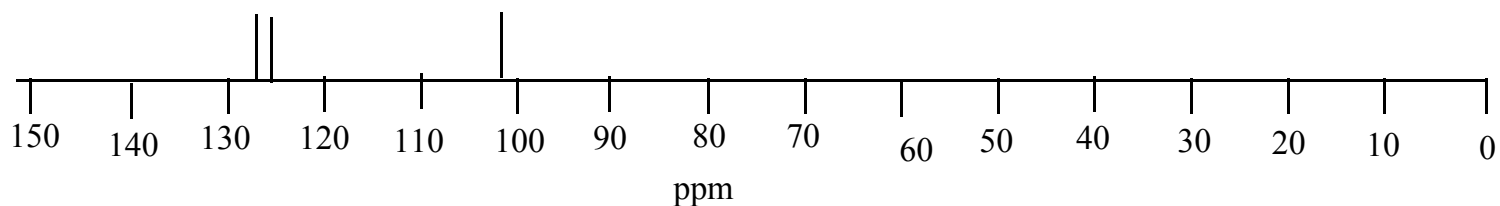
off
resonance
data

143.0, s
136.4, s
128.2, d
126.5, d
101.7, d
61.0, t
35.4, t
33.6, t
22.3, t
15.2, q
13.9, q

DEPT-135 shows CH and CH₃ carbon atoms up and CH₂ carbon atoms down.



DEPT-90 shows CH carbon atoms up .

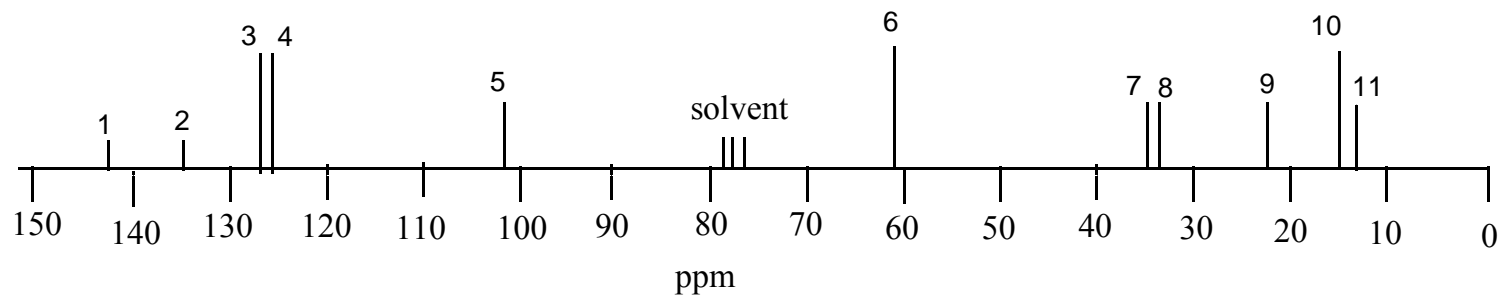


C₁₅H₂₄O₂

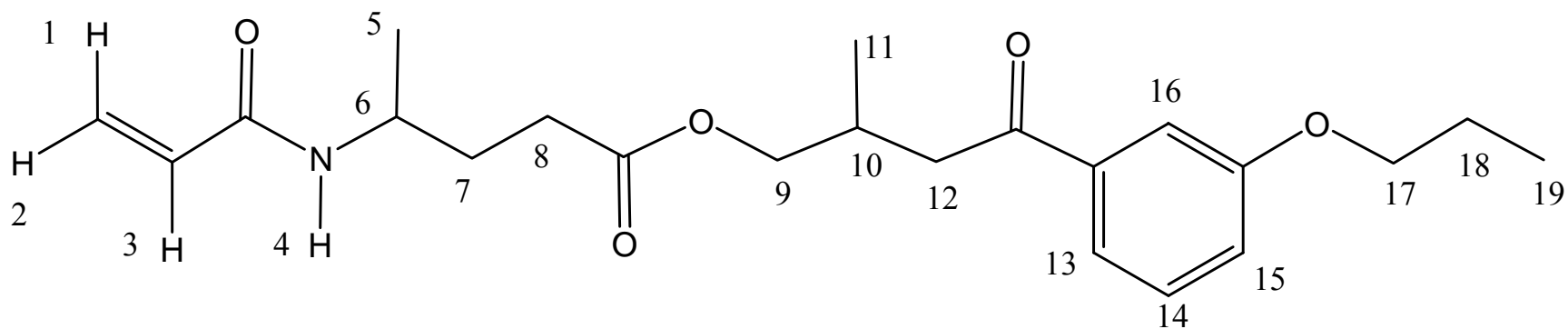
ppm

1 = 143.0
2 = 136.4
3 = 128.2
4 = 126.5
5 = 101.7
6 = 61.0
7 = 35.4
8 = 33.6
9 = 22.3
10 = 15.2
11 = 13.9

¹³C NMR shows a peak for each type of carbon. (4° carbon peaks tend to be smaller.)

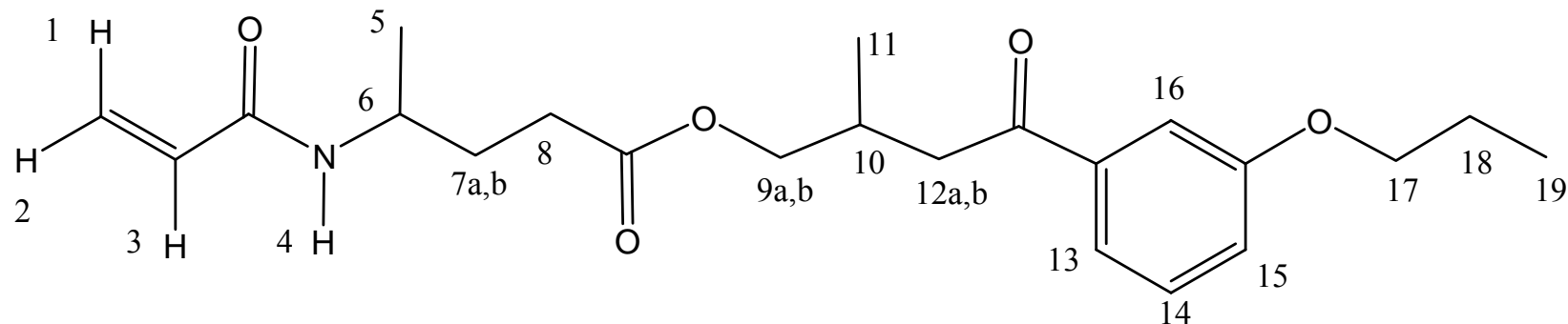


Predict a proton NMR (chemical shifts, integrations and multiplicities).

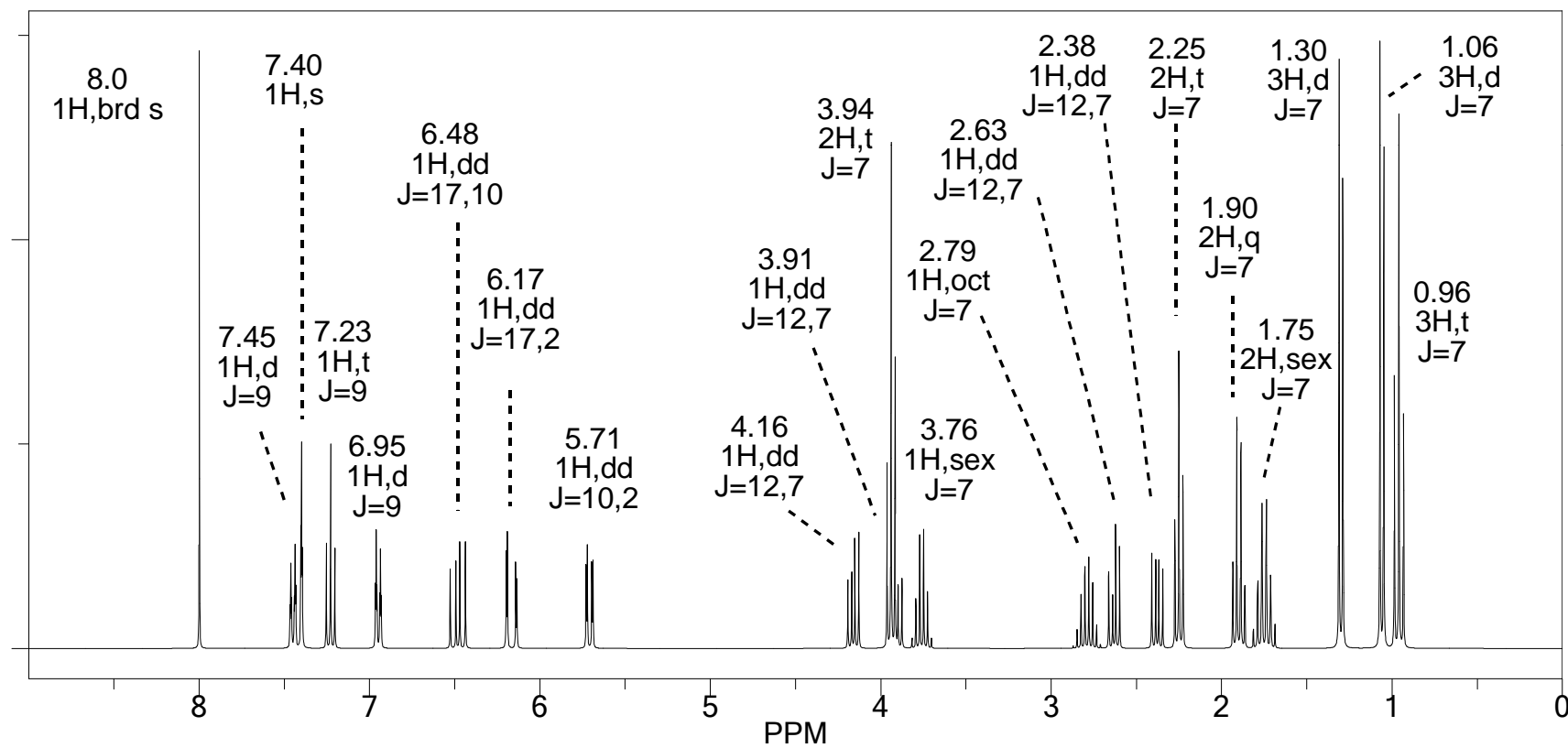
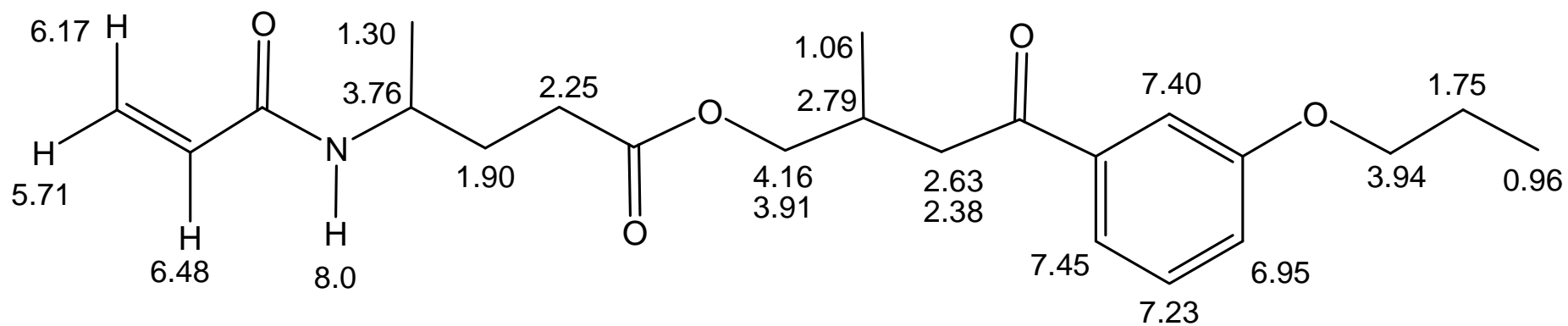


1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	14	16	17	18	19	

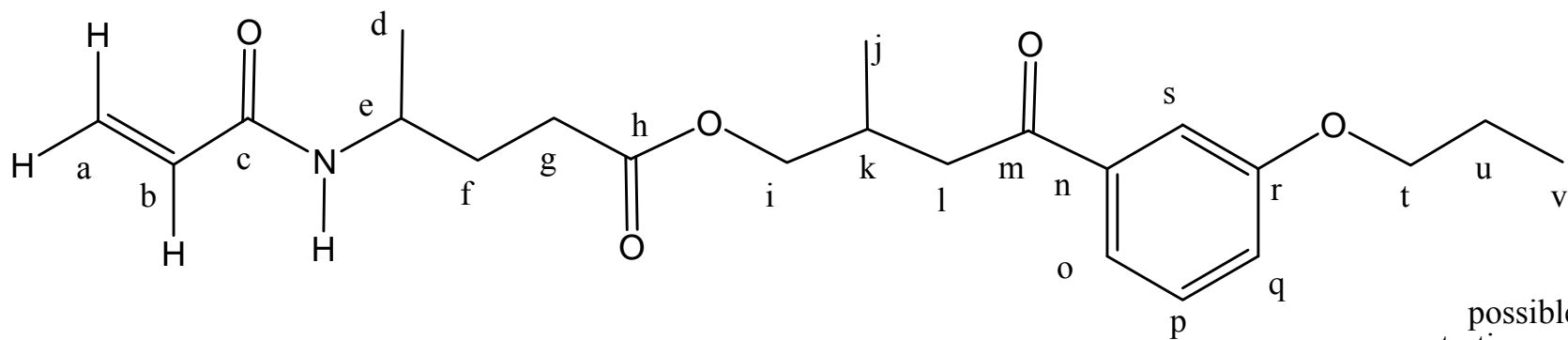
Predict a proton NMR (chemical shifts, integrations and multiplicities).



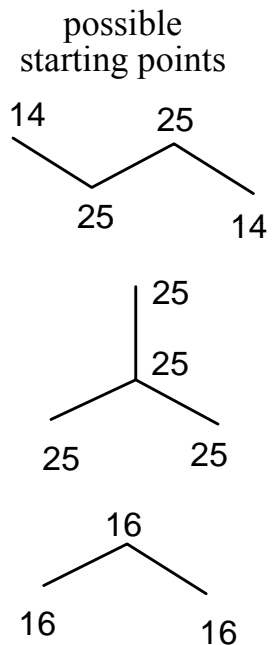
1 1H,dd J=17,2 <u> </u> 5.2 1.0 <u>6.2</u>	2 1H,dd J=10,2 <u> </u> 5.2 0.5 <u>5.7</u>	3 1H,dd J=17,10 <u> </u> 5.2 1.3 <u>6.5</u>	4 1H brd s <u>^</u> $\delta \approx 5-8$	5 3H,d J=7 <u> </u> 0.9 0.4 <u>1.3</u>	6 1H,sex J=7 <u> </u> 1.5 2.0 0.1 <u>3.6</u>	7a 1H,dq J=12,7 <u> </u> 1.2 0.4 0.5 <u>2.1</u>	$C_{22}H_{31}NO_5$ Exact Mass: 389.22 M+ = 389.22 (100.0%), M+1 = 390.22 (24.4%), M+2 = 391.23 (3.9%),		
7b 1H,dq J=12,7 <u> </u> 2.1 -0.3 <u>1.8</u>	8 2H,t J=7 <u> </u> 1.2 0.1 1.1 <u>2.4</u>	9a 1H,dd J=12,7 <u> </u> 1.2 2.9 0.1 <u>4.2</u>	9b 1H,dd J=12,7 <u> </u> 4.2 -0.3 <u>3.9</u>	10 1H,oct J=7 <u> </u> 1.5 0.4 0.3 <u>2.2</u>	11 3H,d J=7 <u> </u> 0.9 0.1 0.1 <u>1.1</u>	12a 1H,dd J=12,7 <u> </u> 1.2 1.4 0.1 <u>2.7</u>			
12b 1H,dd J=12,7 <u> </u> 2.7 -0.3 <u>2.4</u>	13 1H,d J=9 <u> </u> 7.3 0.6 -0.4 <u>7.5</u>	14 1H,t J=9 <u> </u> 7.3 0.1 -0.1 <u>7.3</u>	15 1H,d J=9 <u> </u> 7.3 0.2 -0.5 <u>7.0</u>	16 1H,s <u> </u> 7.3 0.6 -0.5 <u>7.4</u>	17 2H,t J=7 <u> </u> 1.2 2.7 <u>3.9</u>	18 2H,sex J=7 <u> </u> 1.2 0.6 <u>1.8</u>	19 3H,t J=7 <u> </u> 0.9 0.1 <u>1.0</u>		



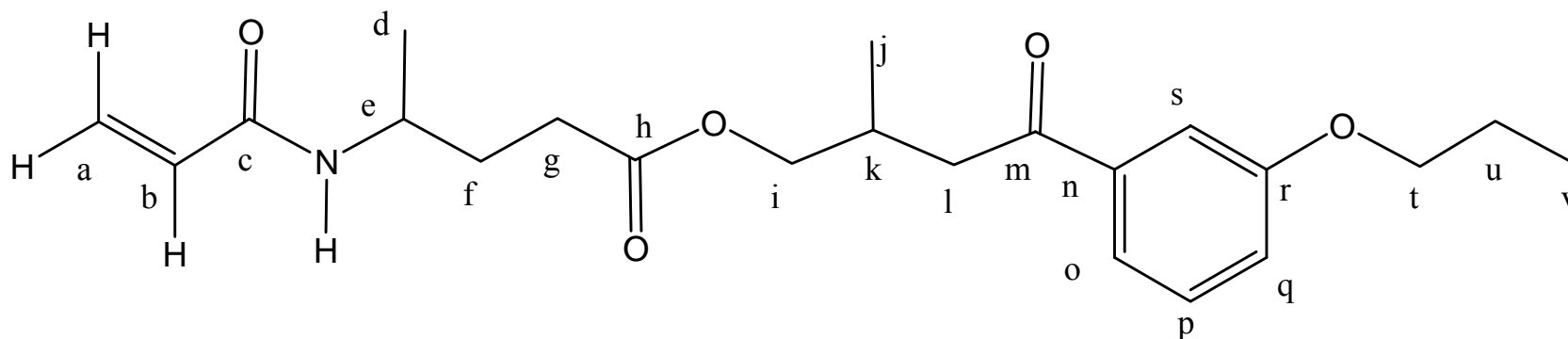
Predict a carbon NMR (calculate chemical shifts where possible and estimate when not)



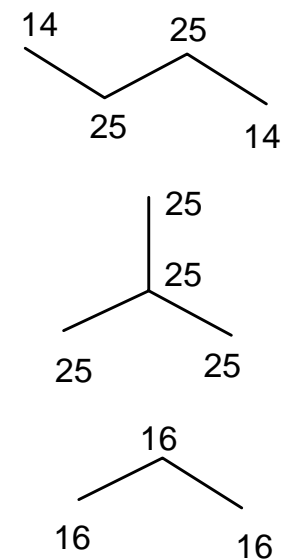
a	b	c	d	e	f	g	
h	i	j	k	l	m	n	
o	p	q	r	s	t	u	v

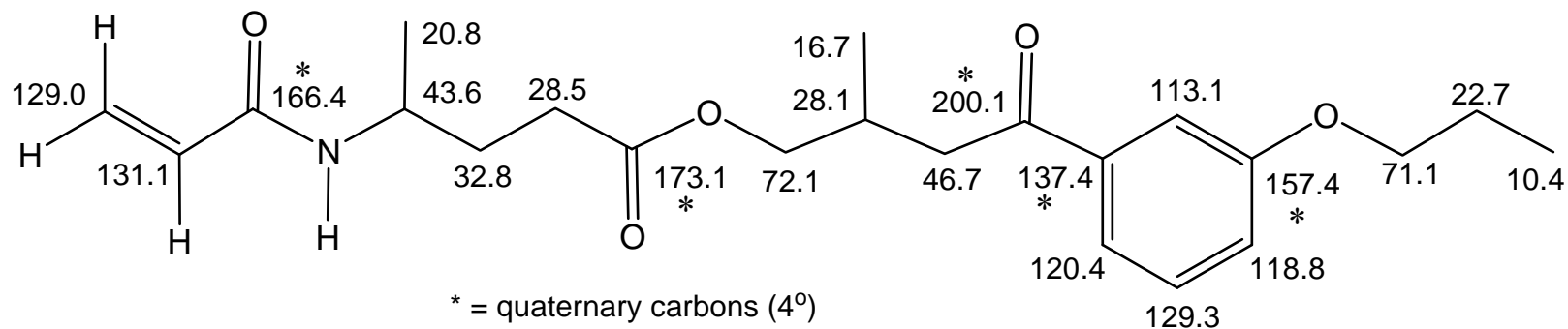


Predict a carbon NMR (calculate chemical shifts where possible and estimate when not)

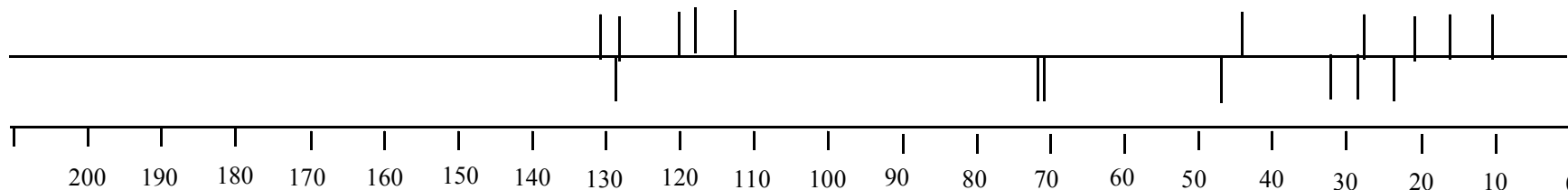


<p>a</p> <p>DEPT</p> <p>123</p> <p>6</p> <p>129</p> <p>DEPT</p> <p>123</p> <p>8</p> <p>131</p> <p>DEPT</p>	<p>b</p> <p>DEPT</p> <p>123</p> <p>8</p> <p>131</p> <p>DEPT</p>	<p>c</p> <p>DEPT</p> <p>$\delta_c \approx 170 \pm$</p> <p>DEPT</p>	<p>d</p> <p>DEPT</p> <p>14</p> <p>6</p> <p>20</p> <p>DEPT</p>	<p>e</p> <p>DEPT</p> <p>25</p> <p>18</p> <p>-3</p> <p>40</p> <p>DEPT</p>	<p>f</p> <p>DEPT</p> <p>25</p> <p>6</p> <p>2</p> <p>33</p> <p>DEPT</p>	<p>g</p> <p>DEPT</p> <p>14</p> <p>-5</p> <p>20</p> <p>29</p> <p>DEPT</p>	<p>h</p> <p>DEPT</p> <p>$\delta_c \approx 170 \pm$</p> <p>DEPT</p>	<p>i</p> <p>DEPT</p> <p>25</p> <p>51</p> <p>-3</p> <p>73</p> <p>DEPT</p>	<p>j</p> <p>DEPT</p> <p>25</p> <p>-6</p> <p>-3</p> <p>16</p> <p>DEPT</p>	<p>k</p> <p>DEPT</p> <p>25</p> <p>6</p> <p>1</p> <p>32</p> <p>DEPT</p>	<p>l</p> <p>DEPT</p> <p>25</p> <p>31</p> <p>-6</p> <p>50</p> <p>DEPT</p>	<p>m</p> <p>DEPT</p> <p>$\delta_c \approx 200 \pm$</p> <p>DEPT</p>	<p>n</p> <p>DEPT</p> <p>128</p> <p>8</p> <p>1</p> <p>137</p> <p>DEPT</p>	<p>o</p> <p>DEPT</p> <p>128</p> <p>0</p> <p>-7</p> <p>122</p> <p>DEPT</p>	<p>p</p> <p>DEPT</p> <p>128</p> <p>0</p> <p>1</p> <p>129</p> <p>DEPT</p>	<p>q</p> <p>DEPT</p> <p>128</p> <p>4</p> <p>-14</p> <p>118</p> <p>DEPT</p>	<p>r</p> <p>DEPT</p> <p>128</p> <p>0</p> <p>32</p> <p>160</p> <p>DEPT</p>	<p>s</p> <p>DEPT</p> <p>128</p> <p>0</p> <p>-14</p> <p>114</p> <p>DEPT</p>	<p>t</p> <p>DEPT</p> <p>16</p> <p>58</p> <p>74</p> <p>DEPT</p>	<p>u</p> <p>DEPT</p> <p>16</p> <p>7</p> <p>23</p> <p>DEPT</p>	<p>v</p> <p>DEPT</p> <p>16</p> <p>-6</p> <p>10</p> <p>DEPT</p>
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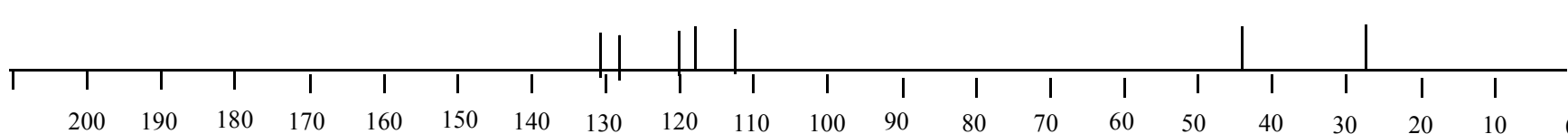




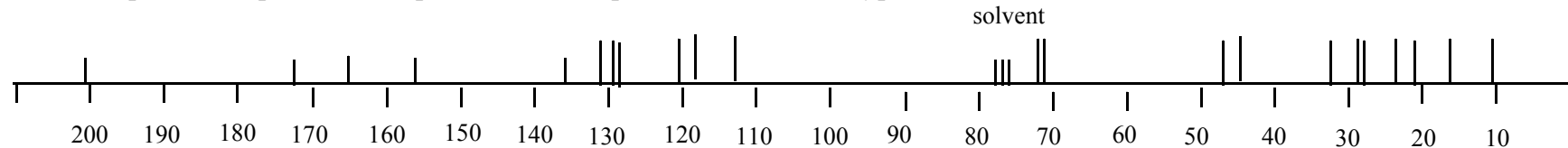
Top spectrum = DEPT-135 ¹³C NMR - CH₃ and CH appear (up) and CH₂ appears (down)



Middle spectrum = DEPT-90 ¹³C NMR - only C-H appears (up)

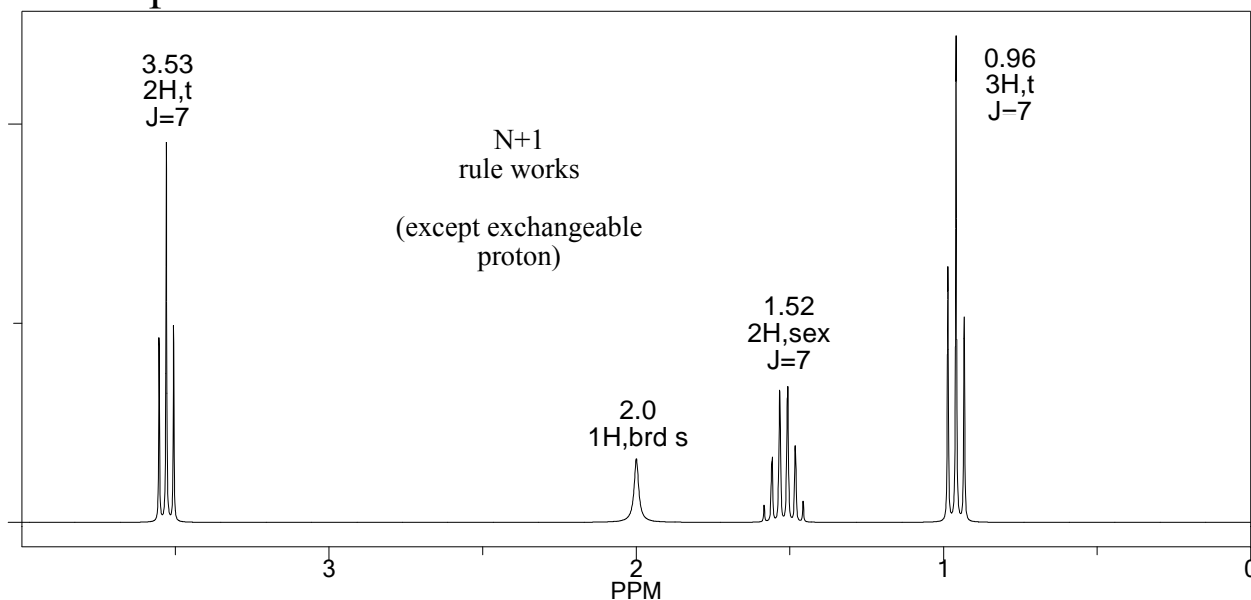


Bottom spectrum = proton decoupled ¹³C NMR spectrum - shows all types of carbon



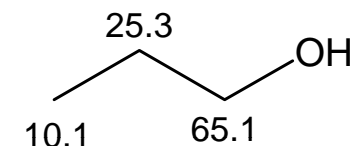
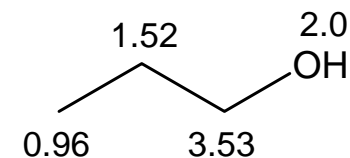
- *200.1
- *173.1
- *166.4
- *157.4
- *137.4
- 131.1
- 129.3
- 129.0
- 120.4
- 118.8
- 113.1
- 72.1
- 71.1
- 46.7
- 43.6
- 32.8
- 28.5
- 28.1
- 22.7
- 20.8
- 16.7
- 10.4

Interpretation of H and C NMR

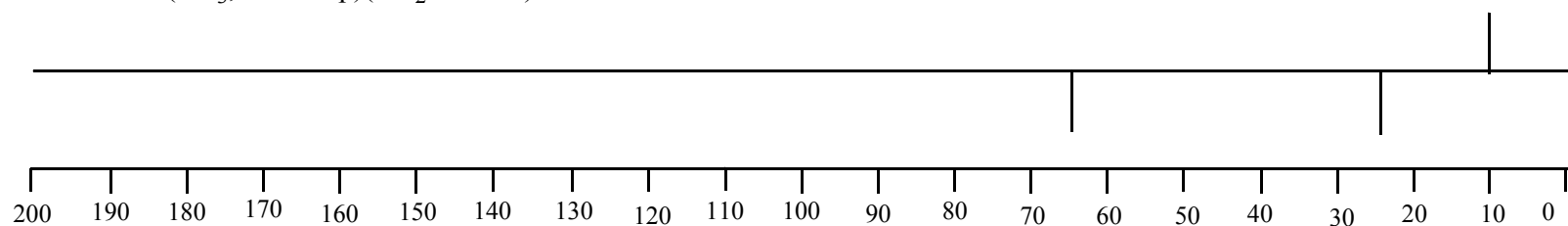


Exact Mass: 60.06

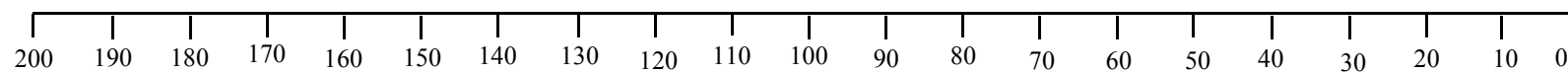
M+ = 60.06 (100.0%),
M+1 = 61.06 (3.4%)



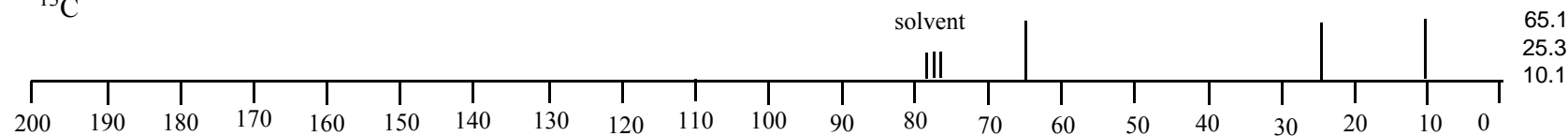
DEPT-135 (CH₃, CH = up)(CH₂ = down)



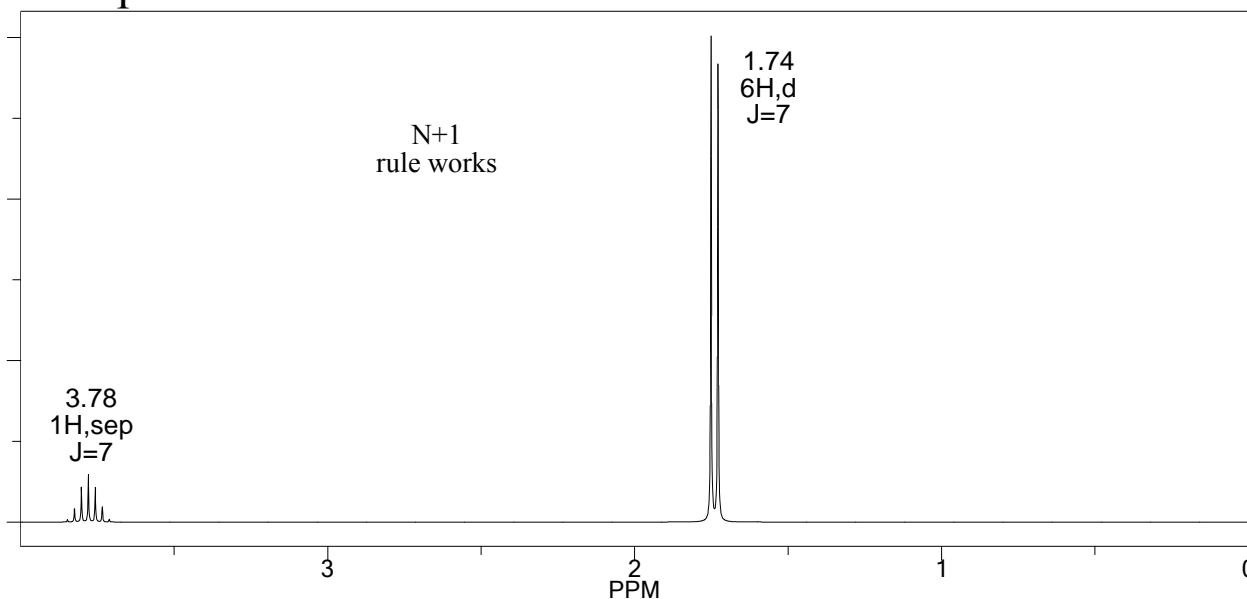
DEPT-90 (CH = up)



¹³C

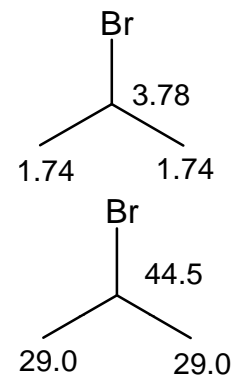


Interpretation of H and C NMR

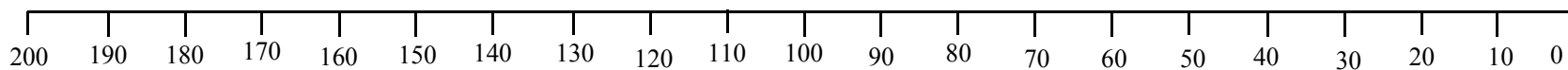
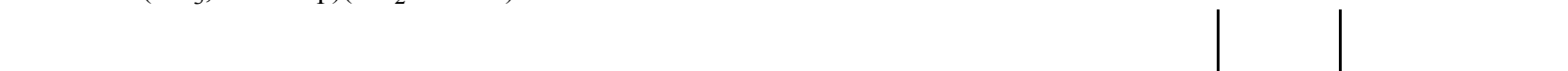


Exact Mass: 121.97

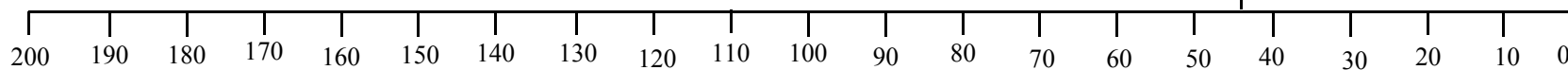
M+ = 121.97 (100.0%),
 M+1 = 122.98 (3.3%),
 M+2 = 123.97 (97.3%),
 M+3 = 124.97 (3.2%)



DEPT-135 (CH₃, CH = up)(CH₂ = down)



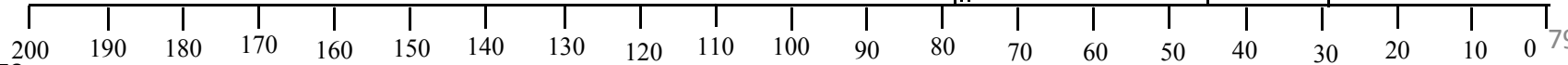
DEPT-90 (CH = up)



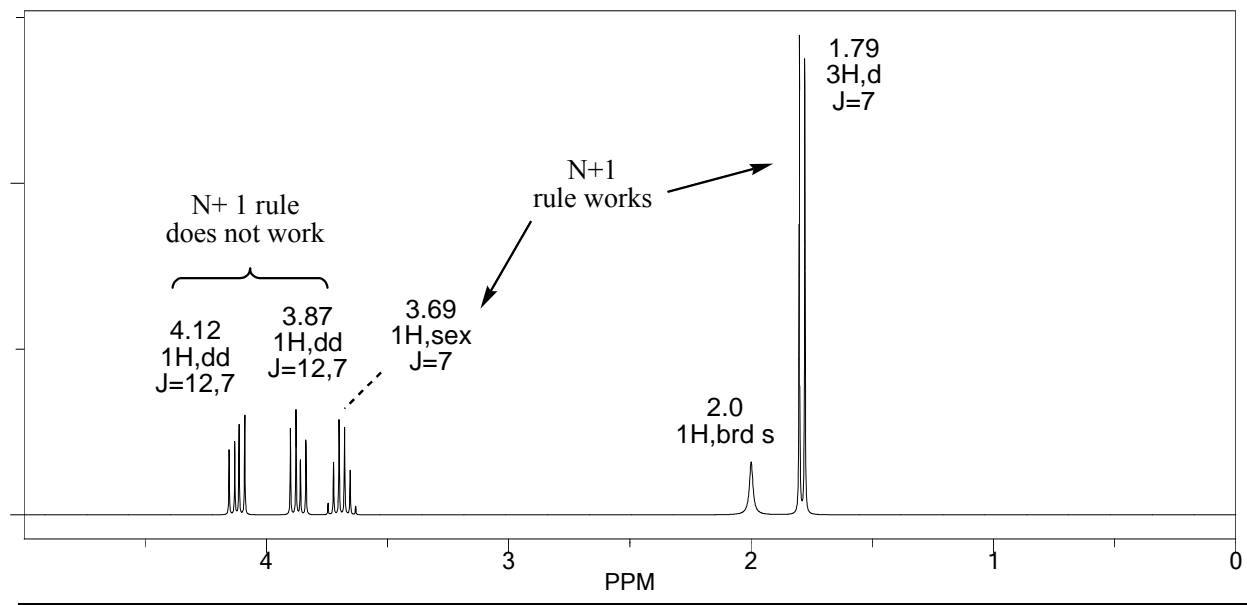
¹³C

solvent

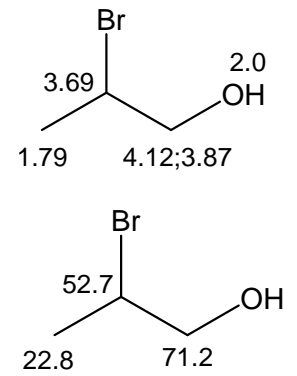
44.5
29.0



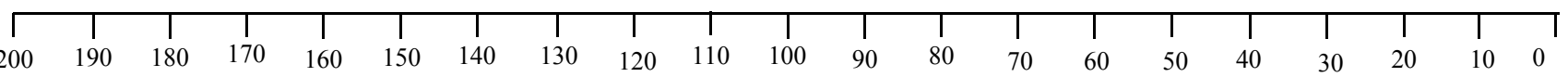
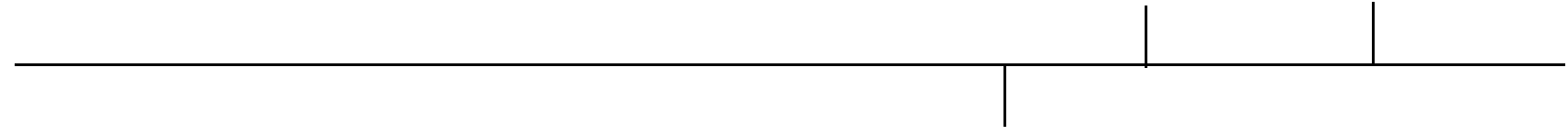
Interpretation of H and C NMR



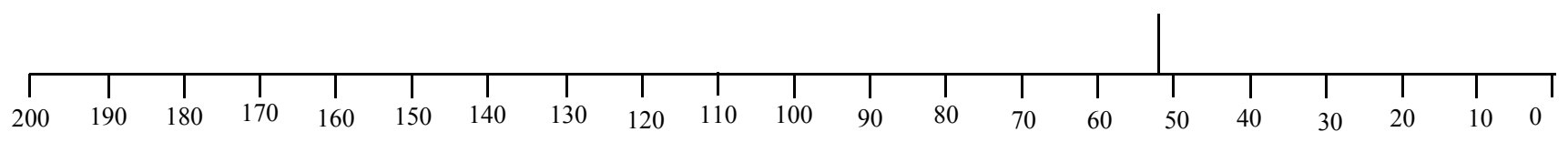
Exact Mass: 137.97
 M+ = 137.97 (100.0%),
 M+1 = 138.97 (3.4%),
 M+2 = 139.97 (97.5%),
 M+3 = 140.97 (3.3%)



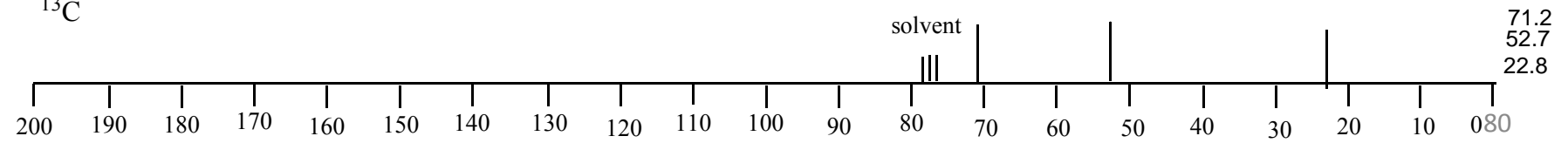
DEPT-135 (CH₃, CH = up)(CH₂ = down)



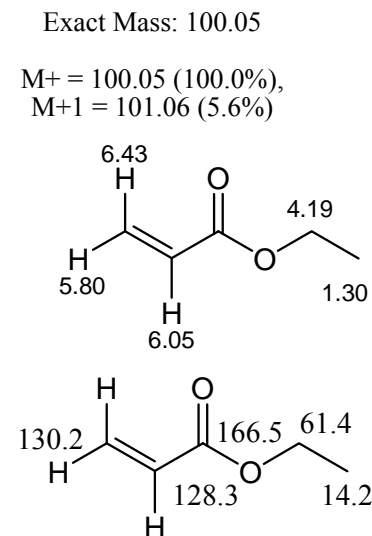
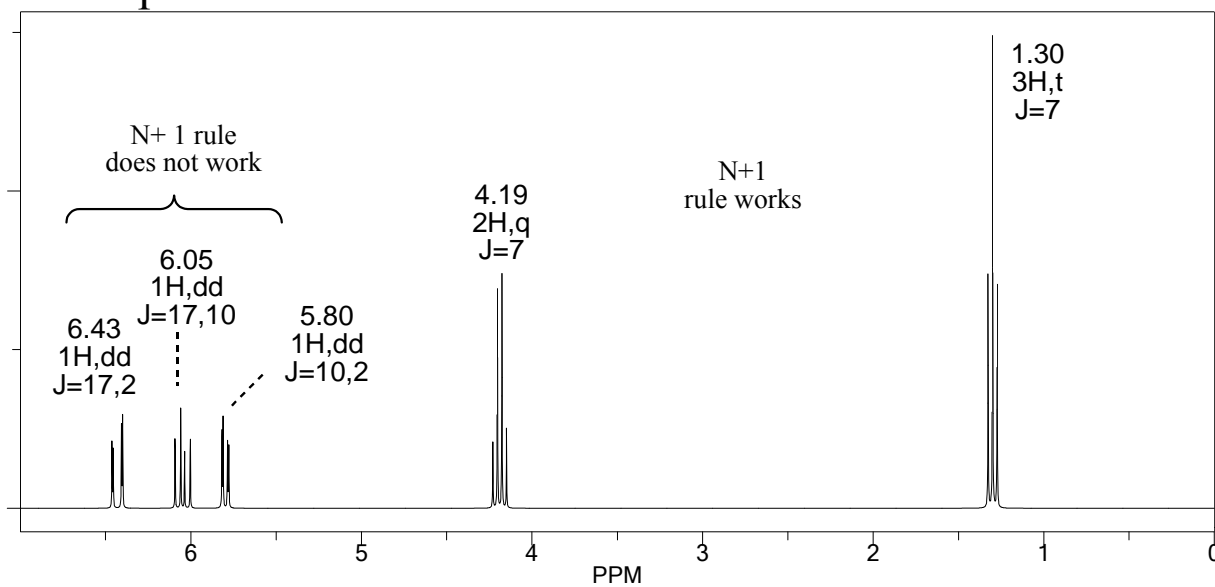
DEPT-90 (CH = up)



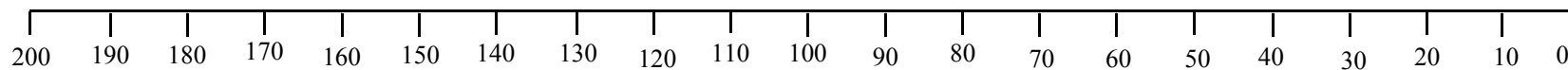
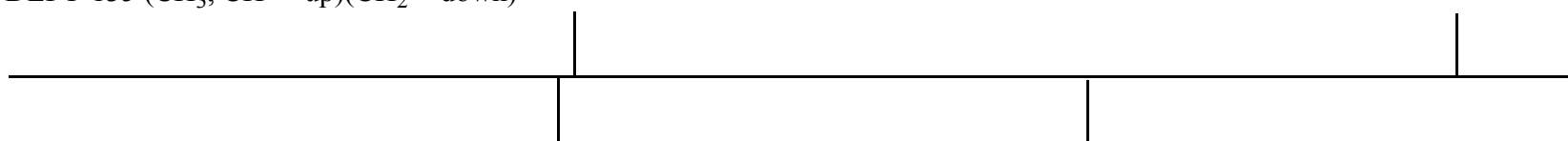
¹³C



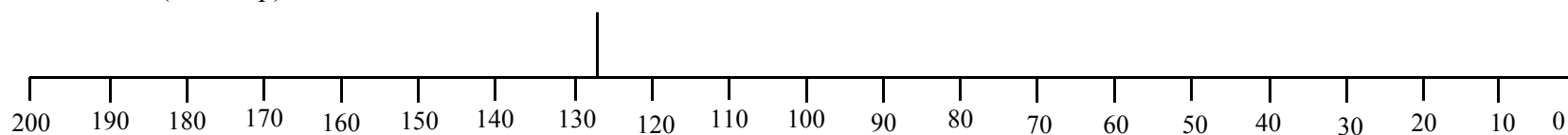
Interpretation of H and C NMR



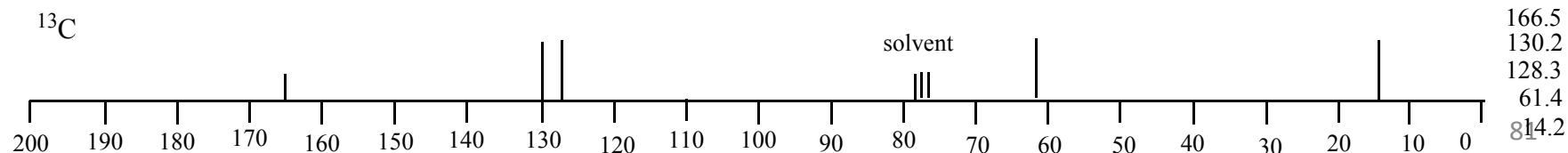
DEPT-135 (CH₃, CH = up)(CH₂ = down)

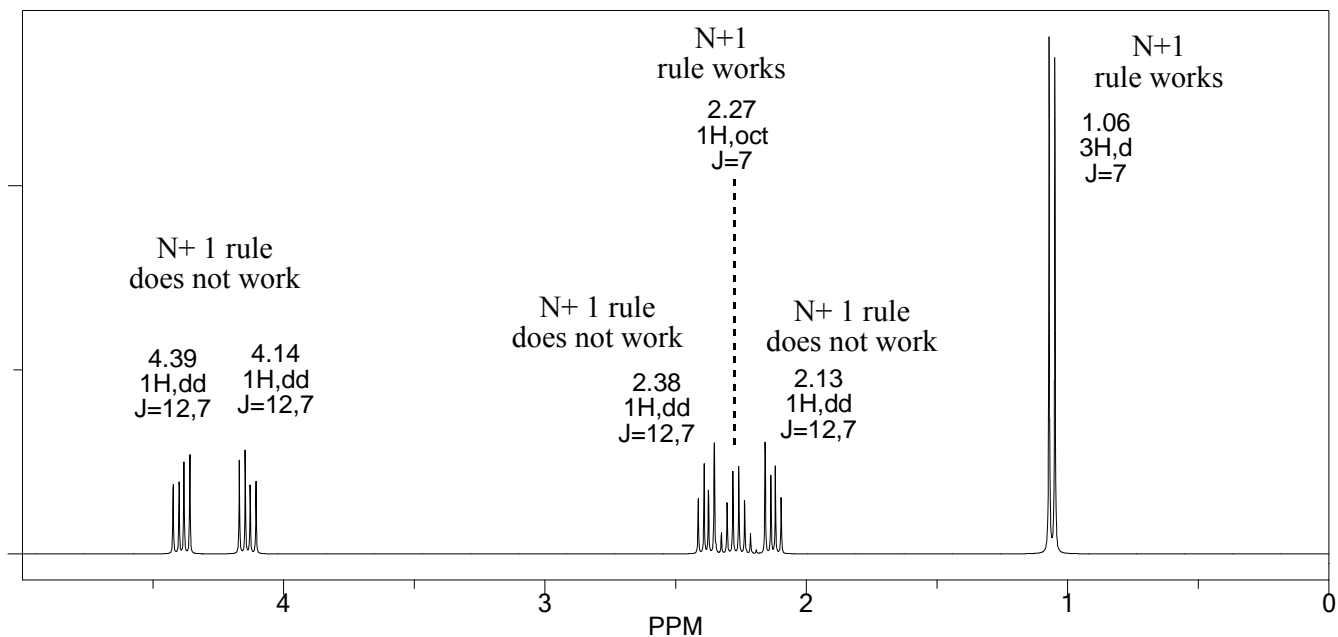


DEPT-90 (CH = up)



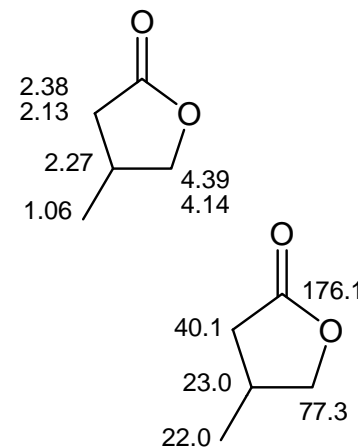
¹³C



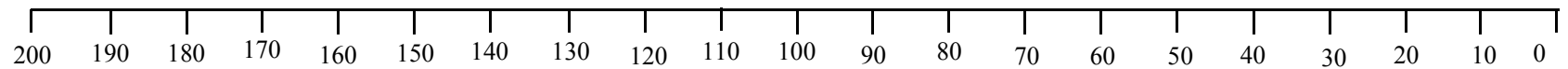
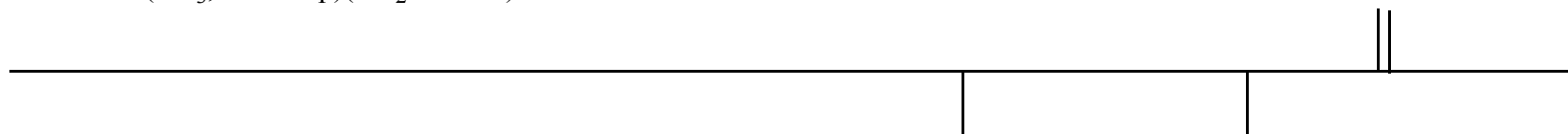


Exact Mass: 100.05

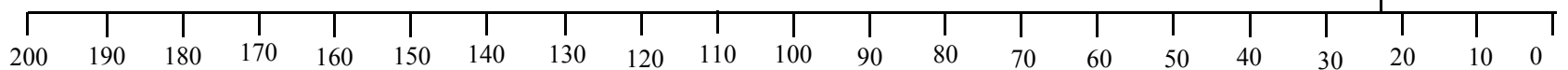
M+ = 100.05 (100.0%),
M+1 = 101.06 (5.6%)



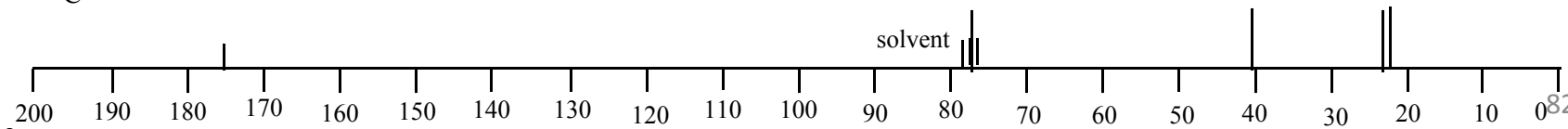
DEPT-135 (CH₃, CH = up)(CH₂ = down)



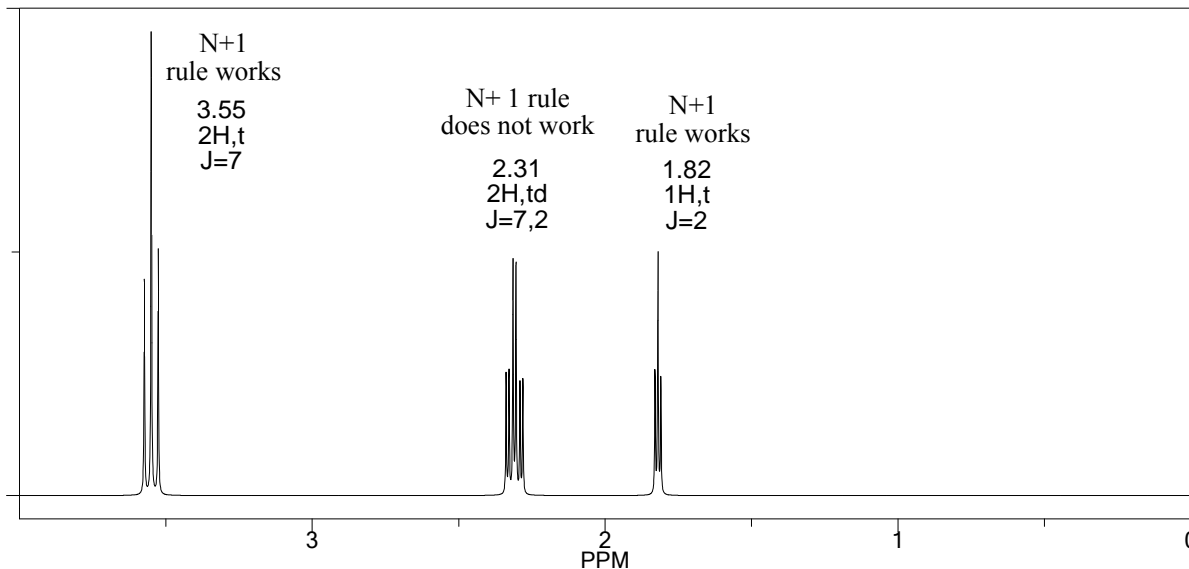
DEPT-90 (CH = up)



¹³C

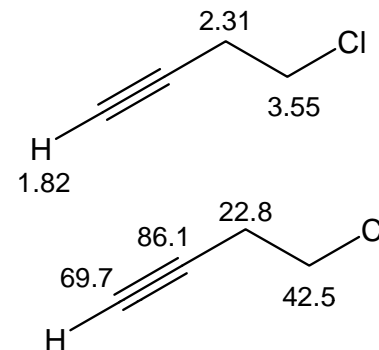


Interpretation of H and C NMR

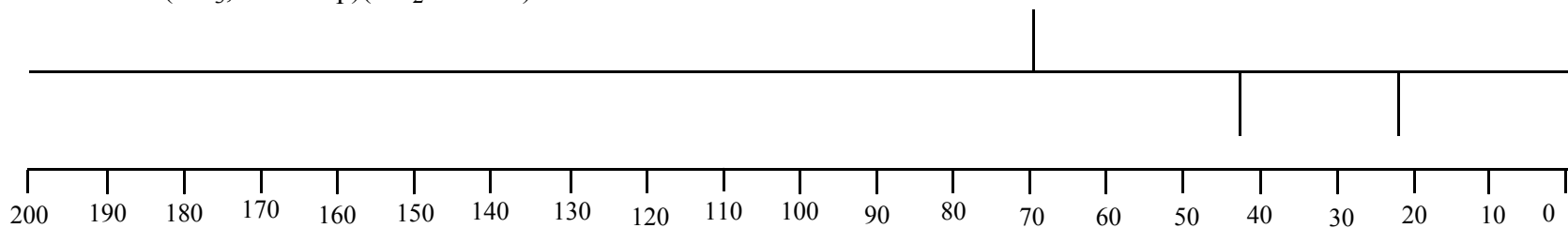


Exact Mass: 88.01

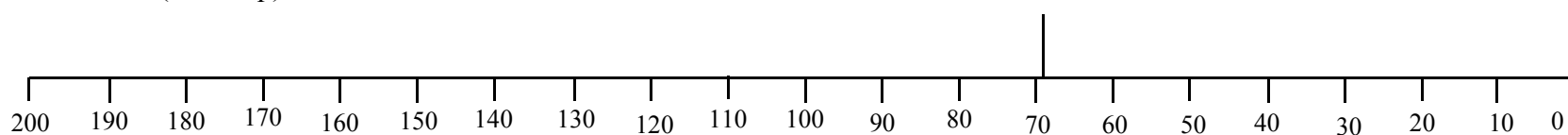
M+ = 88.01 (100.0%),
 M+1 = 89.01 (4.4%),
 M+2 = 90.01 (32.0%),
 M+3 = 91.01 (1.4%)



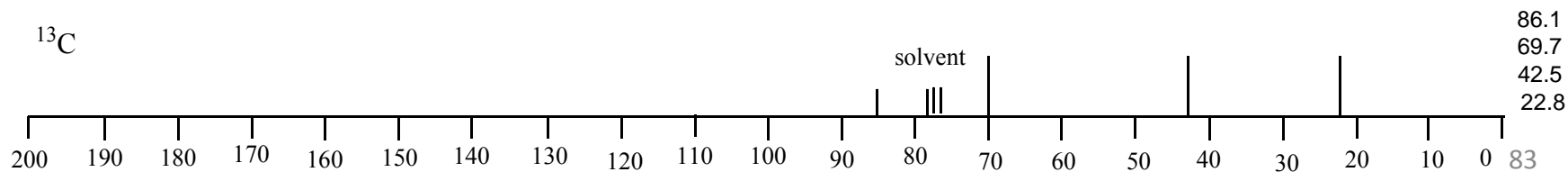
DEPT-135 (CH₃, CH = up)(CH₂ = down)



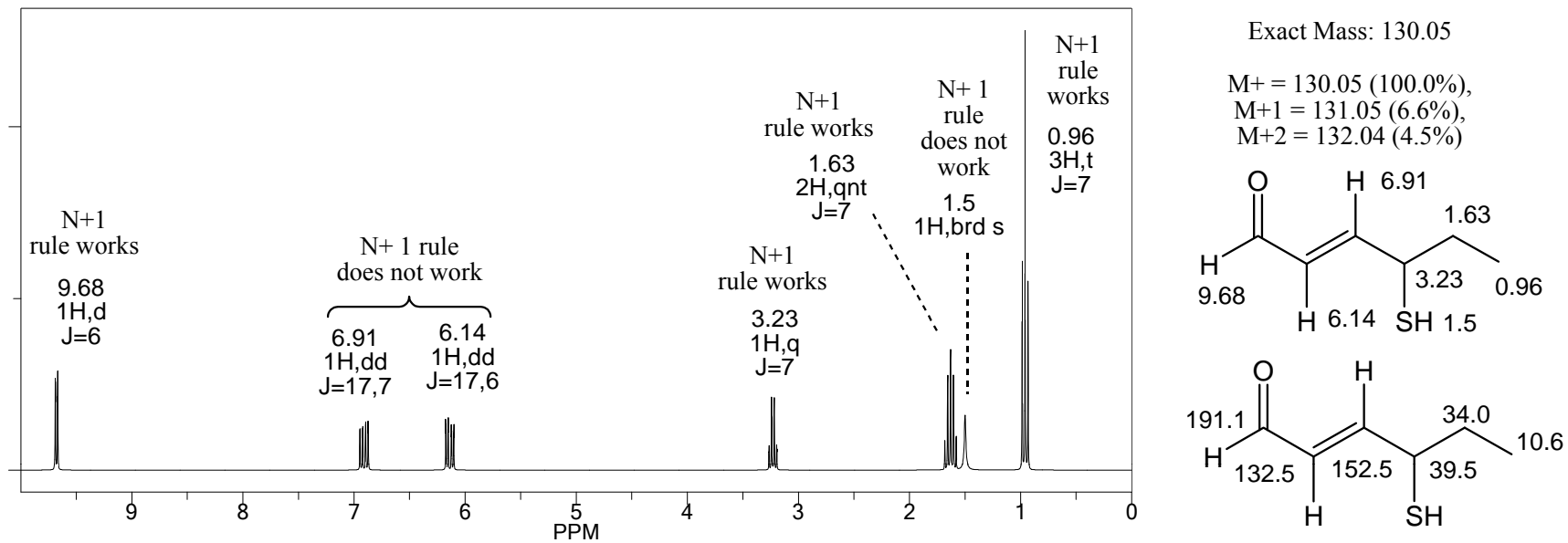
DEPT-90 (CH = up)



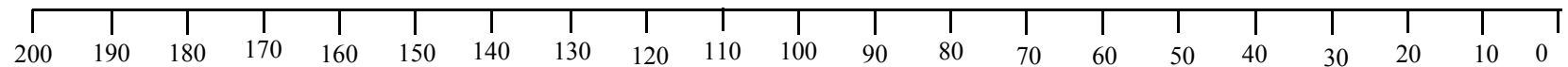
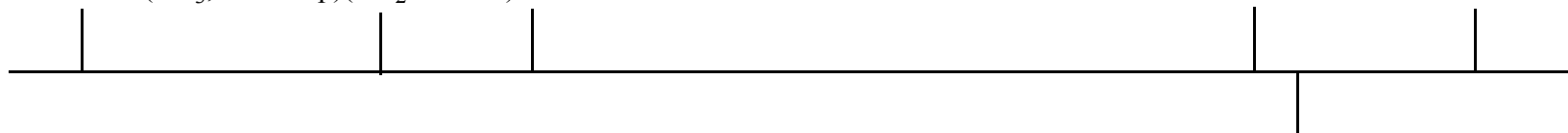
¹³C



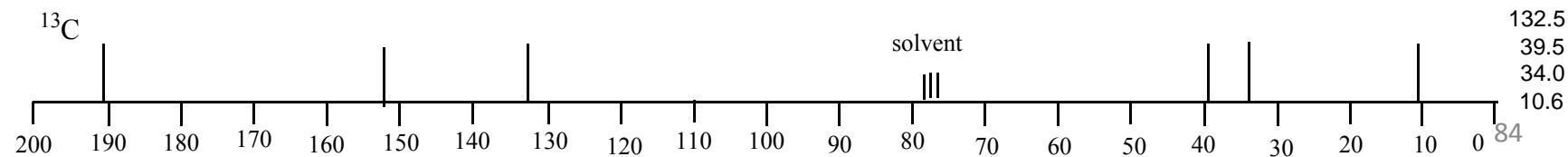
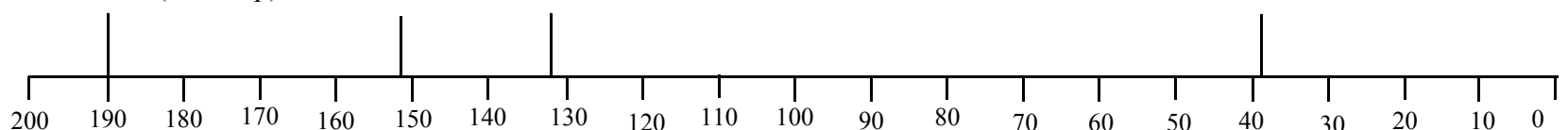
Interpretation of H and C NMR



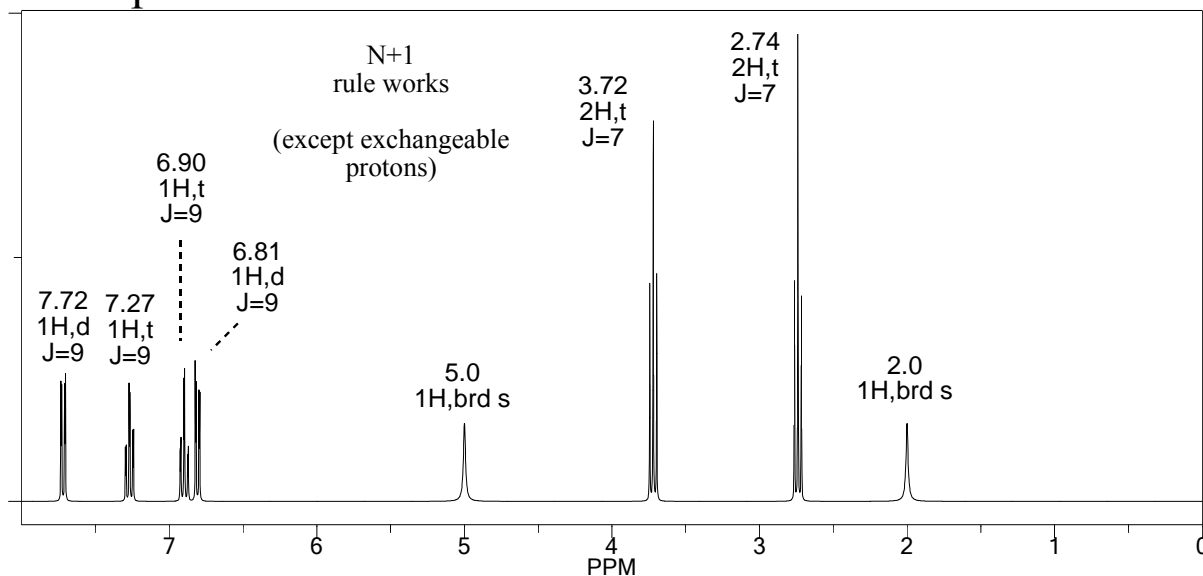
DEPT-135 (CH₃, CH = up)(CH₂ = down)



DEPT-90 (CH = up)

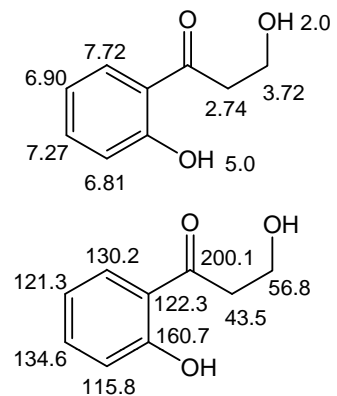


Interpretation of H and C NMR

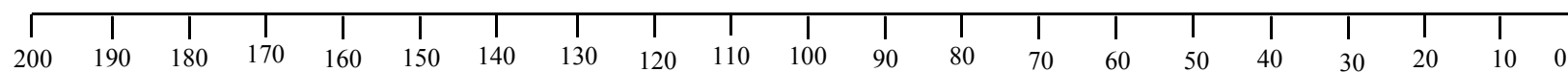


Exact Mass: 166.06

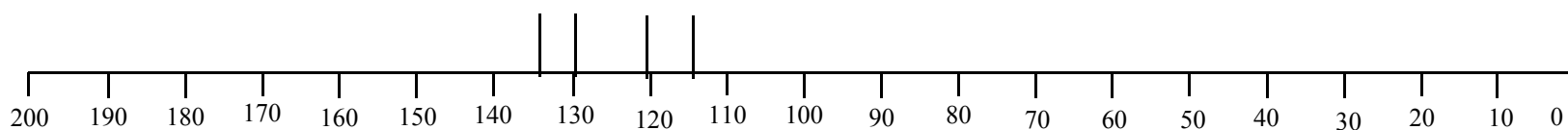
$M^+ = 166.06$ (100.0%),
 $M+1 = 167.07$ (10.0%),
 $M+2 = 168.07$ (1.1%)



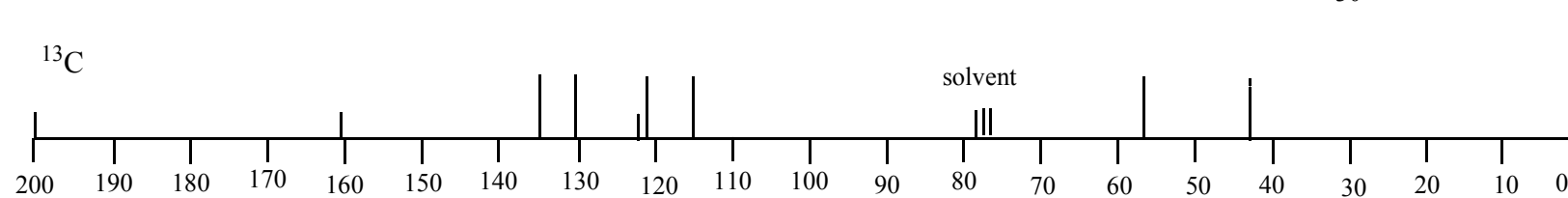
DEPT-135 ($CH_3, CH = up$)($CH_2 = down$)



DEPT-90 ($CH = up$)



^{13}C



1. \square C₆H₁₃NO₂

a. 1.3(t,3H), 2.4(s,6H), 3.2(s,2H), 4.2(q,2H) \square

b. 2.1(s,3H), 2.3(s,6H), 2.6(t,2H), 4.2(t,2H)

c. 2.2(s,6H), 2.5(t,2H), 2.6(t,2H), 3.7(s,3H)

d. 1.7(2H,q), 1.8(2H,q), 2.0(3H,brd s), 2.4(2H,td,J=7,2), 2.6(1H,qnt), 3.5(2H,t), 9.7(1H,d,J=2)

e. 1.1(t,3), 1.8(qnt,2H), 2.0(brd s,2H), 2.3(q,2H), 2.6(t,2H), 4.1(t,2H)

ex = exchangeable = OH or NH₂

2. \square C₄H₈O₂

a. 1.1(t,3H), 2.3(q,2H), 3.7(s,3H)

b. 1.0(t,3H), 1.7(sex,2H), 2.3(t,2H), 11.5(s,1H)

c. 1.3(t,3H), 2.0(s,3H), 4.1(q,2H)

d. 2.1(s,3H), 3.4(s,3H), 4.0(s,2H)

e. 2.2(s,3H), 2.7(t,2H), 3.4(s,1H,ex), 3.8(t,2H)

f. 2.4(s,1H,ex), 3.8(m,4H), 4.0(dd,1H), 4.2(dd,1H), 6.5(dd,1H)

3. \square C₆H₁₂O₂

a. 1.5(s,9H), 2.0(s,3H)

b. 1.3(s,6H), 2.2(s,3H), 2.6(s,2H), 3.8(s,1H,ex)

c. 1.2(t,3H), 2.2(s,3H), 2.7(t,2H), 3.5(q,2H), 3.7(t,2H)

d. 1.0(t,6H), 1.6(m,4H), 2.2(qnt,1H), 11.7(s,1H,ex)

4. \square C₉H₁₀O

a. 1.2(t,3H), 3.0(q,2H), 7.3-7.7 (m,3H), 7.9(m,2H)

b. 2.0(s,1H,ex), 4.3(d,2H), 6.4(m,1H), 6.6(d,1H,J=17), 7.3-7.7(m,5H)

c. 2.8(m,2H), 2.9(t,2H), 7.2(m,5H), 9.8(t,1H)

d. 2.4(s,3H), 2.6(s,3H), 7.2(d,1H), 7.3(d,1H), 7.6(s,1H), 10.2(s,1H)

e. 1.3(t,3H), 2.7(q,2H), 7.3(d,2H), 7.8(d,2H), 10.0(s,1H)

f. 2.5(s,3H), 2.5(s,3H), 7.2(m,1H), 7.2(m,1H), 7.3(t,1H), 7.7(d,1H)

5. \square C₅H₁₀O₂

a. 1.2(d,6H), 2.0(s,3H), 5.0(sep,1H)

b. 1.2(3H,d), 2.0(1H,brd s), 2.1(3H,s), 2.5(1H,dd,J=12,7), 2.7(1H,dd,J=12,7), 3.6(1H,sex)

c. 2.2(s,3H), 2.7(t,2H), 3.3(s,3H), 3.6(t,2H)

d. 3.3(s,6H), 4.8(d,1H,J=7), 5.3(dd,1H,J=10,2), 5.4(dd,1H,16,2), 5.8(ddd,1H,J=16,10,7)

6. \square C₁₀H₁₂O₂

a. 2.0(s,3H), 2.9(t,2H), 4.3(t,2H), 7.1-7.4(s,5H)

b. 1.2(t,3H), 2.3(s,3H), 2.5(q,2H), 7.0(d,1H), 7.2(m,2H), 7.3(d,1H)

c. 1.2(3H,d), 2.6(1H,dd,J=12,7), 2.9(1H,dd, J=12,7), 2.9+(1H,sex), 7.1-7.2(5H,m), 11.0(1H,brd s)

d. 1.3(t,3H), 2.6(s,3H), 4.0(q,2H), 6.9(d,2H), 7.8(d,2H)

Use the molecular formulas along with the ^{13}C chemical shifts and multiplicities to determine a reasonable structure for the following molecules (There may be more than one reasonable possibility.) The multiplicities are s = singlet, d = doublet, t = triplet, q = quartet. The degree of unsaturation can help determine the possible number of rings and/or bonds. Draw an approximate sketch of each spectrum. Use arrows drawn from each type of carbon pointing to the appropriate chemical shift to indicate the correct correspondence.

1. C_8H_{18} - 24.9d, 25.5q, 30.2q, 31.2s, 53.4t
2. $\text{C}_5\text{H}_{11}\text{Cl}$ - 22.0q, 25.7d, 41.6t, 43.1t
3. $\text{C}_4\text{H}_8\text{O}_2$ - 14.4q, 20.9q, 60.4t, 170.7s
4. $\text{C}_4\text{H}_7\text{Br}$ - 17.5q, 32.9t, 127.8d, 131.0d
5. $\text{C}_6\text{H}_8\text{O}$ - 18.7q, 130.2d, 130.4d, 141.6d, 153.3d, 193.0d
6. C_9H_{12} - 21.2q, 127.2d, 137.5s
7. $\text{C}_6\text{H}_{15}\text{NO}$ - 27.0t, 27.9t, 34.2t, 34.9t, 43.2t, 62.9t
8. $\text{C}_9\text{H}_{10}\text{O}$ - 8.2q, 31.6t, 128.0d, 128.6d, 132.8d, 137.2s, 200.0s
9. $\text{C}_5\text{H}_8\text{O}_2$ - 14.4q, 60.4t, 129.3t, 130.0d, 166.0s
10. $\text{C}_9\text{H}_{10}\text{O}_3$ - 56.0q, 56.1q, 109.4d, 110.7d, 126.5d, 130.3s, 149.8s, 154.6s, 190.7d
11. $\text{C}_{12}\text{H}_{14}\text{O}_4$ - 14.2q, 61.5t, 129.0d, 131.1d, 132.7s, 167.5s
12. $\text{C}_9\text{H}_8\text{O}_3$ - 115.4d, 115.9d, 125.4s, 130.0d, 144.2d, 159.7s, 168.1s
13. $\text{C}_8\text{H}_{11}\text{N}$ - 13.0q, 23.9t, 115.4d, 118.6d, 126.8d, 128.0s, 128.4d, 144.3s
14. $\text{C}_{11}\text{H}_{14}\text{O}$ - 14q, 23t, 26t, 38t, 128d, 129d, 132d, 136s, 201s
15. $\text{C}_4\text{H}_{11}\text{N}$ - 13q, 44q, 52t
16. $\text{C}_4\text{H}_8\text{O}$ - 14q, 16t, 45t, 202d
17. $\text{C}_5\text{H}_{12}\text{O}$ - 22q, 24t, 42d, 62t
18. $\text{C}_{10}\text{H}_9\text{NO}_2$ - 15q, 62t, 116s, 118s, 129d, 132d, 134s, 165s
19. $\text{C}_9\text{H}_9\text{ClO}$ - 39t, 41t, 127d, 128d, 133d, 136s, 196s
20. $\text{C}_{13}\text{H}_{20}\text{N}_2\text{O}_2$ - 12q(x2), 46t(x2), 51t, 63t, 114d, 120s, 131d, 151s, 166s
21. $\text{C}_{11}\text{H}_{14}\text{O}$ - 27q, 44s, 127d, 127.5d, 131d, 138s, 209s
22. $\text{C}_3\text{H}_4\text{Br}_2\text{O}_2$ - 28.8t, 40.4d, 173.6s
23. $\text{C}_3\text{H}_5\text{Br}$ - 32.6t, 118.8t, 134.2d
24. $\text{C}_3\text{H}_6\text{C}_{12}$ - 22.4q, 49.5t, 55.8d

2D NMR experiments will help us solve complex structures

These experiments work via coupling between the atoms. Three examples for us:

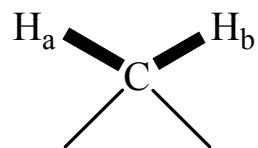
COSY (H/H, $^nJ_{HH}$),

HETCOR/HSQC ($^1J_{CH}$)

HMBC ($^2J_{CH}$ and $^3J_{CH}$).

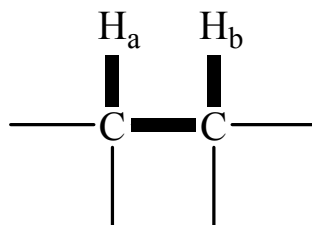
COSY - uses H/H couplings

geminal coupling
when protons are
diastereotopic.



$$^2J_{ab} \approx 12 \text{ Hz}$$

vicinal coupling
when protons are
neighbors.

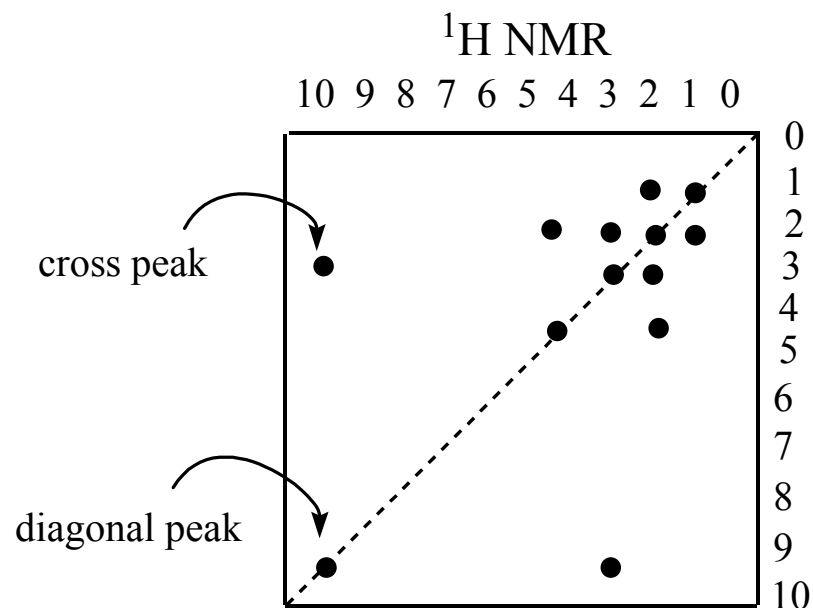


$$^3J_{ab} \approx 7 \text{ Hz}$$

diagonal peaks correlates each proton with itself
(locates protons of interest)

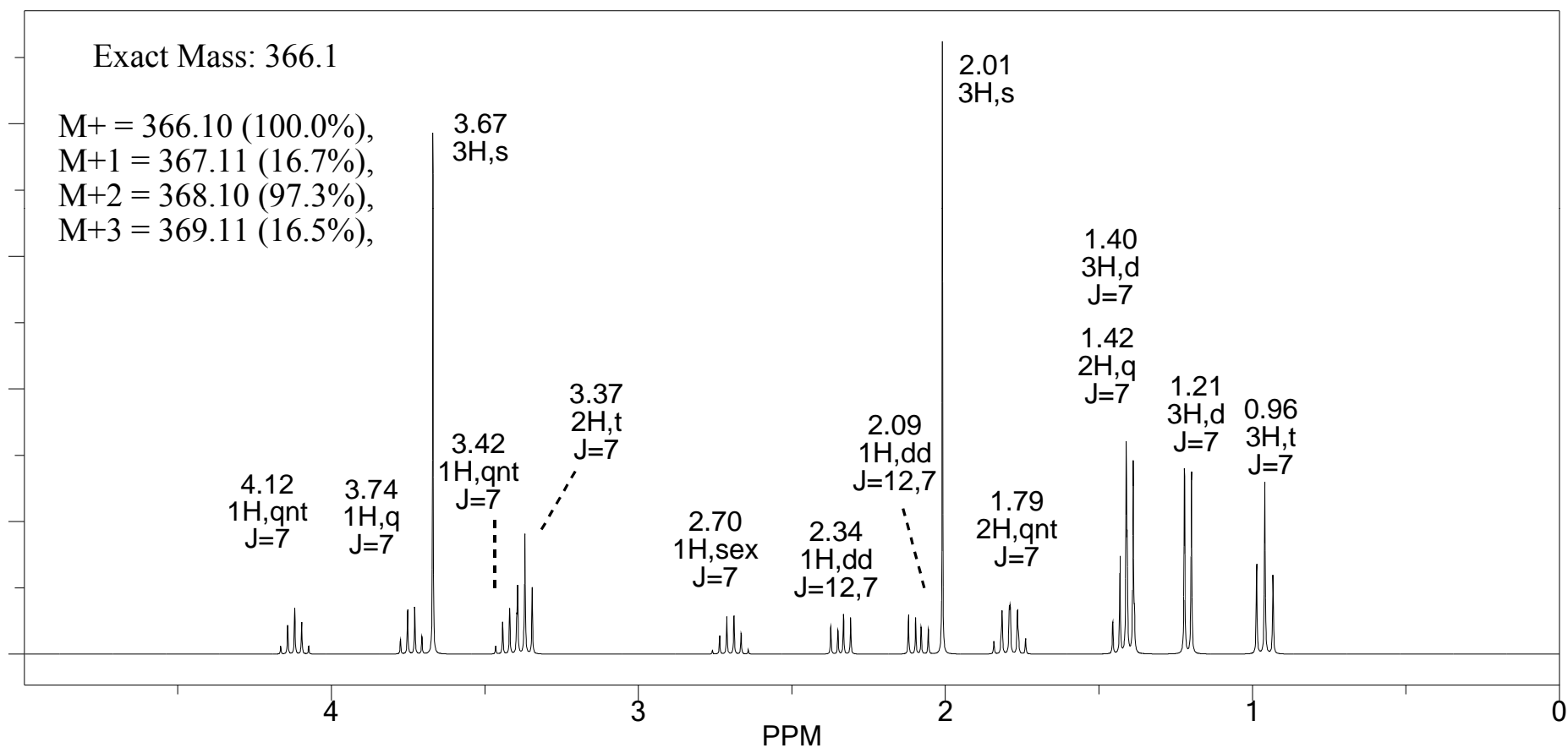
cross peaks correlate protons with any coupled H
partners

COSY = correlation spectroscopy (proton-proton)



This problem would be challenging using only the ¹H NMR and a few extra hints.

Formula = C₁₅H₂₇BrO₅, Possibly helpful IR bands: 1740, 1730, 1250, 1230, 1100, 1070, 1040 cm⁻¹ (assume that sp³ CH peaks are in all IR spectra). Hint: Ether linkage across 3.42 and 3.37.



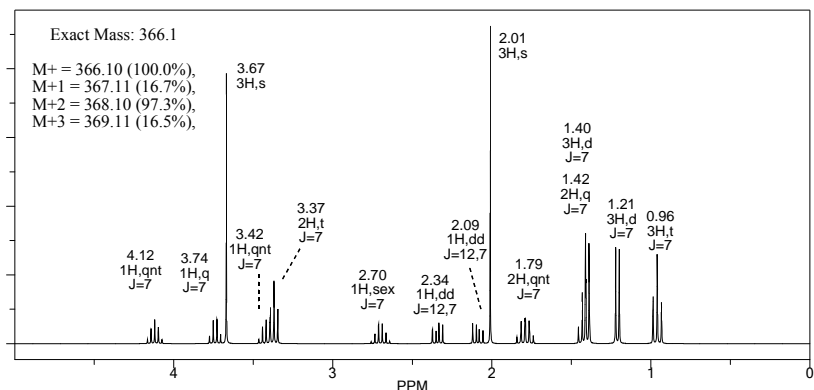
^1H NMR interpretation (Can we solve the structure from these?)

0.96 3H,t J=7	1.21 3H,d J=7	1.40 3H,d J=7	1.42 2H,q J=7	1.79 2H,qnt J=7
2.01 3H,s	2.09 1H,dd J=12,7 2.34 1H,dd J=12,7	2.70 1H,sex J=7	3.37 2H,t J=7	3.42 1H,qnt J=7
3.67 3H,s	3.74 1H,q J=7	4.12 1H,qnt J=7		

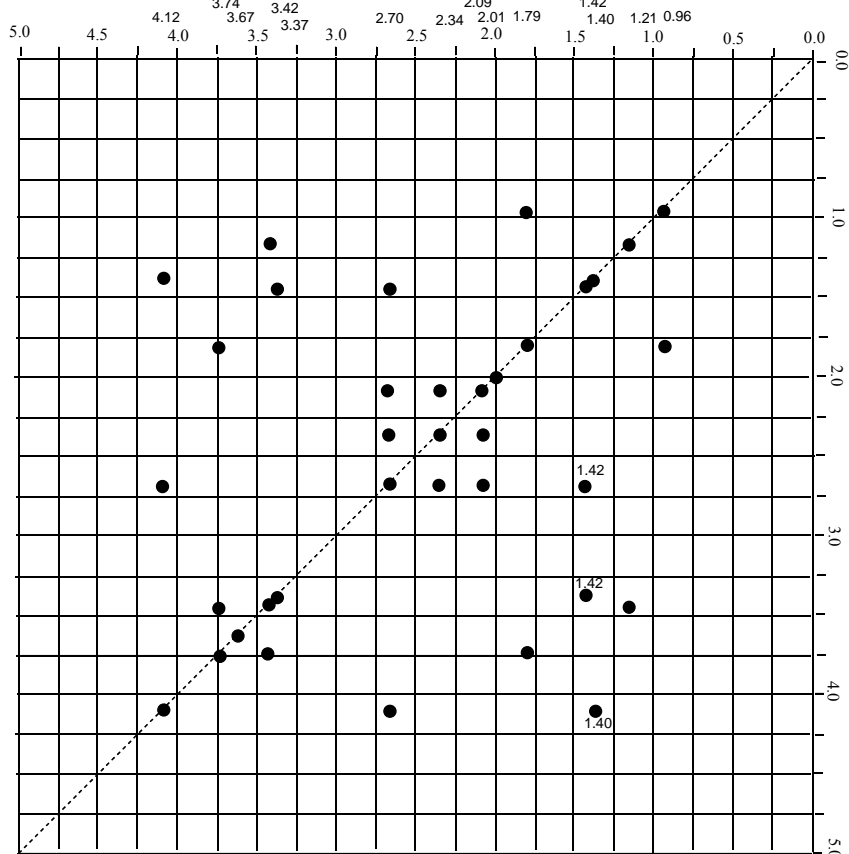
¹H NMR interpretation (Can we solve the structure from these?)

<p>0.96 3H,t J=7</p> <p>↓</p> <p>H₃C—C—H₂—</p>	<p>1.21 3H,d J=7</p> <p>↓</p> <p>H₃C—C—H</p>	<p>1.40 3H,d J=7</p> <p>↓</p> <p>H₃C—C—H</p>	<p>1.42 2H,q J=7</p> <p>↘</p> <p>—C—</p> <p>N = 3 CH₃ CH₂/CH</p>	<p>1.79 2H,qnt J=7</p> <p>↘</p> <p>—C—H₂—</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>
<p>2.01 3H,s</p> <p>↓</p> <p>H₃C—C(=O)—</p>	<p>2.09 1H,dd J=12,7</p> <p>2.34 1H,dd J=12,7</p> <p>H—C—C—H</p> <p>* = chiral center</p>	<p>2.70 1H,sex J=7</p> <p>↓</p> <p>—C—H</p> <p>N = 5 CH₃/CH₂ CH₂/CH₂/CH</p>	<p>3.37 2H,t J=7</p> <p>↘</p> <p>—C—H₂—</p> <p>N = 2 CH₂ CH/CH</p>	<p>3.42 1H,qnt J=7</p> <p>↓</p> <p>—C—H</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>
<p>3.67 3H,s</p> <p>↓</p> <p>H₃C—O—</p>	<p>3.74 1H,q J=7</p> <p>↓</p> <p>Br—C—H</p> <p>N = 3 CH₃ CH₂/CH</p>	<p>4.12 1H,qnt J=7</p> <p>↘</p> <p>O—C—</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>		

Possibly helpful IR bands: 1740, 1730, 1250, 1230, 1100, 1070, 1040 cm^{-1} (assume that sp^3 CH peaks are in all IR spectra). 15 carbons in ^{13}C NMR. Hint: Ether linkage across 3.42 and 3.37.

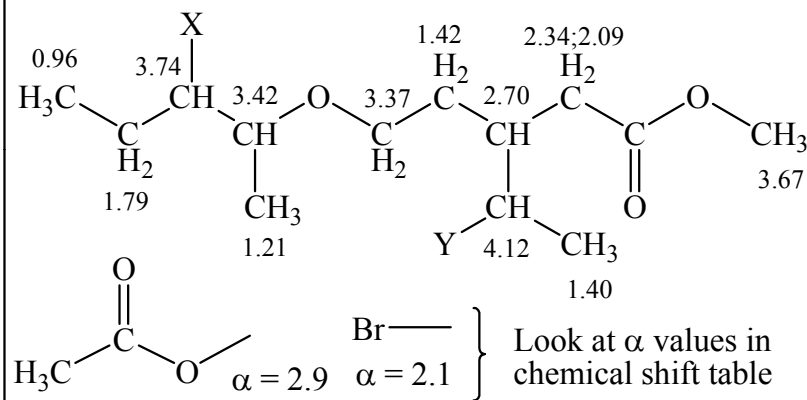


COSY: H-H correlations Trace out Spin Systems. Start at end positions, if possible.

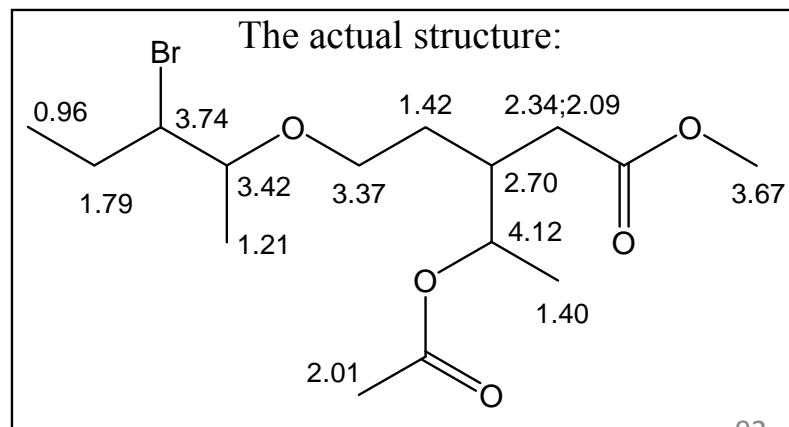


Formula calculations: $1 \times \text{Br}, 15 \times \text{C}, 27 \times \text{H} = 286$
 $366 - 286 = 80$
 $80 / 16 = 5 \times \text{O}$
 Degrees of unsaturation
 $2 \times 15 + 2 = 32$
 $(32 - 28) / 2 = 4 / 2 = 2^\circ$
 (looks like 2 C=O in IR)
 formula = $\text{C}_{15}\text{H}_{27}\text{BrO}_5$

Spin systems from COSY

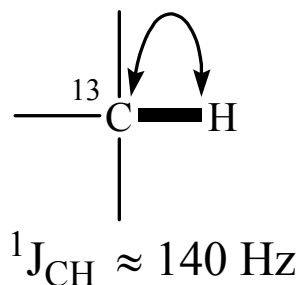


The actual structure:



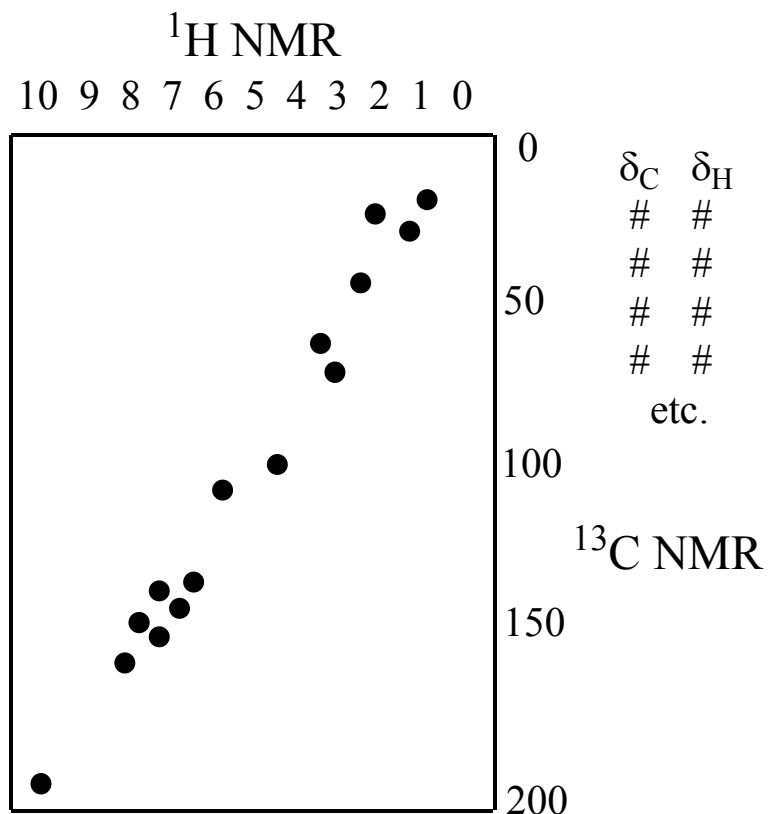
HETCOR (HSQC) - uses one bond C/H couplings

One bond C/H coupling constants are approximately 140 Hz.

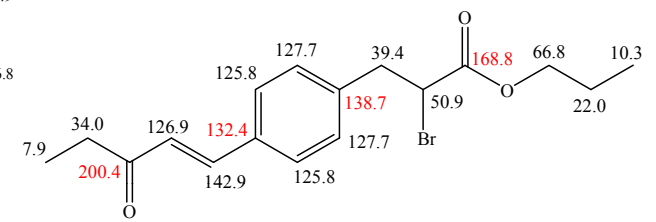
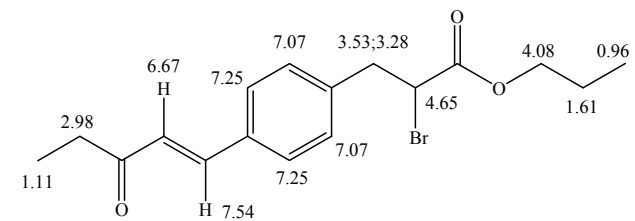
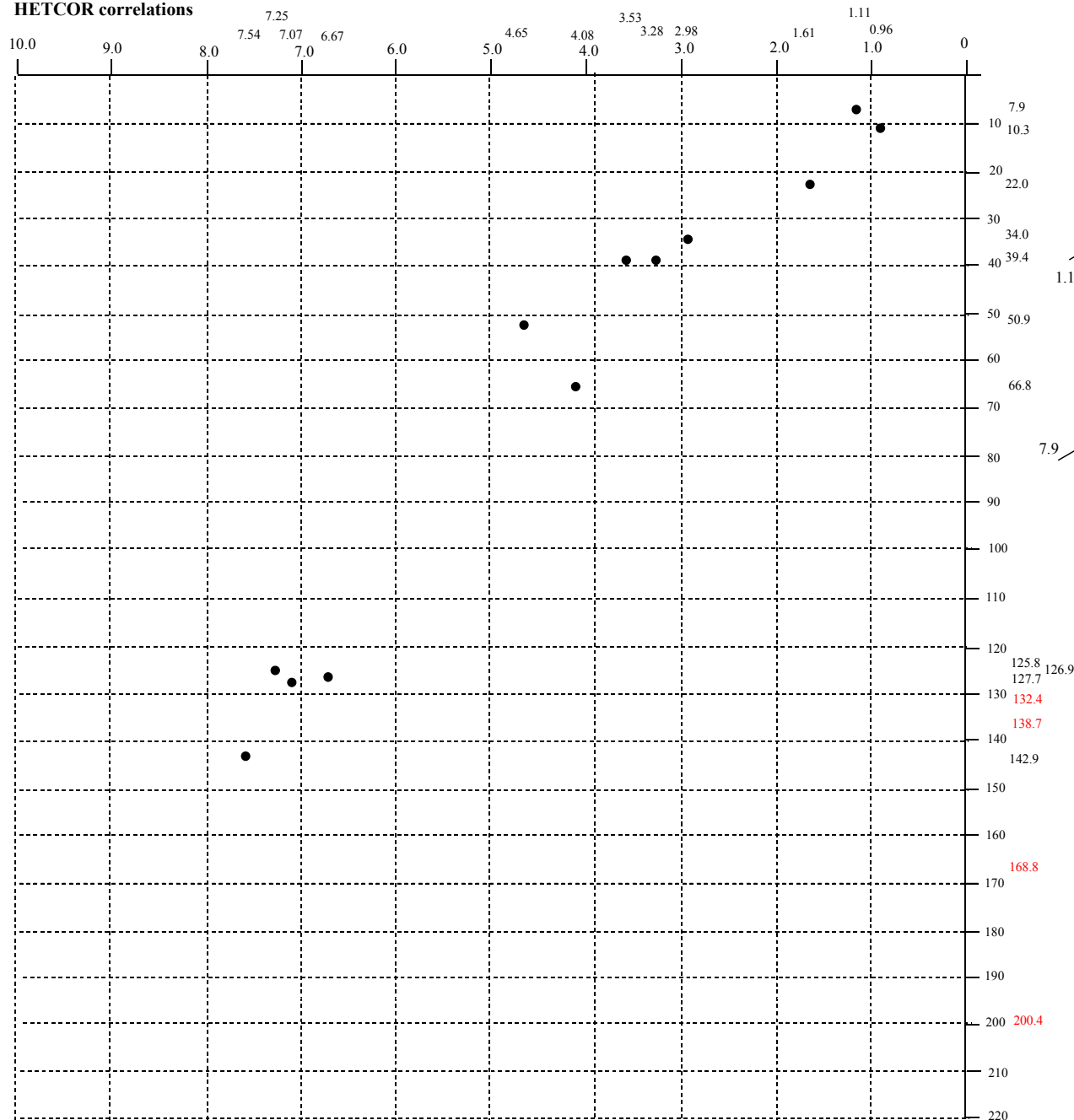


correlates directly attached protons and carbon atoms

HETCOR = heteronuclear correlation spectroscopy
HSQC - heteronuclear single quantum correlations



HETCOR correlations

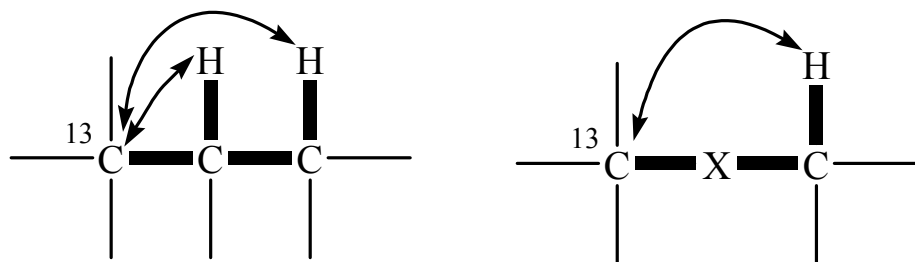


¹³ C	¹ H
200.4	
168.8	
142.9	
138.7	
132.4	
127.7	
126.9	
125.8	
66.8	
50.9	
39.4	
34.0	
22.0	
10.3	
7.9	

C₁₇H₂₁BrO₃
 Exact Mass: 352.07
 M+ = 352.07 (100.0%),
 M+1 = 353.07 (18.7%),
 M+2 = 354.07 (99.5%),
 M+3 = 355.07 (18.2%),
 M+4 = 356.07 (2.2%)

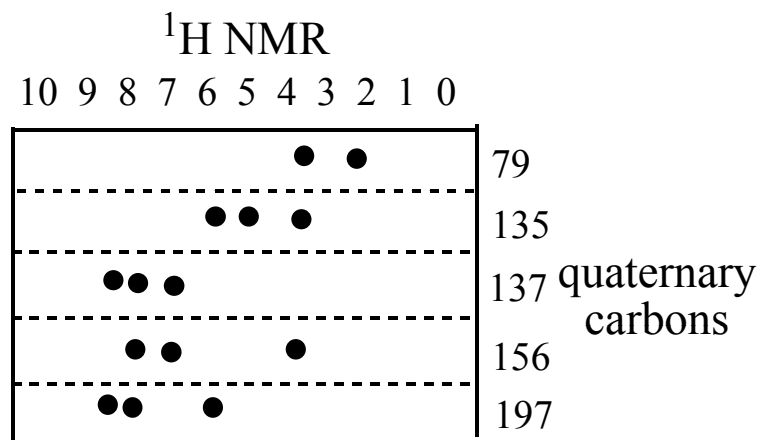
HMBC - uses C/H couplings

Two and three bond C/H coupling constants are approximately 10 Hz. This experiment allows quaternary carbon atoms to see neighbor protons and carbons attached to N or O to see across the heteroatom.

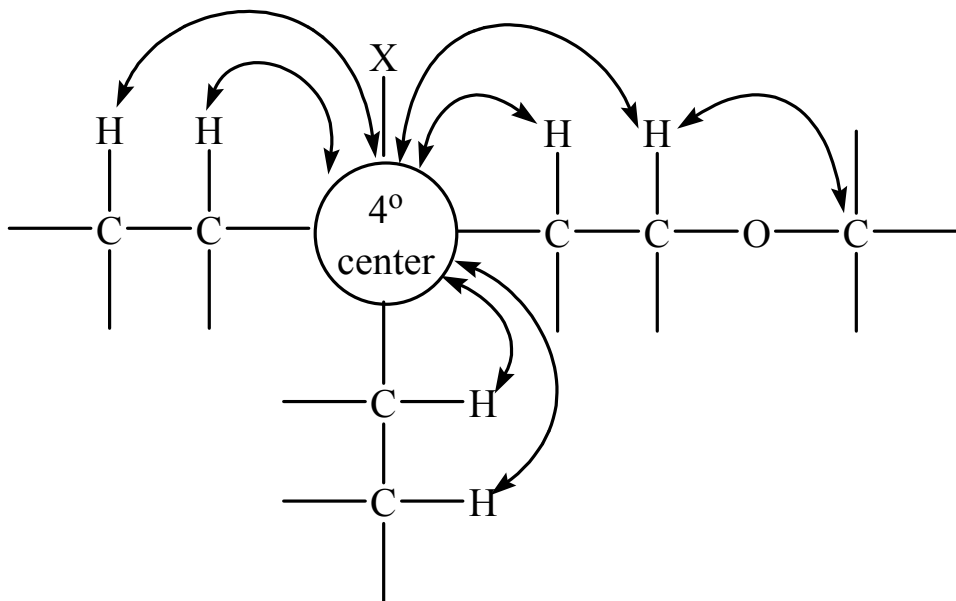


$${}^2J_{CH}, {}^3J_{CH} \approx 7-10 \text{ Hz}$$

X = nitrogen, oxygen
or sulfur atom

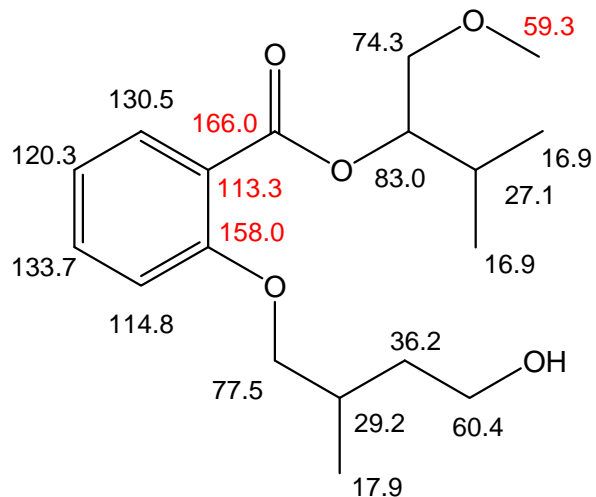
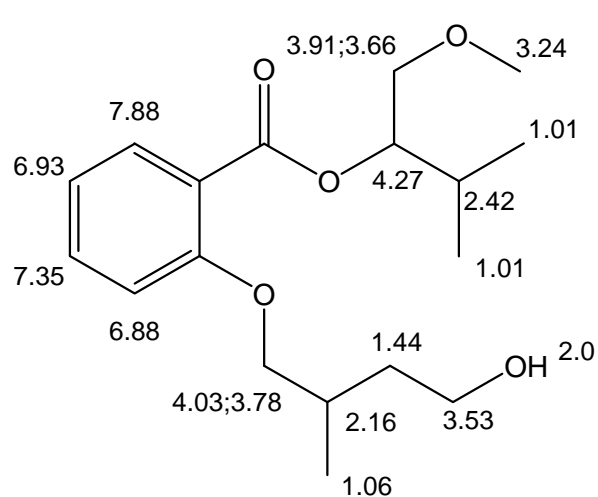


HMBC - heteronuclear multiple bond correlations



HMBC looks for correlations that answer questions about which way spin systems are connected to the quaternary centers and across heteroatoms. There can be many possibilities.

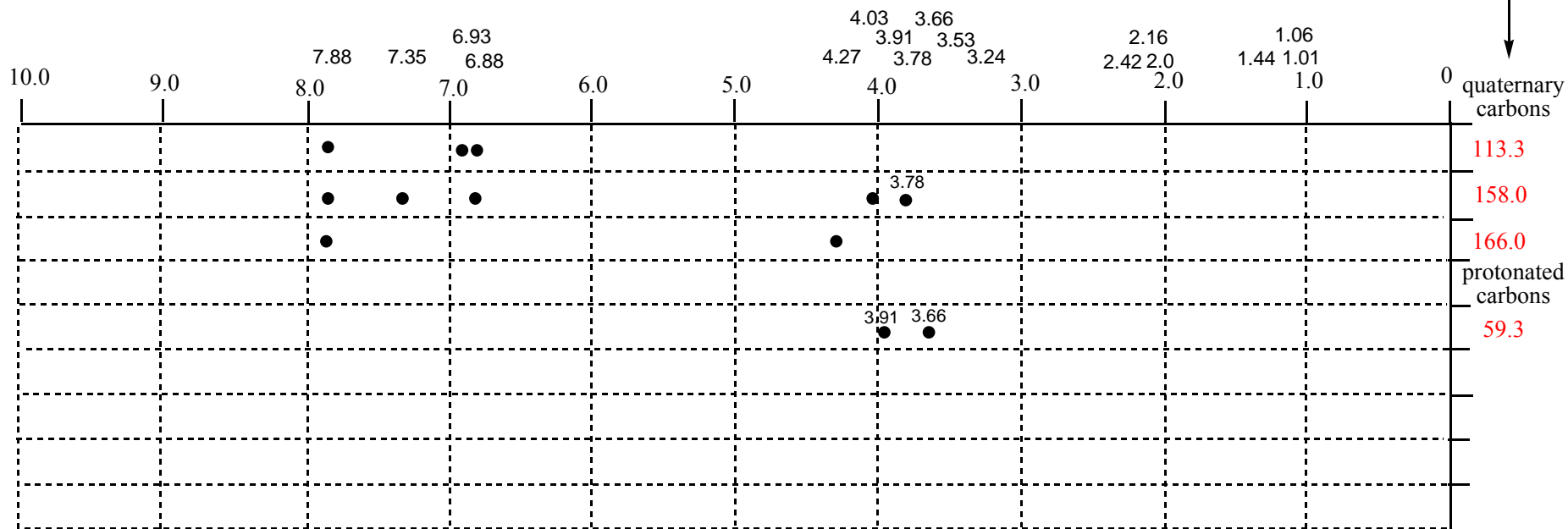
HMBC example - selected carbons



$C_{18}H_{28}O_5$
Exact Mass: 324.19

M+ = 324.19 (100.0%),
M+1 = 325.20 (20.0%),
M+2 = 326.20 (2.9%)

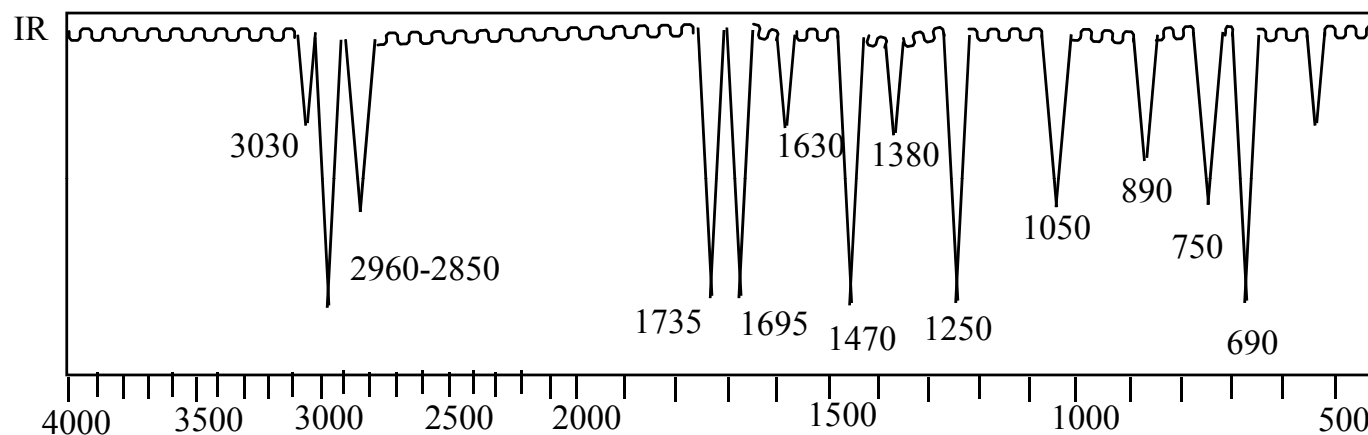
Quaternary carbon atoms can see protons 2 and 3 bonds away and methoxy methyl can see across the ether oxygen atom.



Example problem 1 - Predict a reasonable structure from the spectral information provided below. As much as possible match the spectral information to the part of the structure that it explains. Show all of your work.

MW and IR Spectrum: Interpret as fully as possible from structure. Not every peak is interpretable. (units = cm^{-1})

mass spec data
(exact mass)
MW = 384.1
M+ = 100%
M+1 = 19.9%
M+2 = 97.3%
M+3 = 18.9%



Solve for a molecular formula and degrees of unsaturation.

M+ and M+2 peaks are approximately equal so there is one Br present.

The M+1 peak divided by 1.1 = $19.9/1.1 = 18$ = approximate number of carbon atoms.

The proton NMR shows 25 protons and the ^{13}C NMR shows 18 carbon atoms (confirms MS data).

This all totals to $79 + 25 + 216 = 320$ grams

Residual mass = (total mass) - (320) = $384 - 320 = 64$.

This indicates four oxygen atoms so the formula is $\text{C}_{18}\text{H}_{25}\text{BrO}_4$

2 points

Degrees of unsaturation = $[(2 \times 18 + 2) - (26)] / 2 = 12/2 = 6$

Examination of the ^{13}C NMR shows six =C carbons (3 C=C bonds) and two C=O bonds (total of 5 pi bonds), so the number of rings = (total degrees of unsaturation) - (pi bonds) = $6 - 5 = 1$ ring

IR data:

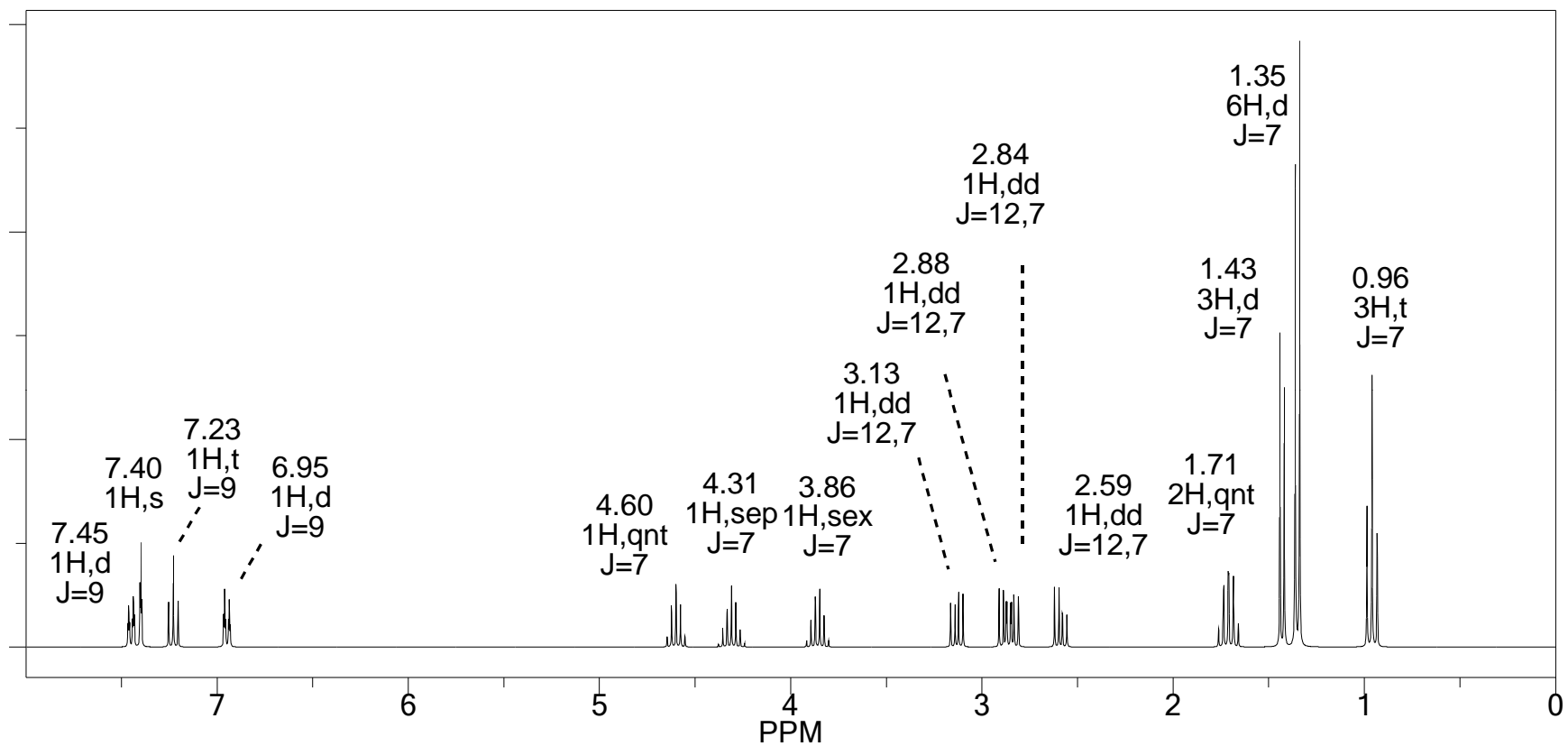
2 points

3030 = sp^2 CH stretch, 1630 = (C=C), 890, 750, 690 possible meta substituted aromatic ring

2960-2850 = sp^3 CH stretch, 1470, 1380 CH bend

1735 = probable ester C=O, 1695 = conjugated ketone 1250 = acyl C-O 1050 = alkoxy C-O

Proton NMR: interpret data (calculate chemical shifts to confirm they match actual values, N = # neighbors)



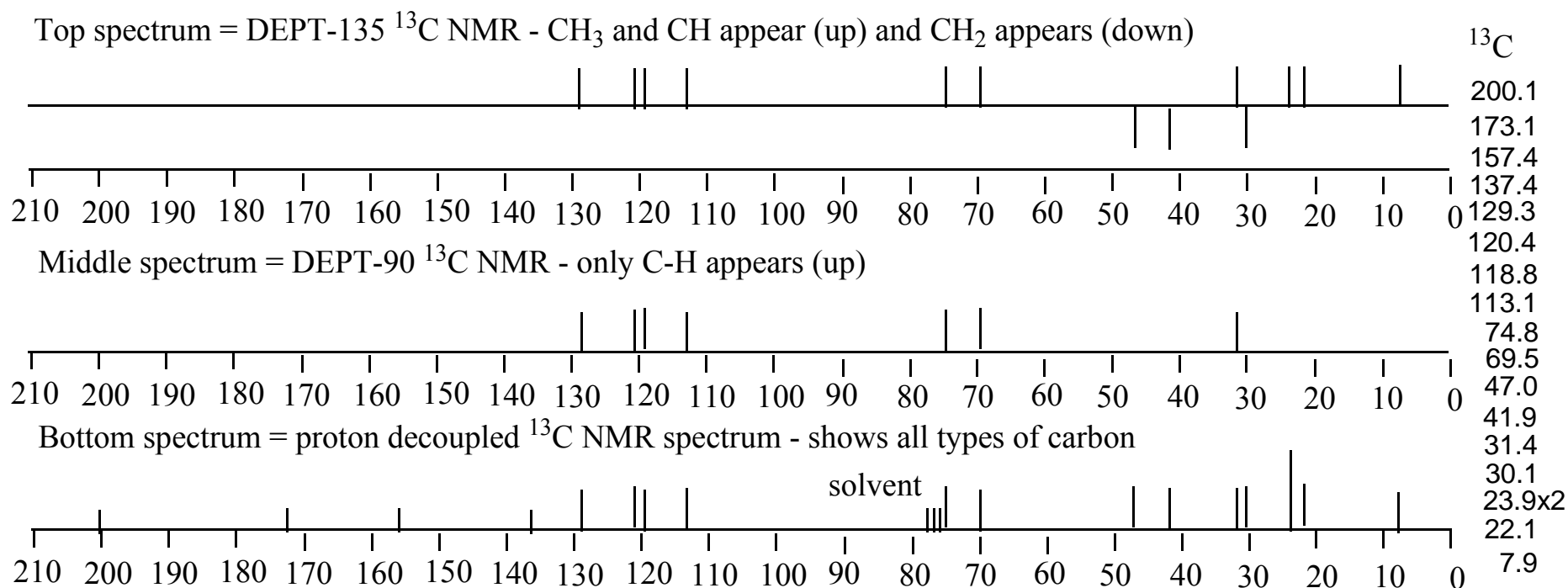
¹H NMR interpretation (4 points)

0.96 3H,t J=7	1.35 6H,d J=7	1.43 3H,d J=7	1.71 2H,qnt J=7	2.84 1H,dd J=12,7	2.59 1H,dd J=12,7
3.13 1H,dd J=12,7	2.88 1H,dd J=12,7	3.86 1H,sex J=7	4.31 1H,sep J=7	4.60 1H,qnt J=7	6.95 1H,d J=9
7.23 1H,t J=9	7.40 1H,s	7.45 1H,d J=9			

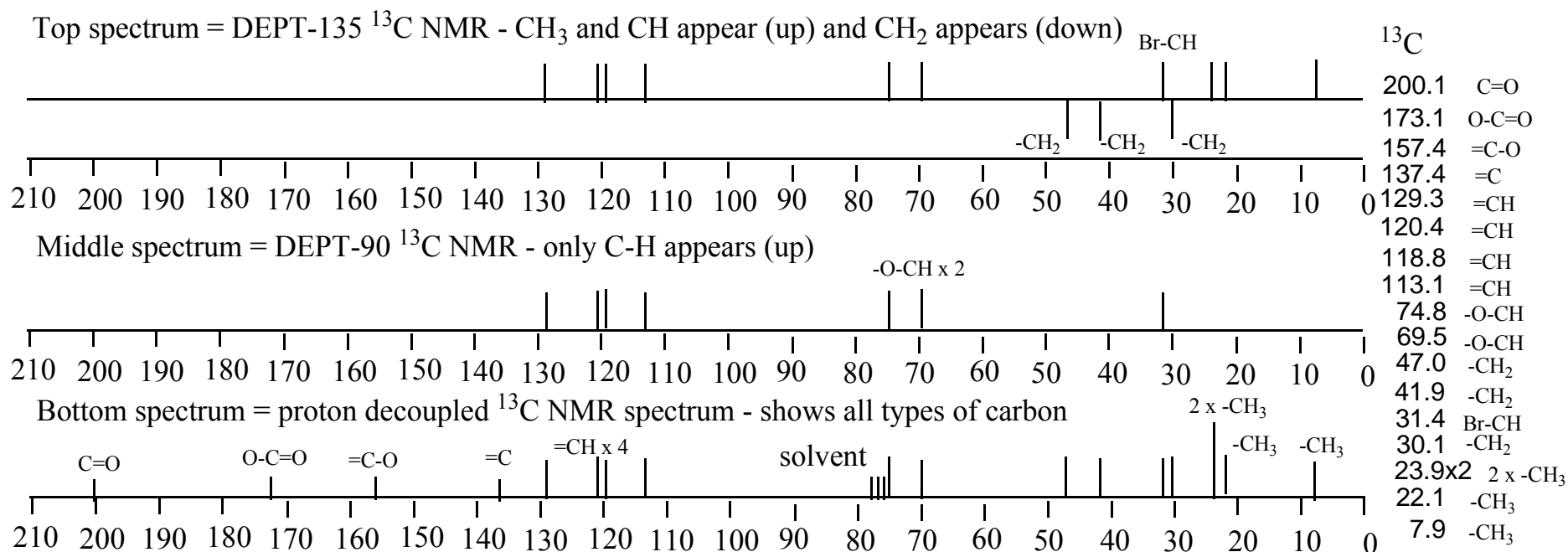
¹H NMR interpretation (4 points)

<p>0.96 3H,t J=7</p> <p>↓</p> <p>H₃C—C—H₂—</p>	<p>1.35 6H,d J=7</p> <p>↙ ↘</p> <p>H₃C—C—CH₃</p> <p> </p>	<p>1.43 3H,d J=7</p> <p>↓</p> <p>H₃C—C—H—</p> <p> </p>	<p>1.71 2H,qnt J=7</p> <p>↘</p> <p>—C—H₂—</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>	<p>2.59 1H,dd J=12,7</p> <p>↘ ↘</p> <p>2.84 1H,dd J=12,7</p> <p>↙ ↘</p> <p>H—C—C*</p> <p> </p> <p>* = chiral center</p>
<p>2.88 1H,dd J=12,7</p> <p>↘ ↘</p> <p>3.13 1H,dd J=12,7</p> <p>↙ ↘</p> <p>H—C—C*</p> <p> </p> <p>* = chiral center</p>	<p>3.86 1H,sex J=7</p> <p>→</p> <p>H</p> <p>↙ ↘</p> <p>O—C—CH₃</p> <p> </p> <p>H₂C—</p>	<p>4.31 1H,sep J=7</p> <p>→</p> <p>H</p> <p>↙ ↘</p> <p>H₃C—C—CH₃</p> <p> </p> <p>O—</p>	<p>4.60 1H,qnt J=7</p> <p>→</p> <p>H</p> <p>↙ ↘</p> <p>Br—C—</p> <p> </p> <p>N = 4 CH₃/CH CH₂/CH₂</p>	<p>6.95 1H,d J=9</p> <p>↘</p> <p>H</p> <p>↙ ↘</p> <p>C=C—H</p> <p> </p> <p>C—H</p>
<p>7.23 1H,t J=9</p> <p>↘</p> <p>H</p> <p>↙ ↘</p> <p>C=C—H</p> <p> </p> <p>C—H</p>	<p>7.40 1H,s</p> <p>↘</p> <p>H</p> <p>↙ ↘</p> <p>C=C—H</p> <p> </p> <p>C—</p>	<p>7.45 1H,d J=9</p> <p>↘</p> <p>H</p> <p>↙ ↘</p> <p>C=C—H</p> <p> </p> <p>C—H</p>		

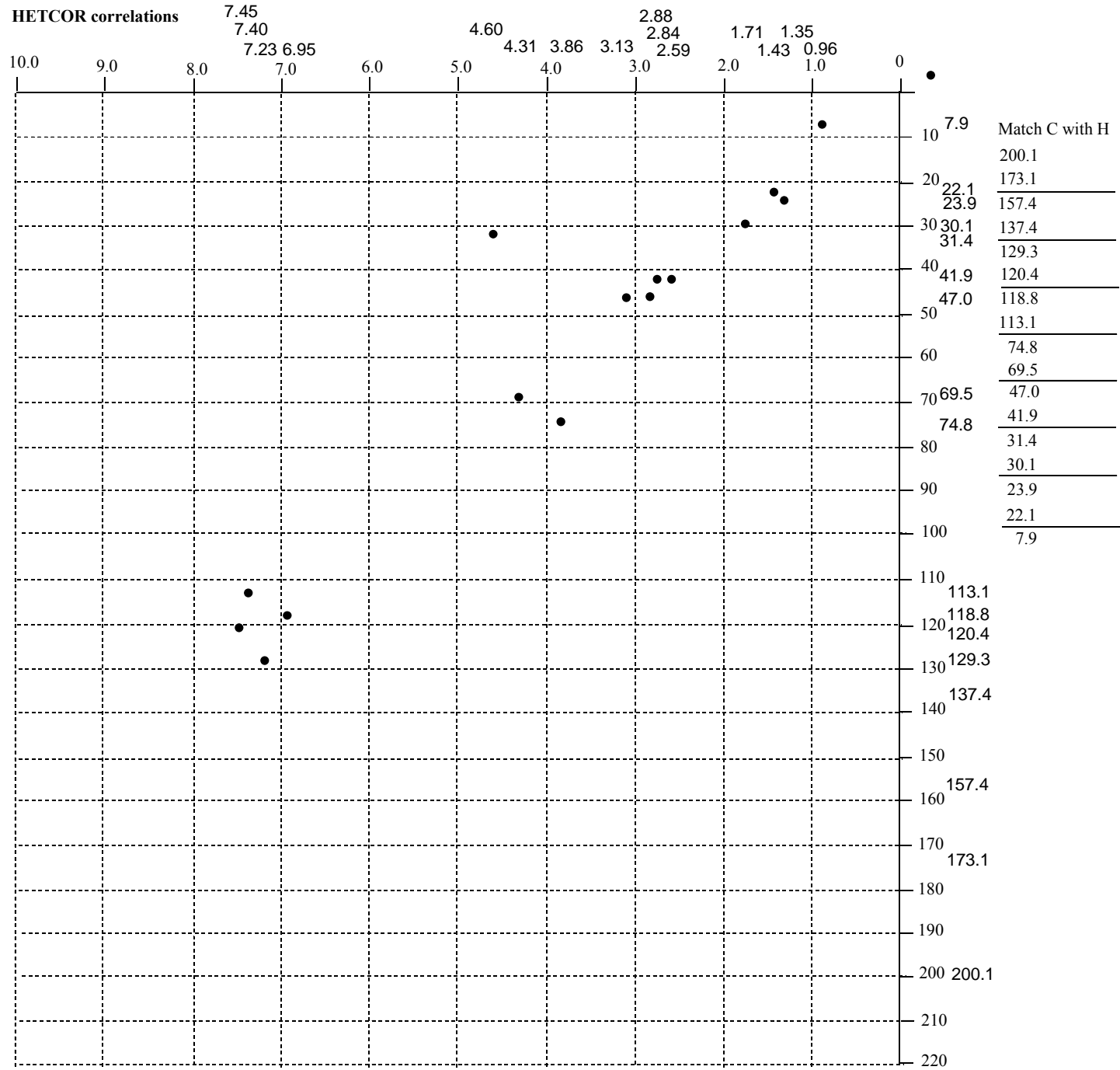
^{13}C and DEPT NMR: As much as possible match the ^{13}C peaks to carbons in your structure.



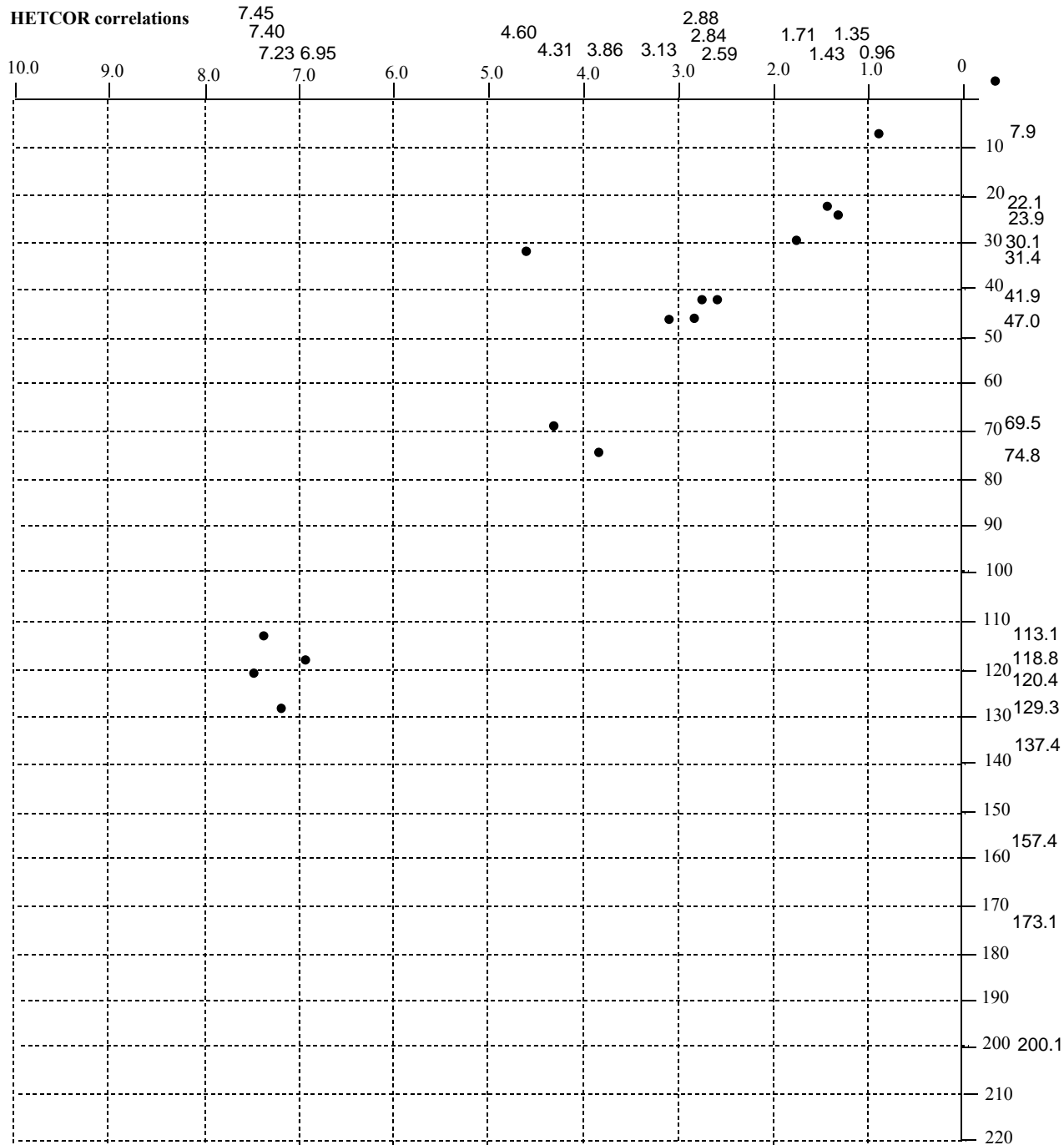
^{13}C and DEPT NMR: As much as possible match the ^{13}C peaks to carbons in your structure.



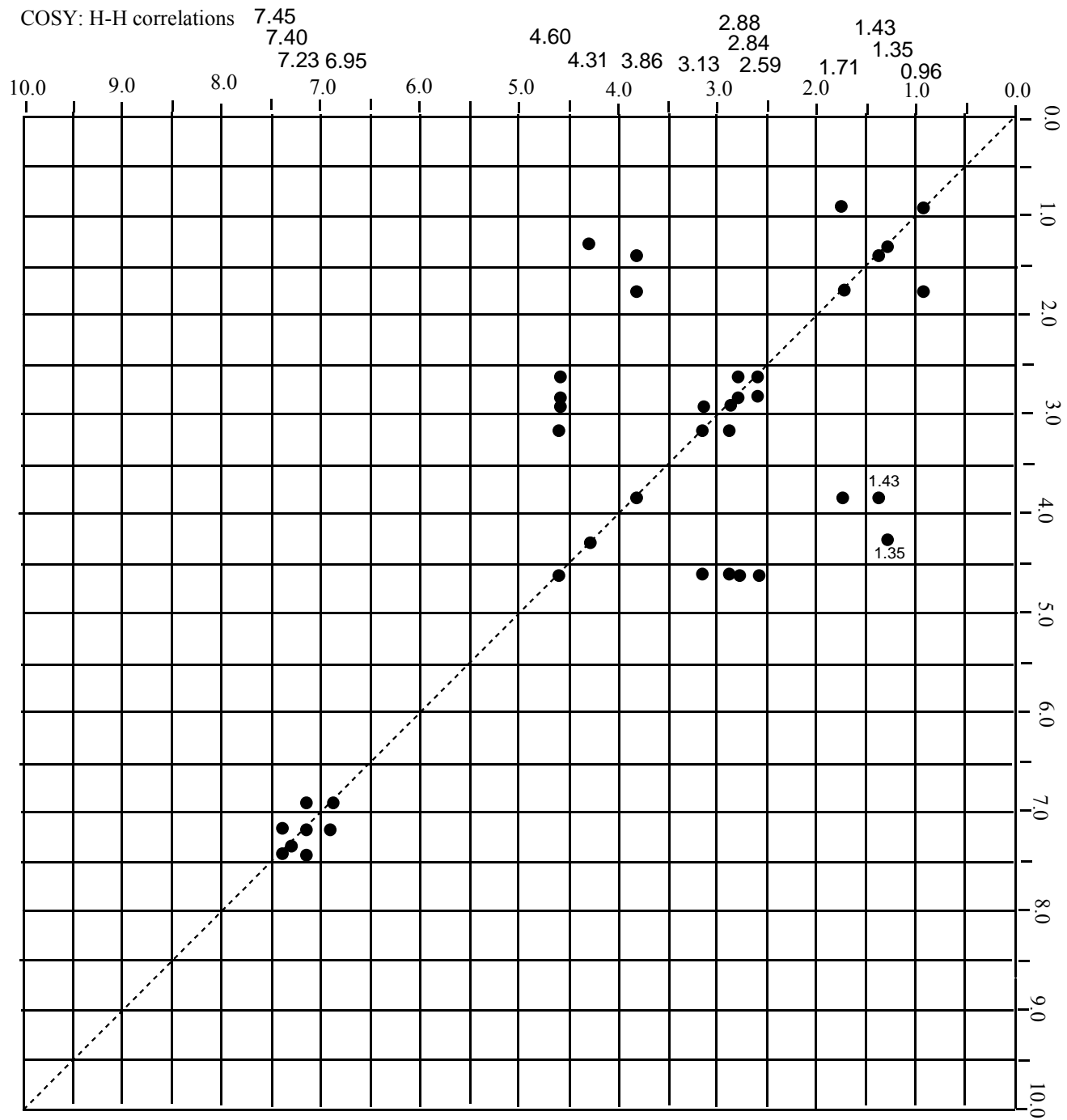
HETCOR correlations



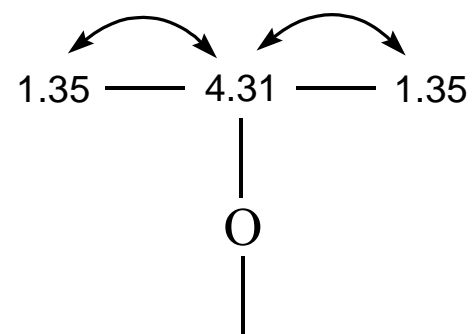
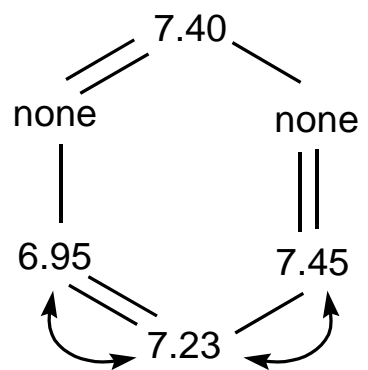
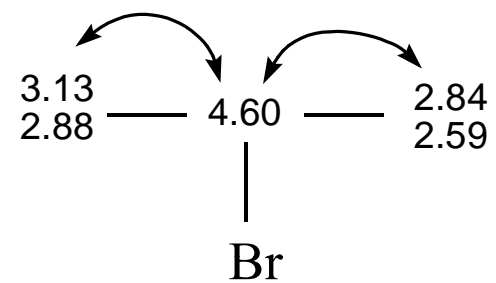
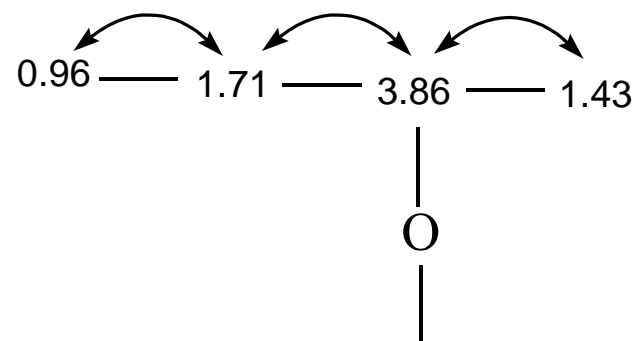
HETCOR correlations



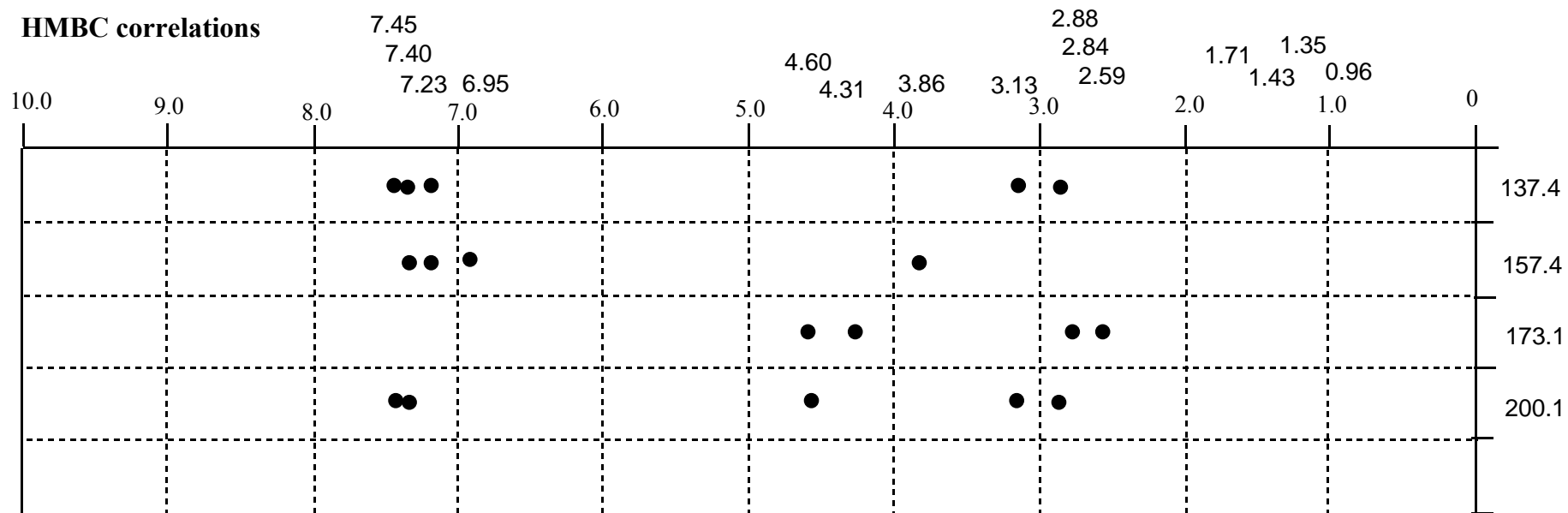
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173.1	none
157.4	none
137.4	none
129.3	7.23
120.4	7.45
118.8	6.95
113.1	7.40
74.8	3.86
69.5	4.31
47.0	3.13, 2.88
41.9	2.84, 2.59
31.4	4.60
30.1	1.71
23.9	1.35
22.1	1.43
7.9	0.96



Spin Systems from COSY

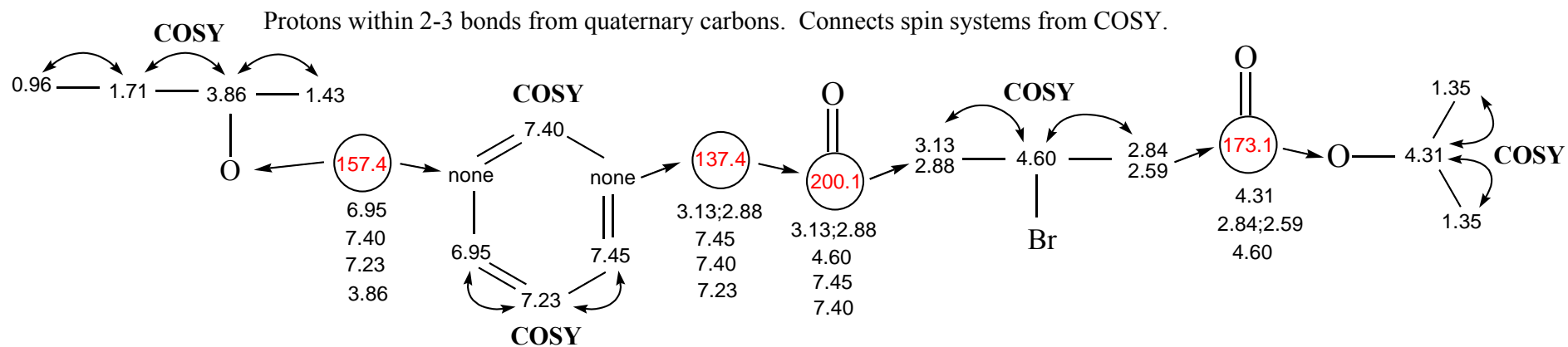


HMBC correlations



HMBC data

protons within 2-3 bonds from quaternary carbons			
157.4	137.4	200.1	173.1
6.95	3.13;2.88	3.13;2.88	4.31
7.40	7.45	4.60	2.84;2.59
7.23	7.40	7.45	4.60
3.86	7.23	7.40	



Solve for a molecular formula and degrees of unsaturation.

2 points

M+ and M+2 peaks are approximately equal so there is one Br present.

The M+1 peak divided by 1.1 = 19.9/1.1 = 18 = approximate number of carbon atoms.

The proton NMR shows 25 protons and the ¹³C NMR shows 18 carbon atoms (confirms MS data).

This all totals to 79 + 25 + 216 = 320 grams

Residual mass = (total mass) - (320) = 384 - 320 = 64.

This indicates four oxygen atoms so the formula is C₁₈H₂₅BrO₄

Degrees of unsaturation = [(2x18 + 2) - (26)] / 2 = 12/2 = 6

Examination of the ¹³C NMR shows six =C carbons (3 C=C bonds) and two C=O bonds (total of 5 pi bonds), so the number of rings = (total degrees of unsaturation) - (pi bonds) = 6 - 5 = 1 ring

IR data:

2 points

3030 = sp² CH stretch, 1630 = (C=C), 890, 750, 690 possible meta substituted aromatic ring

2960-2850 = sp³ CH stretch, 1470, 1380 CH bend

1735 = probable ester C=O, 1695 = conjugated ketone 1250 = acyl C-O 1050 = alkoxy C-O

Tabulated 2D NMR Information

¹³ C	DEPT	HETCOR	COSY	HMBC
200.1	C=O	none	none	7.45 7.40 4.60 3.13,2.88
173.1	O-C=O	none	none	4.60 4.31 2.84,2.59
157.4	=C-O	none	none	7.40 7.23 6.95 3.86
137.4	=C-	none	none	7.45 7.40 7.23 4.60 3.13,2.88
129.3	=C-H	7.23	7.45 6.95	
120.4	=C-H	7.45	7.23	
118.8	=C-H	6.95	7.23	
113.1	=C-H	7.40	none	
74.8	O-CH	3.86	1.71 1.43	
69.5	O-CH	4.31	1.35	
47.0	CH2	3.13,2.88	4.60, gem	
41.9	CH2	2.84,2.59	4.60, gem	
31.4	Br-CH	4.60	3.13,2.88 2.84,2.59	
30.1	CH2	1.71	3.86 0.96	
23.9	CH3	1.35	4.31	
22.1	CH3	1.43	3.86	
7.9	CH3	0.96	1.71	

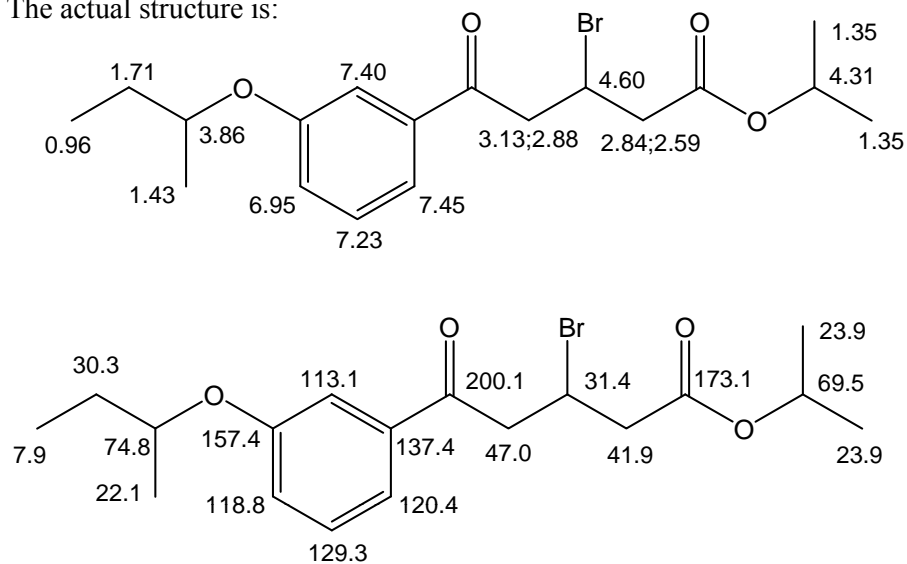
2 points

2 points

2 points

2 points

The actual structure is:



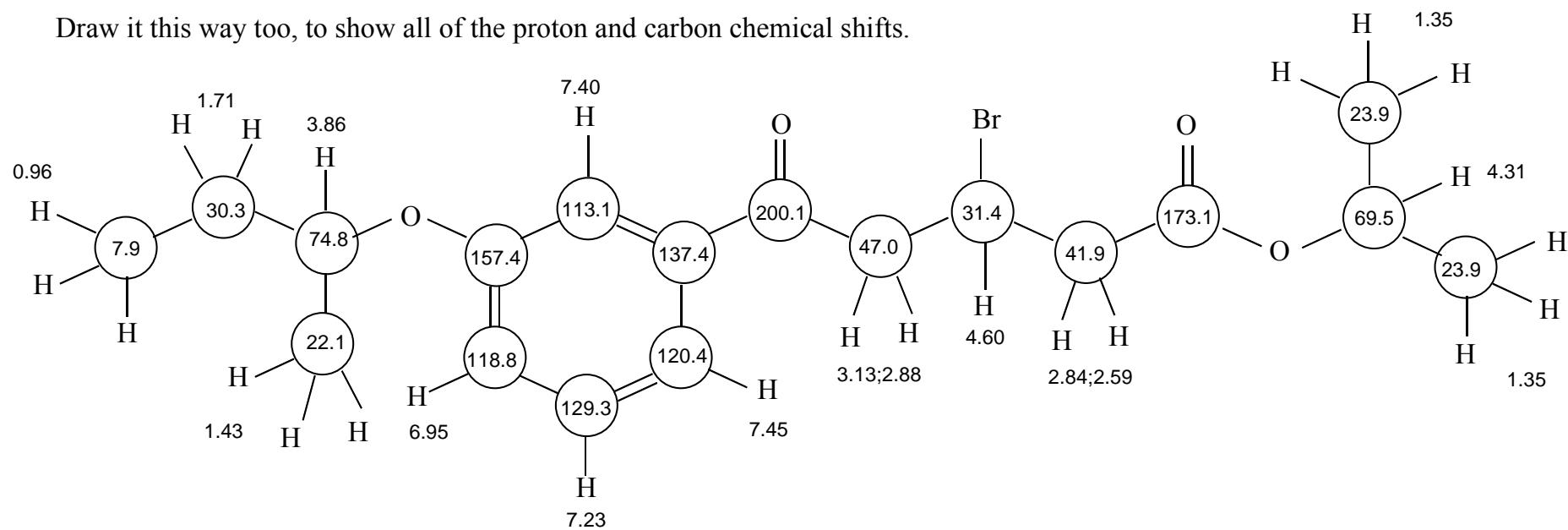
$C_{18}H_{25}BrO_4$
 Exact Mass: 384.09
 M+ = 384.09 (100.0%),
 M+1 = 385.10 (19.9%),
 M+2 = 386.09 (97.3%),
 M+3 = 387.09 (18.9%),

correct structure

4 points

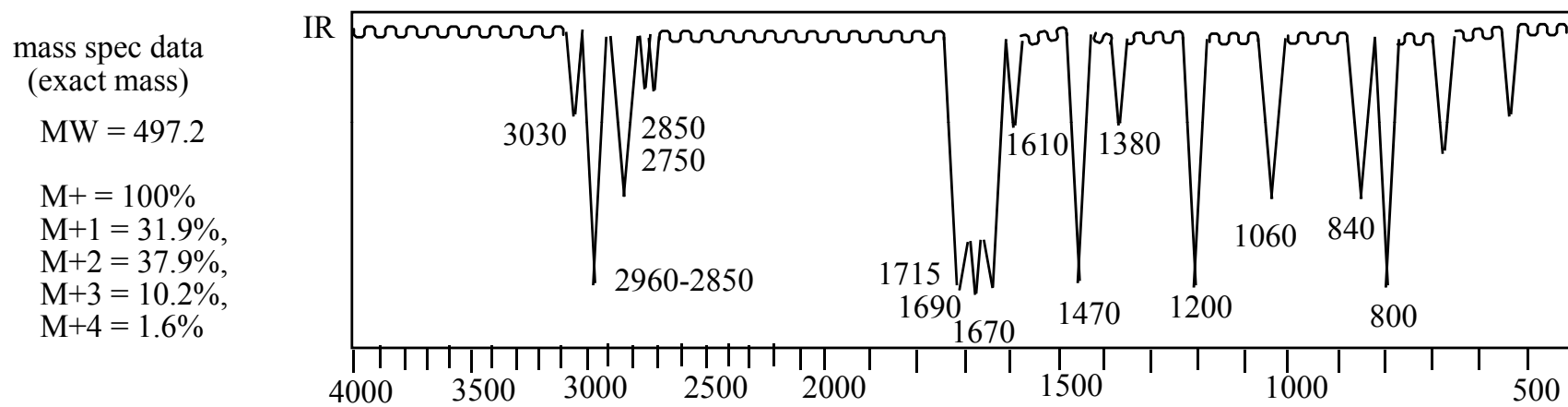
Total = 20 points

Draw it this way too, to show all of the proton and carbon chemical shifts.



Example problem 2 - Predict a reasonable structure from the spectral information provided below. As much as possible match the spectral information to the part of the structure that it explains. Show all of your work.

MW and IR Spectrum: Interpret as fully as possible from structure. Not every peak is interpretable. (units = cm^{-1})



Solve for a molecular formula and degrees of unsaturation.

M+ is odd indicating an odd number of nitrogen atoms

M+ and M+2 peaks are approximately a 3/1 ratio so there is one Cl present.

The M+1 peak divided by 1.1 = $31.9/1.1 = 29$ = approximate number of carbon atoms.

The proton NMR shows 36 protons and the ^{13}C NMR shows 29 carbon atoms (confirms MS data).

This all totals to $35 + 36 + 348 = 419$ grams

Residual mass = (total mass) - (419) = $497 - 419 = 78$.

residual mass $78 - 14 = 64 = 4 \times \text{O}$

This indicates four oxygen atoms so the formula is $\text{C}_{29}\text{H}_{36}\text{ClNO}_4$

2 points

Degrees of unsaturation = $[(2 \times 29 + 2 + 1) - (37)] / 2 = 24/2 = 12$

Examination of the ^{13}C NMR shows 14 =C carbons (7 C=C bonds) and 3 C=O bonds (total of 10 pi bonds), so the number of rings = (total degrees of unsaturation) - (pi bonds) = $12 - 10 = 2$ rings

IR data:

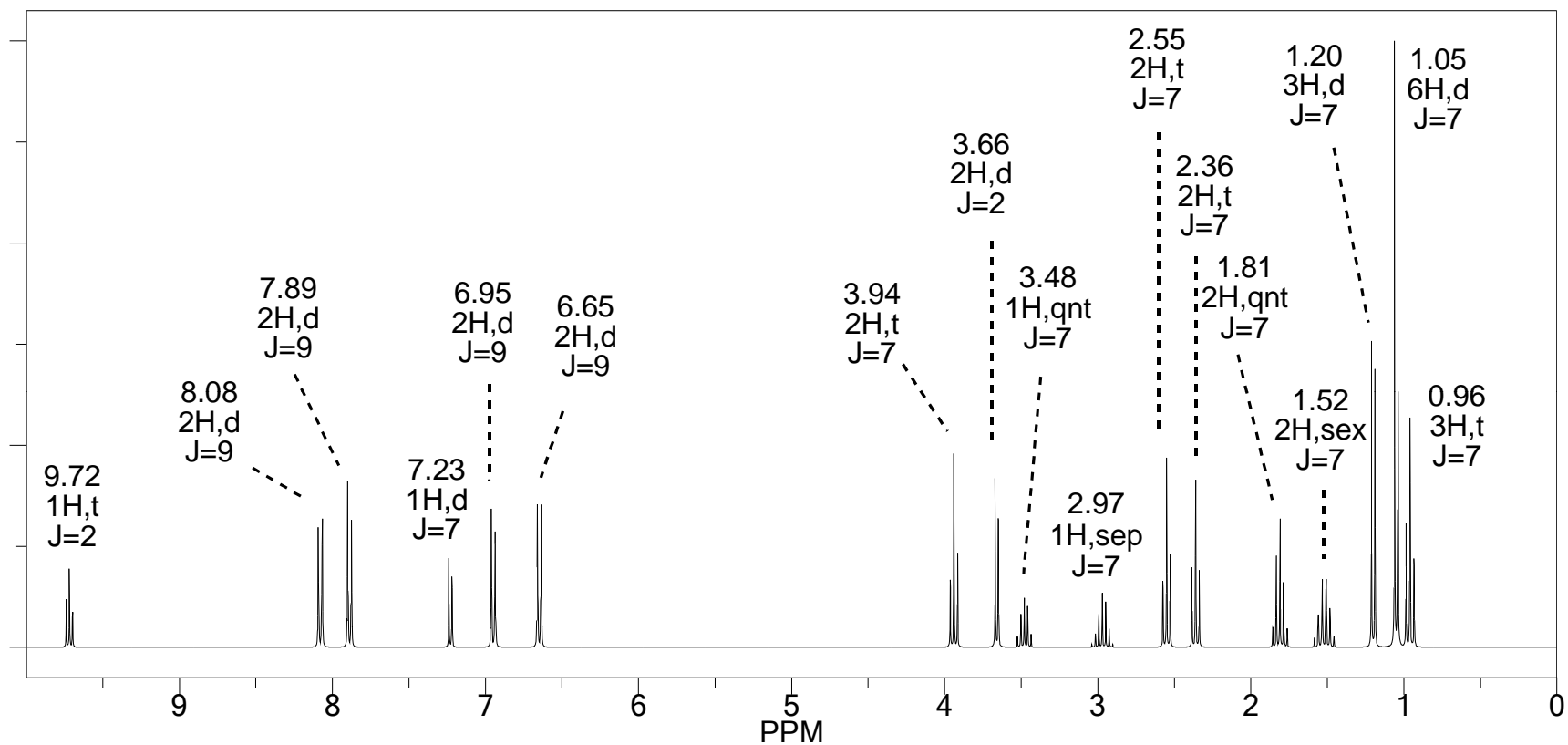
2 points

3030 = sp^2 CH stretch, 1630 = (C=C), 840 and 800 possible para substituted aromatic ring,
possible trisubstituted alkene

2960-2850 = sp^3 CH stretch, 1470, 1380 CH bend,
aldehyde C-H stretch, 2850 and 2750

3 x C=O, 1715 1690, 1670, 2 are conjugated, 1 is aldehyde 1200 = sp^2 C-O 1060 = alkoxy C-O
at least 1 nitrogen, but no nitrile or primary NH_2 or secondary NH or nitro; maybe a tertiary amine

Proton NMR: interpret data (calculate chemical shifts to confirm they match actual values, N = # neighbors)



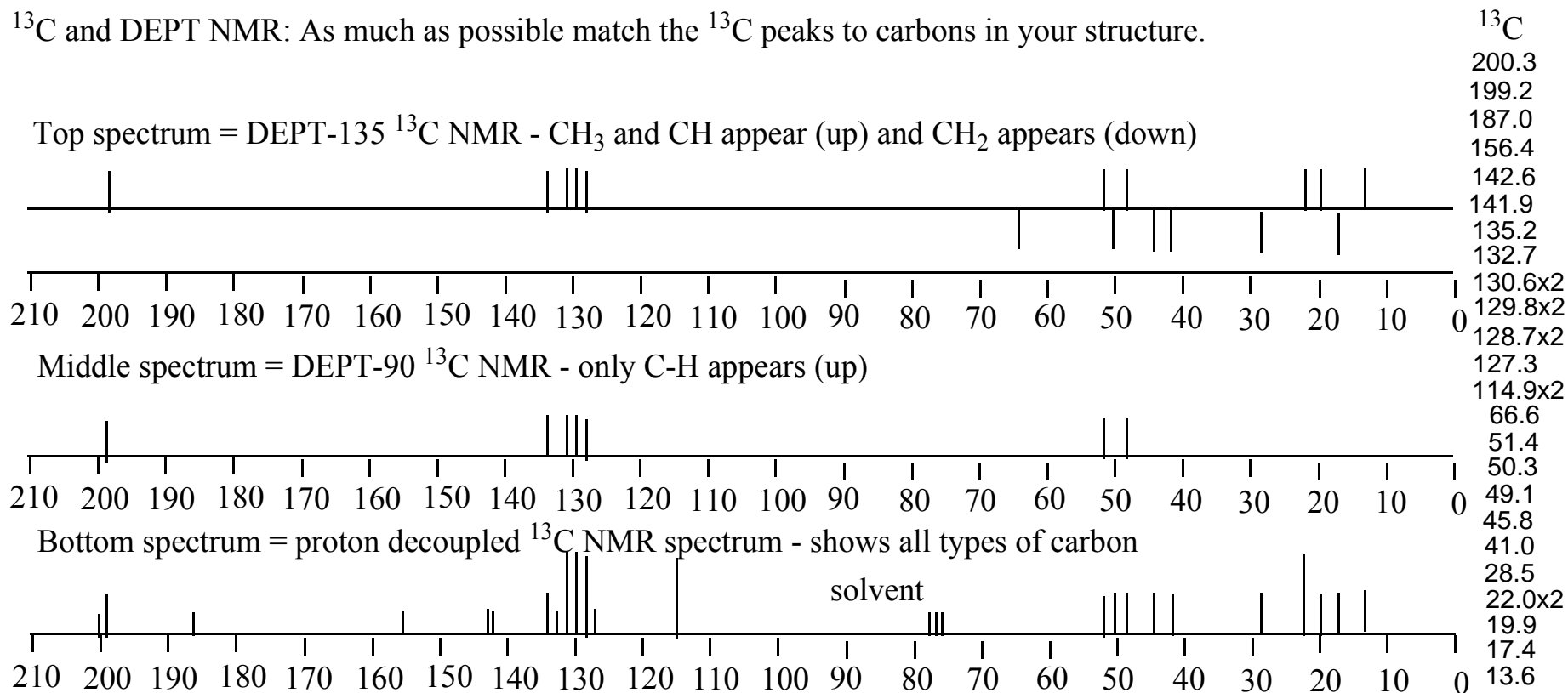
^1H NMR interpretation (4 points)

0.96 3H,t J=7	1.20 3H,d J=7	1.05 6H,d J=7	1.52 2H,sex J=7	1.81 2H,qnt J=7
2.36 2H,t J=7	2.55 2H,t J=7	2.97 1H,sep J=7	3.48 1H,qnt J=7	3.66 2H,d J=2
3.94 2H,t J=7	6.65 2H,d J=9	6.95 2H,d J=9	7.23 1H,d J=7	7.89 2H,d J=9
8.08 2H,d J=9	9.72 1H,t J=2			

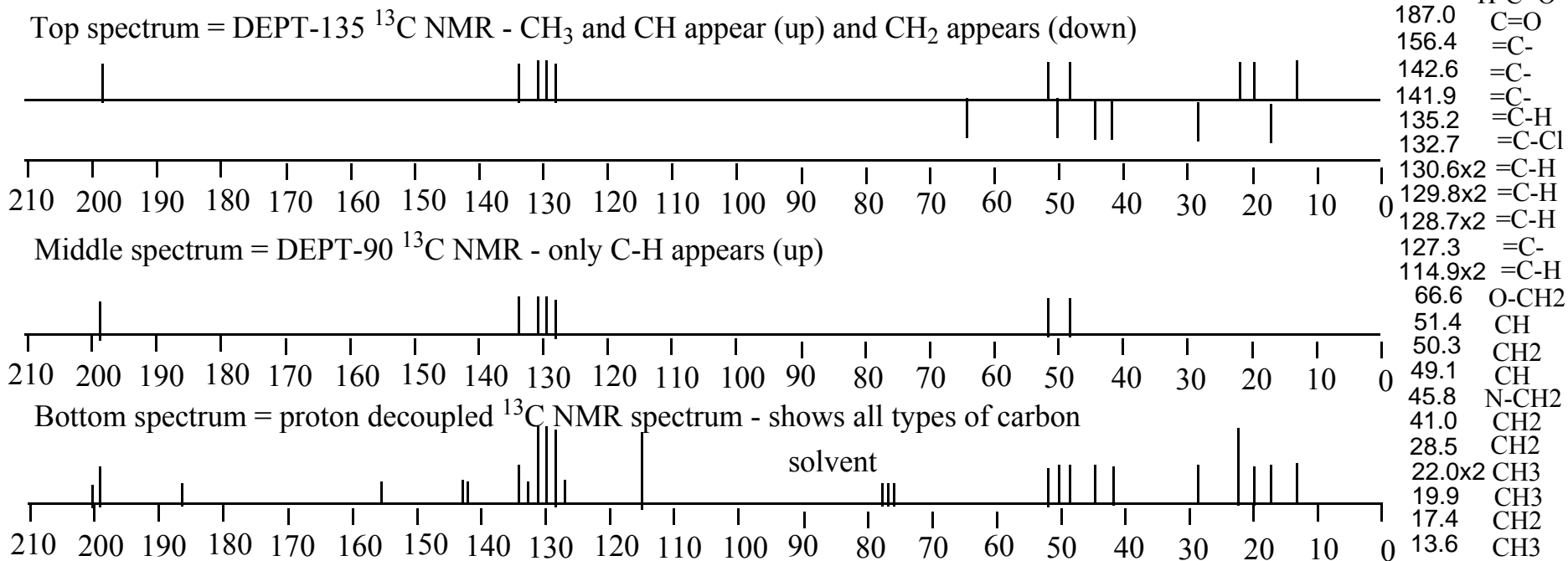
¹H NMR interpretation (4 points)

<p>0.96 3H,t J=7</p> <p>↓</p> <p>H₃C—C—H₂—</p>	<p>1.20 3H,d J=7</p> <p>↓</p> <p>H₃C—C—H</p>	<p>1.05 6H,d J=7</p> <p>↓</p> <p>H₃C—C—H₃C</p>	<p>1.52 2H,sex J=7</p> <p>↓</p> <p>H₃C—C—CH₂—</p>	<p>1.81 2H,qrt J=7</p> <p>↓</p> <p>—C—H₂—</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>
<p>2.36 2H,t J=7</p> <p>↓</p> <p>—C—H₂—</p> <p>N = 2 CH₂ CH/CH</p>	<p>2.55 2H,t J=7</p> <p>↓</p> <p>—C—H₂—</p> <p>N = 2 CH₂ CH/CH</p>	<p>2.97 1H,sep J=7</p> <p>↓</p> <p>H₃C—C—H</p>	<p>3.48 1H,qrt J=7</p> <p>↓</p> <p>—C—H₂—</p> <p>N = 4 CH₃/CH CH₂/CH₂</p>	<p>3.66 2H,d J=2</p> <p>↓</p> <p>H—C(=O)—CH₂—</p>
<p>3.94 2H,t J=7</p> <p>↓</p> <p>—C—H₂—</p> <p>N = 2 CH₂ CH/CH</p>	<p>6.65 2H,d J=9</p> <p>↓</p> <p>—C=C—H</p>	<p>6.95 2H,d J=9</p> <p>↓</p> <p>—C=C—H</p>	<p>7.23 1H,d J=7</p> <p>↓</p> <p>—C=C—H</p>	<p>7.89 2H,d J=9</p> <p>↓</p> <p>—C=C—H</p>
<p>8.08 2H,d J=9</p> <p>↓</p> <p>—C=C—H</p>	<p>9.72 1H,t J=2</p> <p>↓</p> <p>H—C(=O)—CH₂—</p>			

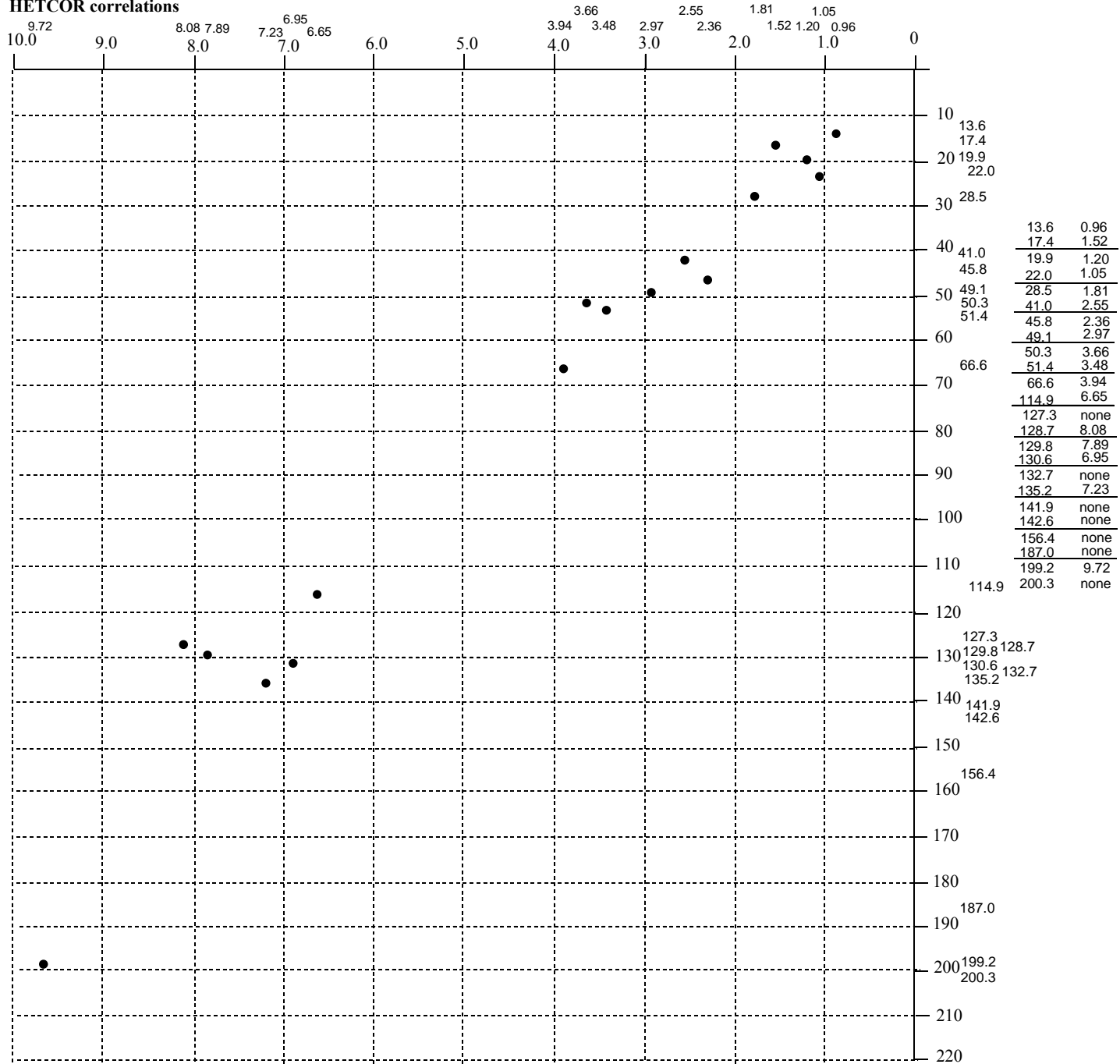
^{13}C and DEPT NMR: As much as possible match the ^{13}C peaks to carbons in your structure.



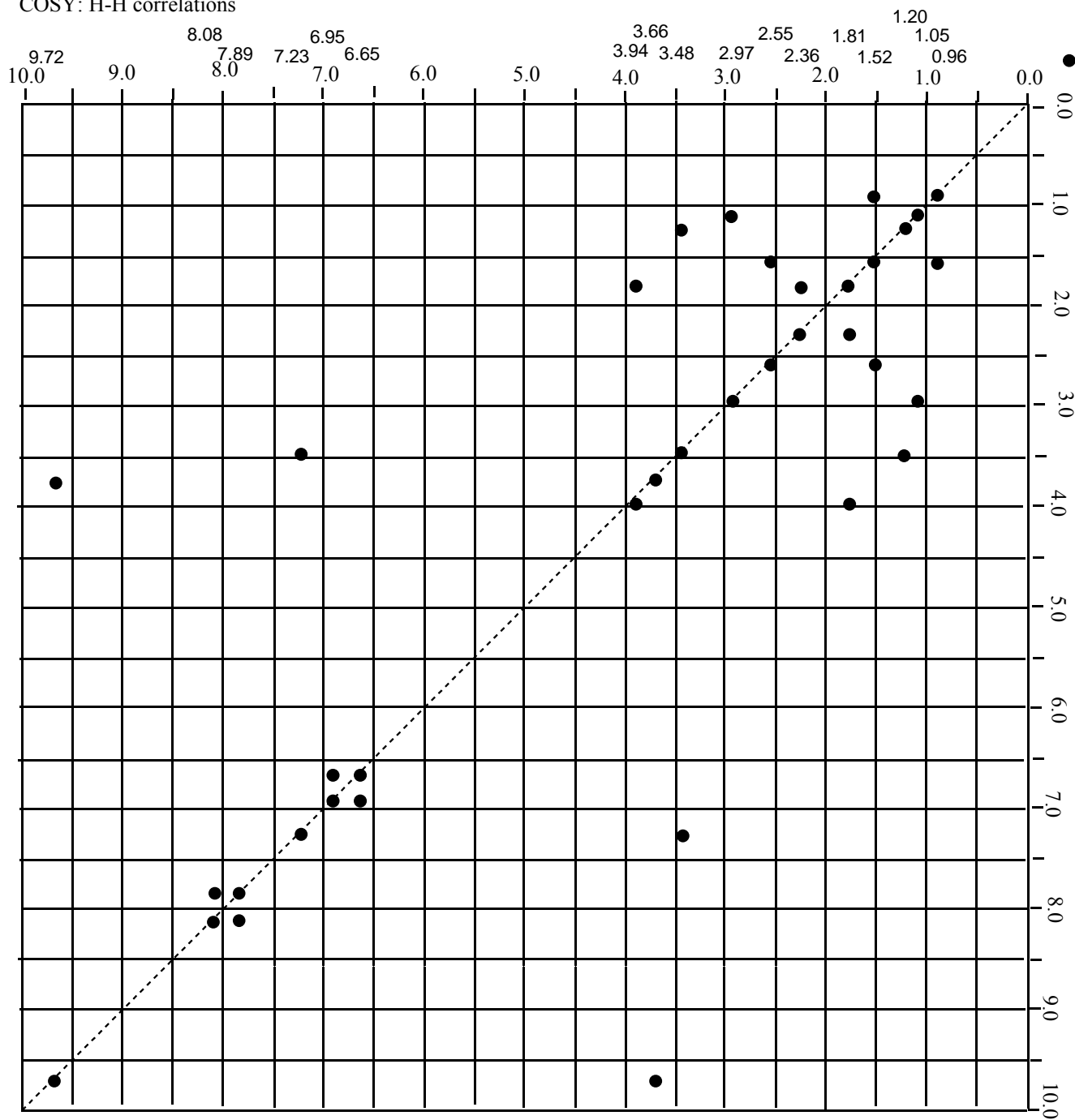
^{13}C and DEPT NMR: As much as possible match the ^{13}C peaks to carbons in your structure.



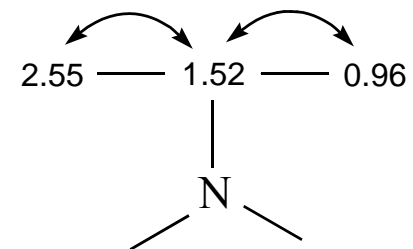
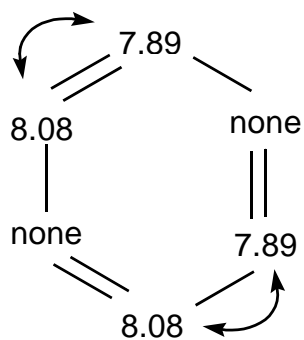
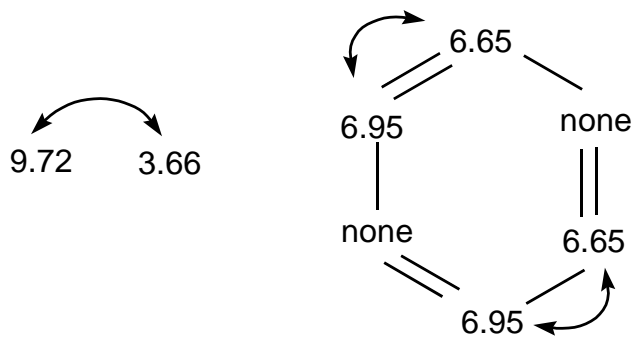
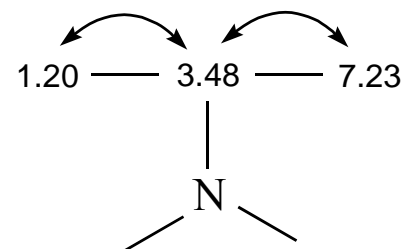
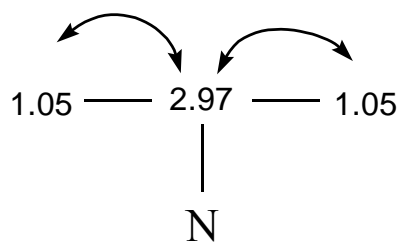
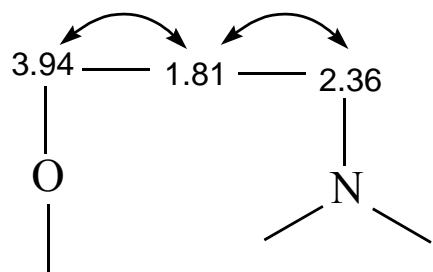
HETCOR correlations



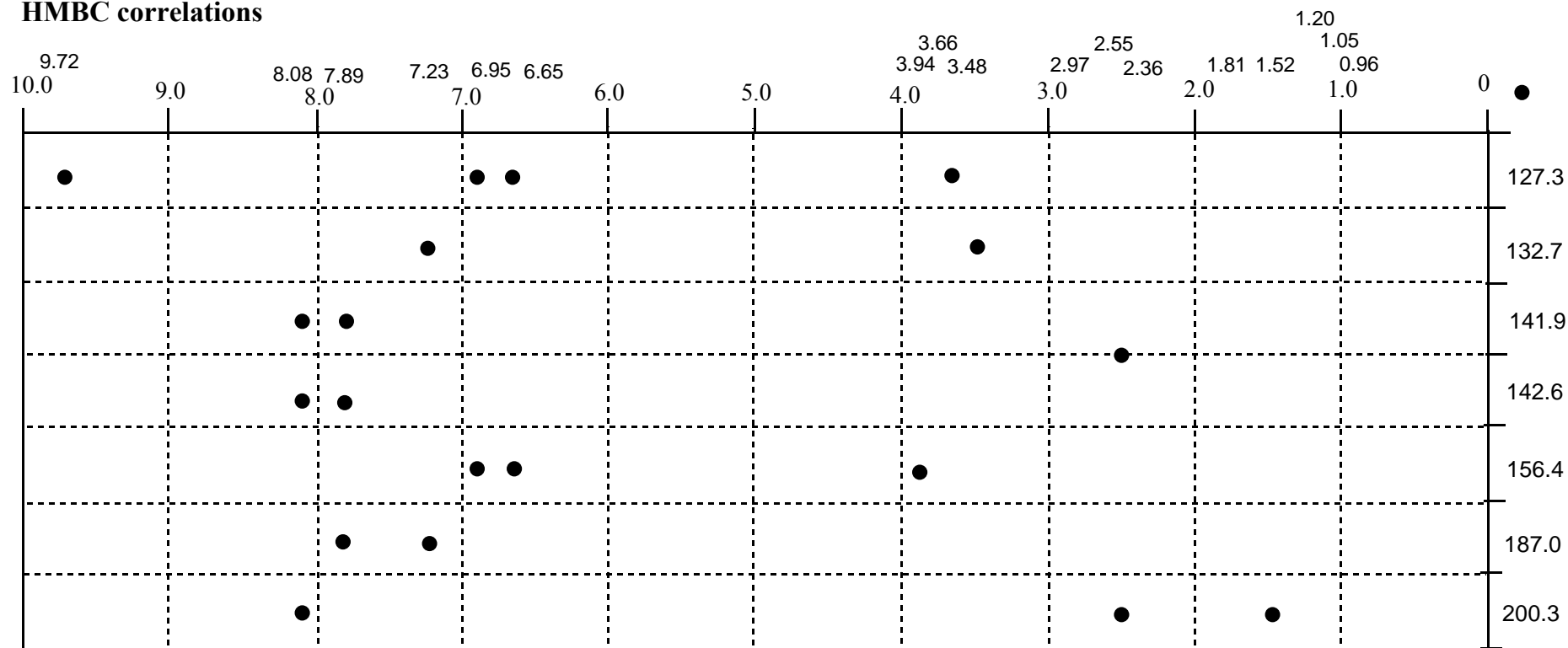
COSY: H-H correlations



Spin Systems from COSY



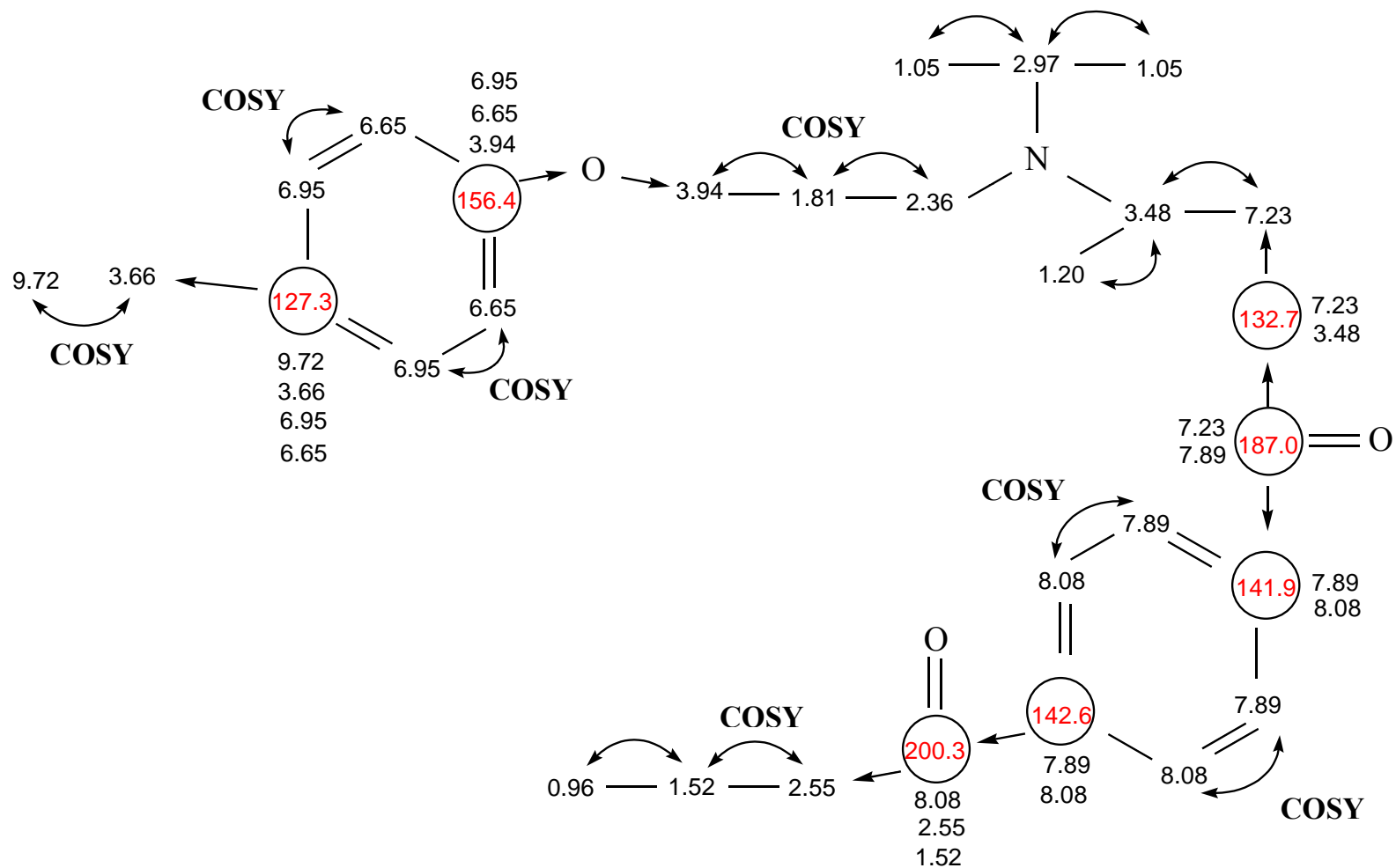
HMBC correlations



HMBC data

127.3	156.4	132.7	187.0	141.9	142.6	200.3
9.72	6.95	7.23	7.23	7.89	7.89	8.08
3.66	6.65	3.48	7.89	8.08	8.08	2.55
6.95	3.94					1.52
6.65						

Protons within 2-3 bonds from quaternary carbons. Connects spin systems from COSY.



Solve for a molecular formula and degrees of unsaturation. 2 points

M+ is odd indicating an odd number of nitrogen atoms

M+ and M+2 peaks are approximately a 3/1 ratio so there is one Cl present.

The M+1 peak divided by 1.1 = 31.9/1.1 = 29 = approximate number of carbon atoms.

The proton NMR shows 36 protons and the ¹³C NMR shows 29 carbon atoms (confirms MS data).

This all totals to 35 + 36 + 348 = 419 grams

Residual mass = (total mass) - (419) = 497 - 419 = 78.

residual mass 78 - 14 = 64 = 4 x O

This indicates four oxygen atoms so the formula is C₂₉H₃₆ClNO₄

Degrees of unsaturation = [(2x29 + 2 + 1) - (37)] / 2 = 24/2 = 12

Examination of the ¹³C NMR shows 14 =C carbons (7 C=C bonds) and 3 C=O bonds (total of

10 pi bonds), so the number of rings = (total degrees of unsaturation) - (pi bonds) = 12 - 10 = 2 rings

IR data:

2 points

3030 = sp² CH stretch, 1630 = (C=C), 840 and 800 possible para substituted aromatic ring, and possible trisubstituted alkene, 2960-2850 = sp³ CH stretch, 1470, 1380 CH bend, aldehyde C-H stretch, 2850 and 2750, 3 x C=O, 1715 1690, 1670, 2 are conjugated, 1 is aldehyde, 1200 = sp² C-O, 1060 = alkoxy C-O, at least 1 nitrogen, but no nitrile or primary NH₂ or secondary NH or nitro; maybe a tertiary amine

Tabulated 2D NMR Information

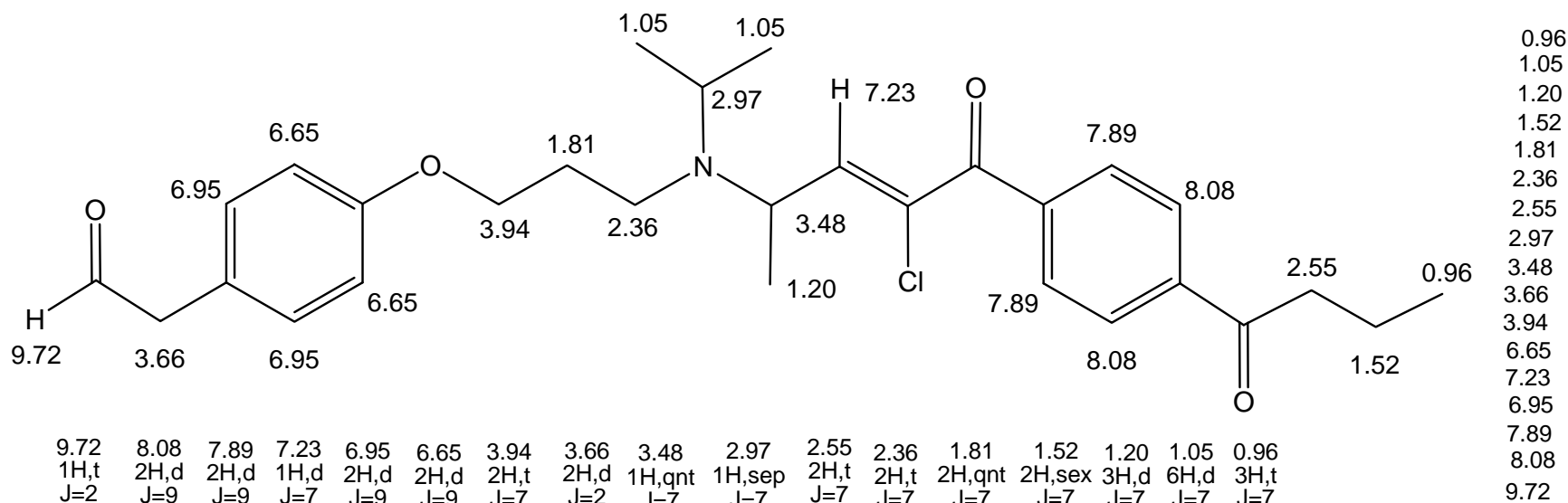
¹³ C	DEPT	HETCOR	COSY	HMBC
200.3 199.2	C=O H-C=O	none 9.72	none 3.66	8.08 2.55 1.52
187.0 156.4	C=O =C-	none none	none none	7.89 7.23 6.95 6.65 3.94
142.6 141.9	=C- =C-	none none	none none	8.08 7.89 2.55 8.08 7.89
135.2 132.7	=C-H =C-Cl	7.23 none	3.48 none	7.23 3.48
130.6x2 129.8x2	=C-H =C-H	6.95 7.89	6.65 8.08	
128.7x2 127.3	=C-H =C-	8.08 none	7.89 none	9.72 6.95 6.65 3.66
114.9x2 66.6	=C-H O-CH ₂	6.65 3.94	6.95 1.81	
51.4 50.3	CH CH ₂	3.48 3.66	7.23 1.20 9.72	
49.1 45.8	CH CH ₂	2.97 2.36	1.05 1.81	
41.0 28.5	CH ₂ CH ₂	2.55 1.81	1.52 3.94 2.36	
22.0x2 19.9	CH ₃ CH ₃	1.05 1.20	2.97 3.48	
17.4 13.6	CH ₂ CH ₃	1.52 0.96	2.55 0.96 1.52	(Prob 84)

2 points

2 points

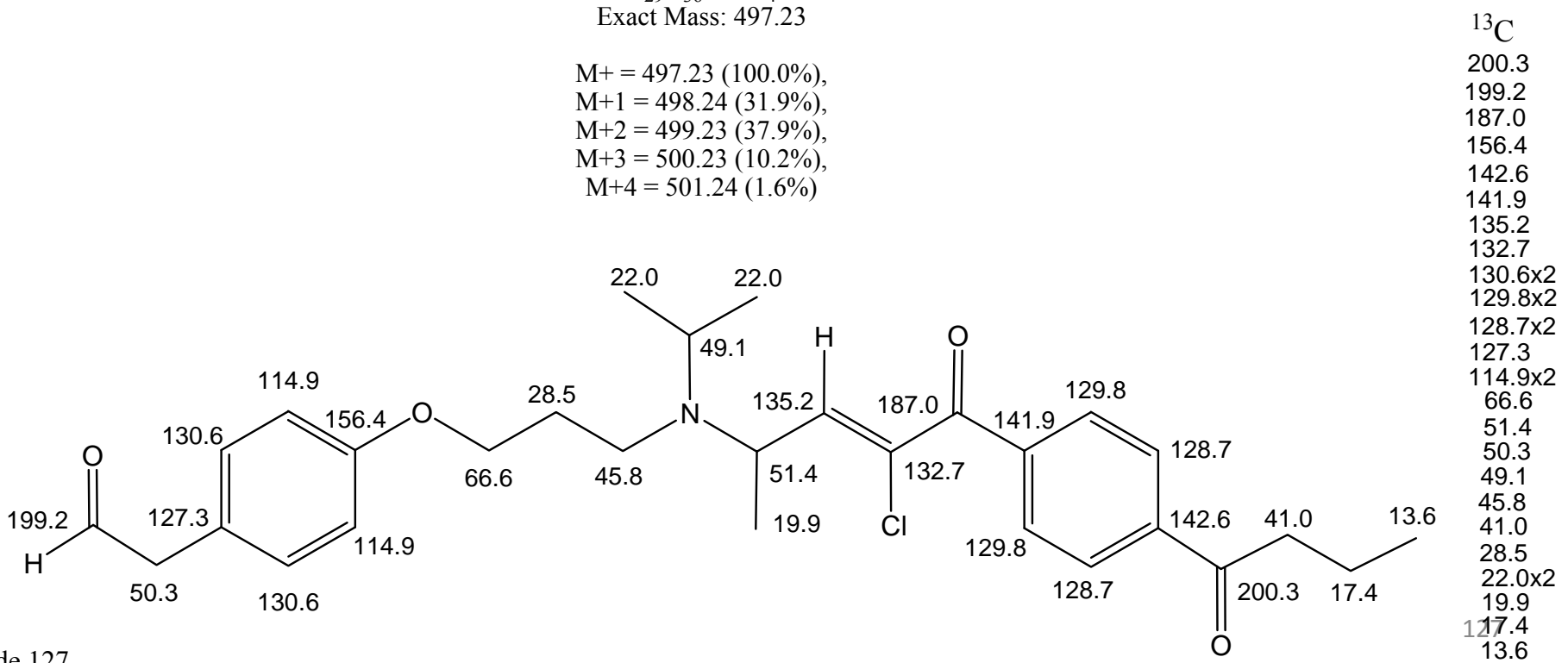
2 points

2 points

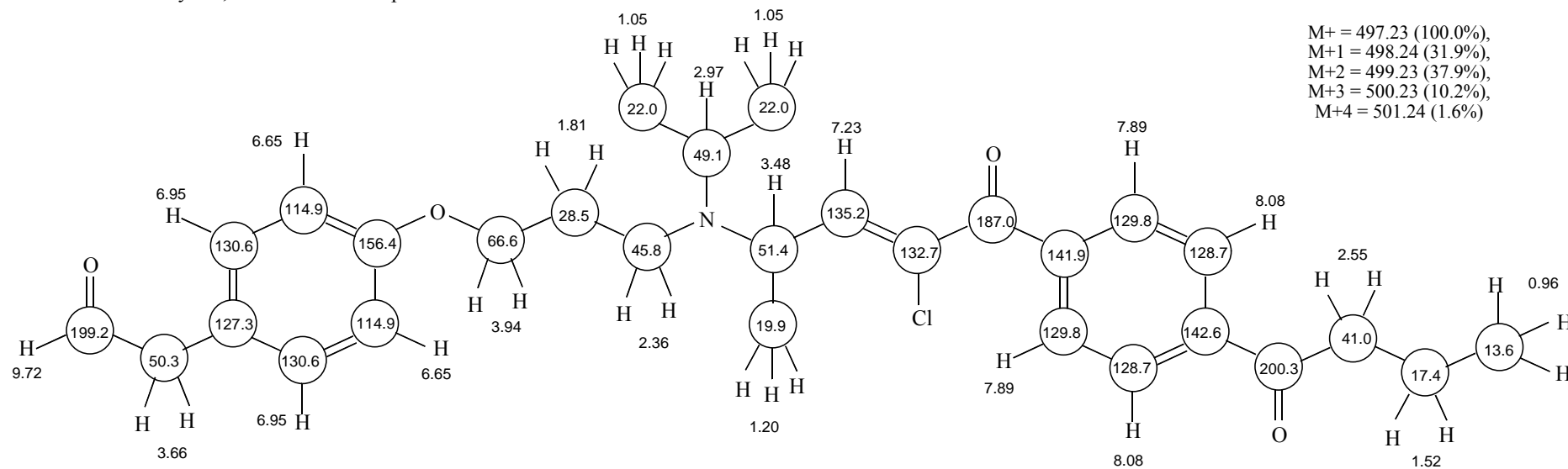


$\text{C}_{29}\text{H}_{36}\text{ClNO}_4$
 Exact Mass: 497.23

$M^+ = 497.23$ (100.0%),
 $M+1 = 498.24$ (31.9%),
 $M+2 = 499.23$ (37.9%),
 $M+3 = 500.23$ (10.2%),
 $M+4 = 501.24$ (1.6%)



Draw it this way too, to show all of the proton and carbon chemical shifts.



$C_{29}H_{36}ClNO_4$
Exact Mass: 497.23

M+ = 497.23 (100.0%),
M+1 = 498.24 (31.9%),
M+2 = 499.23 (37.9%),
M+3 = 500.23 (10.2%),
M+4 = 501.24 (1.6%)