Today: Nuclear Magnetic Resonance Spectroscopy

Apr 16: Exam 3

Apr 11: NMR continued

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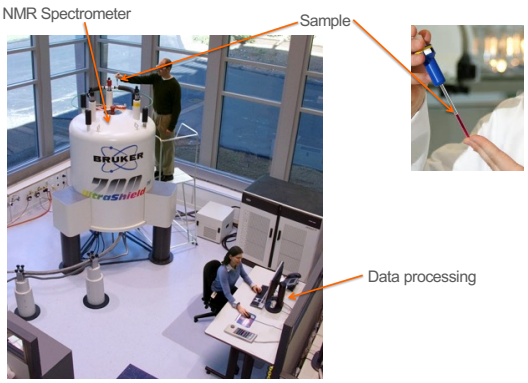
1

Nuclear Magnetic Resonance (NMR)



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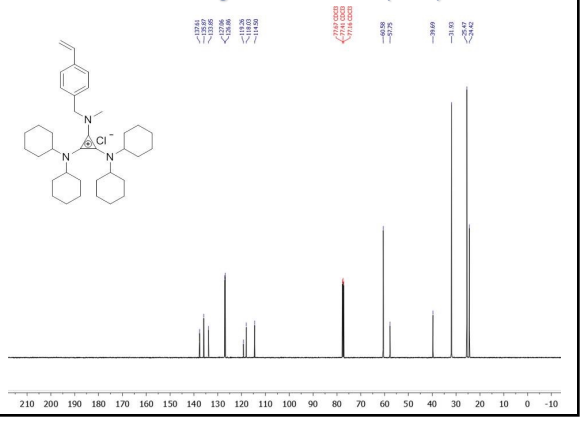
Nuclear Magnetic Resonance (NMR)



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Nuclear Magnetic Resonance (NMR)

NMR Spectrometer, aka. Magnetic Resonance Imaging

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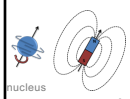
Nuclear Magnetic Resonance (NMR)



-the nuclei of some atoms spin (a magnetic property):

^{1}H, ^{13}C, ^{15}N, ^{19}F, …

-the nuclei of many atoms do not spin: ^{2}H, ^{12}C, ^{16}O, …

-when placed between the poles of a powerful magnet, spinning nuclei will align with or against the applied field creating an energy difference.

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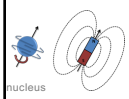
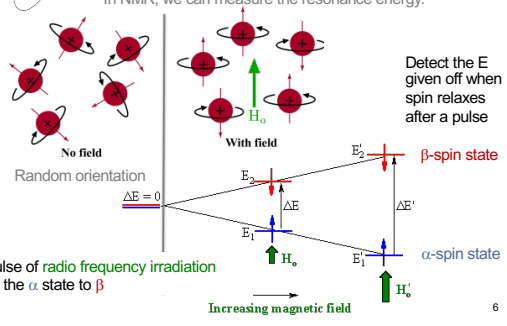
Nuclear Magnetic Resonance (NMR)



The ΔE of each nucleus is quantized
The magnetic environment affects the resonance energy.
(External: Strength of the magnet. Local: Neighboring atoms)
In NMR, we can measure the resonance energy.



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In General, ^{13}C-NMR:

In organic molecules, some carbon atoms are in different chemical environments that change the local magnetic field.
(the electron cloud around the nuclei creates its local magnetic field)

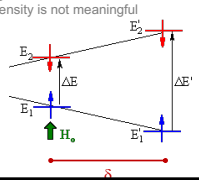
The electron cloud "shields" the nuclei and lowers the energy it senses, which leads to different resonance energies.

Nuclei in electron deficient environments sense a lower resonance energy. Therefore, a lower frequency pulse is required to flip the spin.

Information on the number of different types of carbons in a molecule

The ^{13}C isotope is only 1.1% abundant
-weak signals
-peak intensity is not meaningful

CH_3Cl
Electron withdrawing Cl leads to lower frequency signals (deshielded)



$Si(CH_3)_4$ (TMS)
highest frequency signal (standard, most shielded, C more electroneg than Si)

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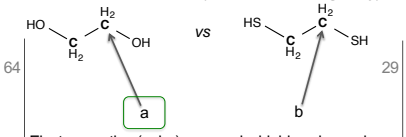
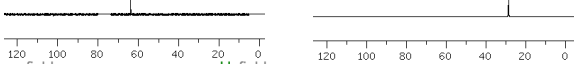
Deshielding Groups (Polarity)

In both cases, the two carbons have same magnetic/chemical environment in each molecule.
Which carbon is more deshielded, **a** or **b**? (consider electronegativity)



Electronegative (polar) groups deshield nuclear spins

δ = chemical shift (Hz/MHz)
(the pulse frequency at which the nucleus resonates)
Measured in ppm
Distance from TMS signal



Downfield Deshielded — Upfield Shielded

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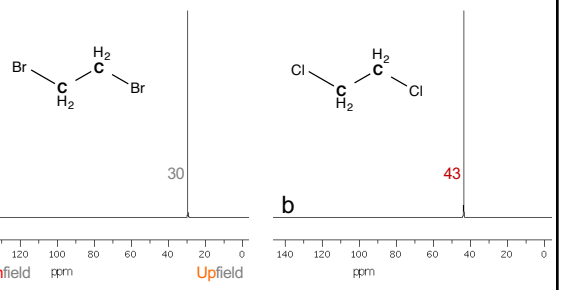
Deshielding Groups (Polarity)

In both cases, the two carbons have same chemical environment.
The carbon attached to Cl is more deshielded.
Therefore, the signal is more downfield than that of the carbon attached to Br



Downfield — Upfield

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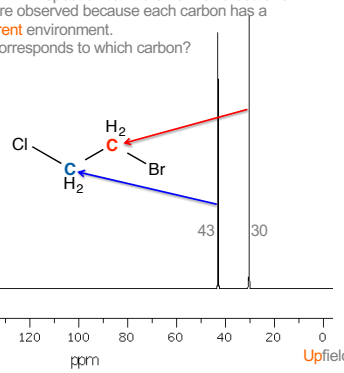
Asymmetric Molecules

This is the ^{13}C NMR spectrum of 1-bromo-2-chloroethane.
Two signals are observed because each carbon has a different environment.
Which peak corresponds to which carbon?



Downfield — Upfield

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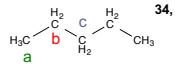
^{13}C-NMR spectra of Cyclopentane and Pentane

Resonance signal given in parts per million (ppm)

All carbon atoms have a similar chemical environment
ONE signal

Downfield — Upfield

The carbon atoms have a different chemical environment
THREE signals!



34, 22, 14 ppm

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^{13}C-NMR spectra of Cyclopentane and Pentane

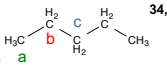
Why is a more c more deshielded than a?

The carbon atoms have a different chemical environment
THREE signals!

Hydrogen is less electronegative than Carbon.

a is attached to one Carbon
(3 protons are less "electron withdrawing than C")
- more shielded carbon

c is attached to two Carbons
(2 protons are less "electron withdrawing than C")
- less shielded carbon



34, 22, 14 ppm

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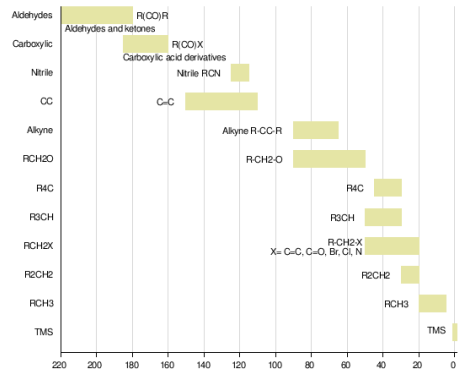
General Peak Regions in ^{13}C-NMR



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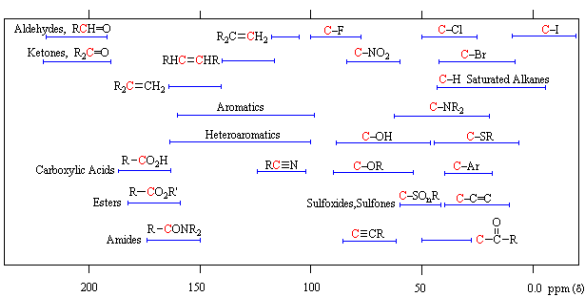
General Peak Regions in ^{13}C-NMR



You will get **both** tables for the exam!!

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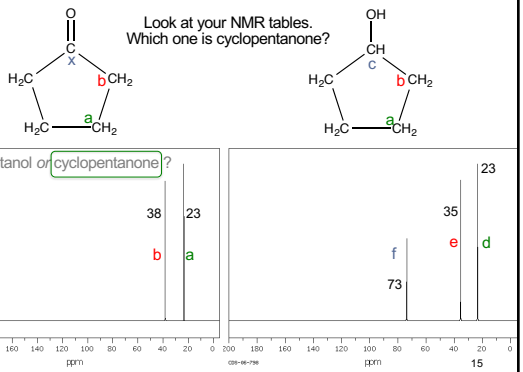
^{13}C-NMR: Cyclopentanol vs. Cyclopentanone



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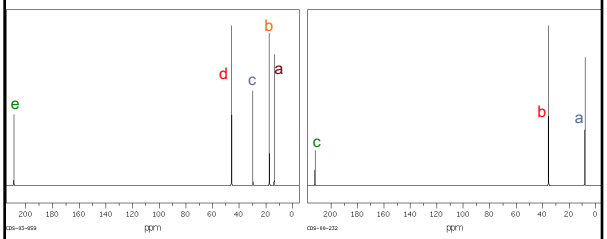
^{13}C-NMR: How many signals (peaks) do you expect?

2-pentanone 3-pentanone



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In General,^{13}C-NMR:

Information on the number of different types of carbons

The ^{13}C isotope is only 1.1% abundant
-weak signals
-peak intensity is not meaningful

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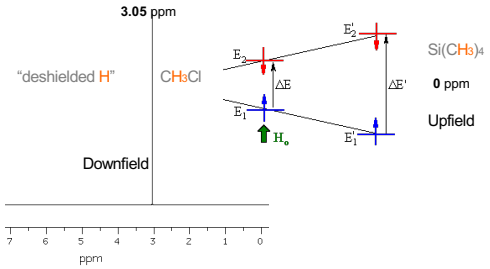
All Protons Have a Spin: ^{1}H-NMR

Resonance energy given in parts per million (ppm)
However, in a different field region (usually 0-14 ppm)



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^{1}H-NMR (aka proton-NMR)

Information from ^{1}H-nmr spectra:

-^{1}H is 99.9% abundant.

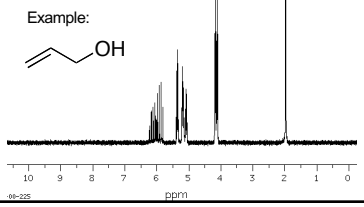
-Number of signals: How many different types of hydrogens in the molecule.

-Position of signals (chemical shift): What types of hydrogens.

-Relative areas under signals (integration): Number of hydrogens of each type.

-Splitting pattern: How many neighboring hydrogens.

Example:



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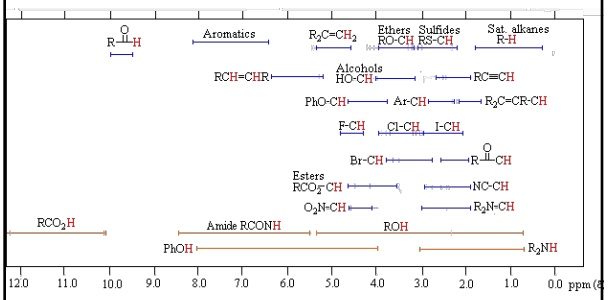
General Peak Regions in ^{1}H-NMR



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General Peak Regions in ^{1}H-NMR

Characteristic Proton Chemical Shifts

Type of Proton		Chemical Shift, ppm
Cyclopropane		0.2
primary	RCH_3	0.9
secondary	R_2CH_2	1.3
tertiary	R_3CH	1.5
vinylic	C=C-H	4.6-5.9
acetylenic	C≡C-H	2-3
Aromatic	Ar-H	6-8.5
Benzylic	Ar-C-H	2.2-3
allylic	C=C-CH_3	1.7
Halides	HC-X	2-4.5
alcohols	HC-O	3.4-4
ethers	HC-OR	3.3-4
esters	HC-CO_2R	2-2.2
esters	HC-O_2CR	3.7-4.1
acids	HC-CO_2	2-2.6
carbonyl	HC-C=O	2-2.7
aldehydic	RCHO	9-10
hydroxlic	ROH	1-5.5
phenolic	ArOH	4-12
enolic	C=C-OH	15-17
carboxlic	RCO_2H	10.5-12
amino	RNH_2	1-5

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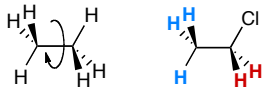
1. Number of signals: How many different types of hydrogens in the molecule.

Chemically equivalent hydrogens resonate at the same applied field.

Chemically equivalent hydrogens are also chemically equivalent.

# of signals? CH_4 CH_3CH_3 $Cl\text{-}CH_2CH_3$



Fast rotation
All H's are **chemically equivalent**

NRM is like a camera with a slow shutter speed

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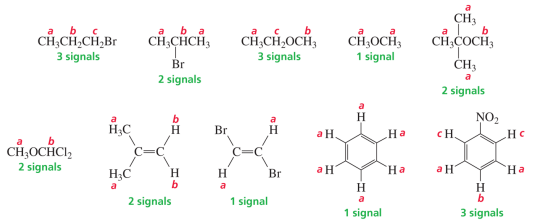
number of signals



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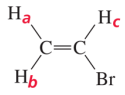
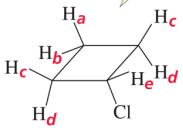
If bonds are prevented from freely rotating or rapid conformational changes:

The protons on the same carbon experience different shielding interactions.

its ^{1}H NMR spectrum has 3 signals



its ^{1}H NMR spectrum has 5 signals



H_a and H_b are not equivalent

H_a and H_b are not equivalent
H_c and H_d are not equivalent

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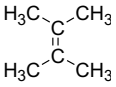
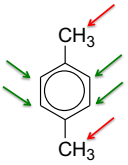
number of signals?

one



one

one



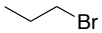
two

25

25

ONE

TWO



THREE

TWO

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26

2. Position of signals (chemical shift): what types of hydrogens.

primary	0.9 ppm	
secondary	1.3	
tertiary	1.5	
aromatic	6-8.5	
allyl	1.7	
benzyl	2.2-3	
chlorides	3-4	H-C-Cl
bromides	2.5-4	H-C-Br
iodides	2-4	H-C-I
alcohols	3.4-4	H-C-O
alcohols	1-5.5	H-O- (variable)

Note: combinations may greatly influence chemical shifts. For example, the benzyl hydrogens in benzyl chloride are shifted to lower field by the chlorine and resonate at 4.5 ppm.

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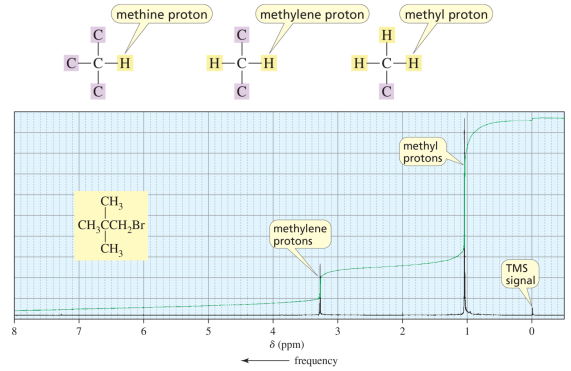

reference compound = tetramethylsilane $(CH_3)_4Si$ @ 0.0 ppm

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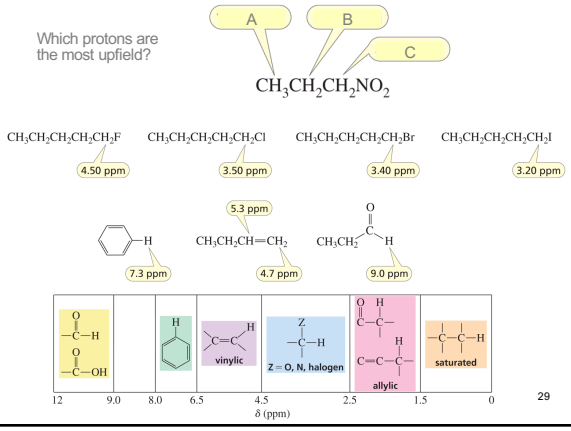
Which protons are the most upfield?



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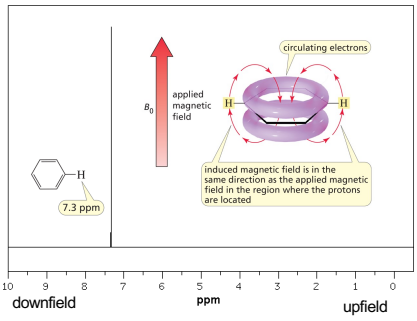
Aromatic π-system deshields the protons

Benzene



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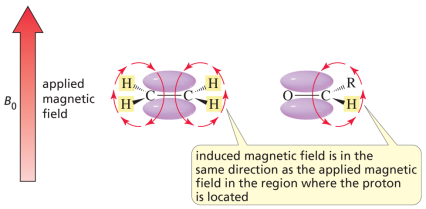

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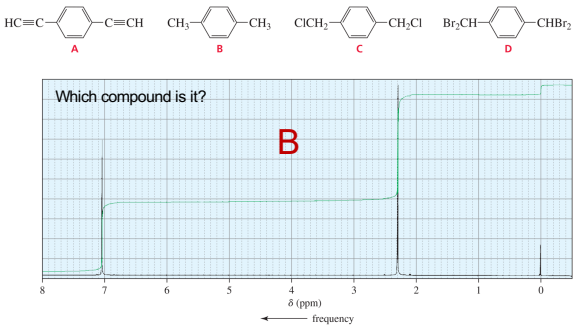

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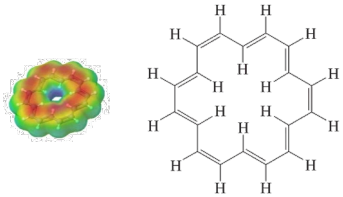
[18]-Annulene shows two signals in its ^{1}H NMR spectrum: one at 9.2 ppm and the other to the right of the TMS signal at -2.8.

What hydrogens are responsible for each of the signals?



[18]-annulene

Petrukhina and Anderson: Nat. Chem. 2024. https://doi.org/10.1038/s41557-024-01469-1

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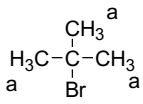
let most upfield signal = a, next most upfield = b, etc.

… c b a tms



a b

CH_3CH_2-Br

a b c

$CH_3CH_2CH_2$-Br

a b a

CH_3CHCH_3
Cl

34

34

let most upfield signal = a, next most upfield = b, etc.

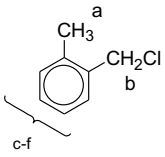
… c b a tms

b d c a

$CH_3CHCH_2CH_3$
Br

b a b

Cl-$CH_2CH_2CH_2$-Cl



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1. Chemical Environment
2. Peak Position
3. **Integration (relative areas under each signal): how many hydrogens of each type.**

a b c
$CH_3CH_2CH_2Br$

a 3H
b 2H
c 2H

a : b : c = 3 : 2 : 2

a b a
CH_3CHCH_3
Cl

a 6H
b 1H

a : b = 6 : 1

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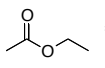
Expected integration
2 : 3 : 3



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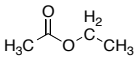
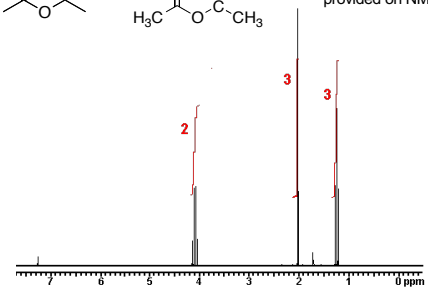


Integration values will be provided on NMR spectra



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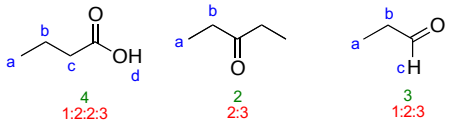
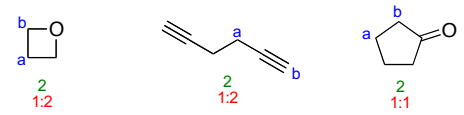


# of signals?
Relative ratio?
Upfield to downfield (a, b, c…)?



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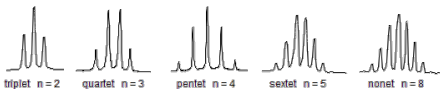
4. Splitting pattern: how many neighboring hydrogens.

In general, n-equivalent neighboring hydrogens will split a ^{1}H signal into an (n + 1) Pascal pattern.

"neighboring" – no more than three bonds away

n	n + 1	Pascal pattern (intensity ratio):	
0	1	1	singlet
1	2	1 1	doublet
2	3	1 2 1	triplet
3	4	1 3 3 1	quartet
4	5	1 4 6 4 1	quintet



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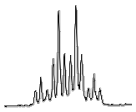
note: n must be equivalent neighboring hydrogens to give rise to a Pascal splitting pattern. If the neighbors are not equivalent, then you will see a complex pattern (aka, multiplet).

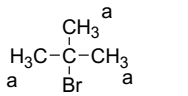
note: the alcohol hydrogen –OH usually does not split neighboring hydrogen signals or split itself. Normally a singlet of integration 1 between 1 – 5.5 ppm (variable).



Complex pattern
"multiplet"

40

40



a 9 H singlet

a b
CH_3CH_2-Br

a 3 H triplet
b 2 H quartet

a b c
$CH_3CH_2CH_2$-Br

a 3 H triplet
b 2 H complex
c 2 H triplet

a b a
CH_3CHCH_3
Cl

a 6 H doublet
b 1 H septet

41

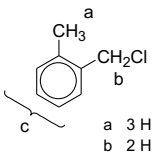
41

b d c a
$CH_3CHCH_2CH_3$
Br

a 3 H triplet
b 3 H doublet
c 2 H complex
d 1 H complex

b a b
Cl-$CH_2CH_2CH_2$-Cl

a 2 H quintet
b 4 H triplet



a 3 H singlet
b 2 H singlet
c 4 H complex

a b c
CH_3CH_2-OH

a 3 H triplet
b 2 H quartet
c 1 H singlet

42

42

Information from ^{1}H-nmr spectra (^{1}H is 99.9% abundant)**:**

-**Number of signals**: How many different types of hydrogens in the molecule.

-Position of signals (**chemical shift**): What types of hydrogens.

-Relative areas under signals (**integration**): Number of hydrogens of each type.

-**Splitting pattern**: How many neighboring hydrogens (different environment).

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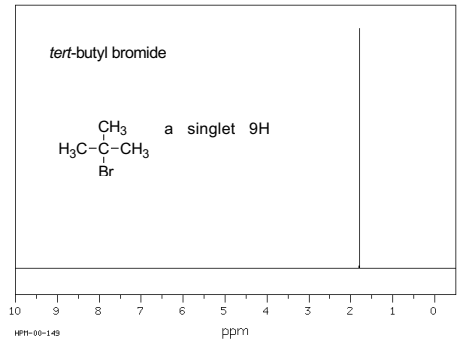
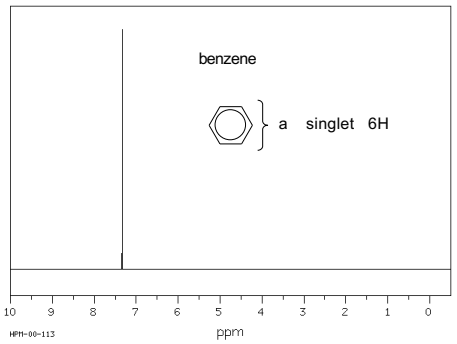


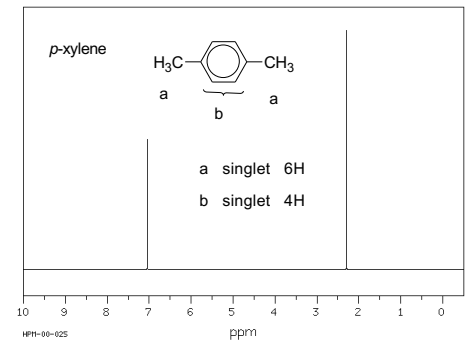
44

44



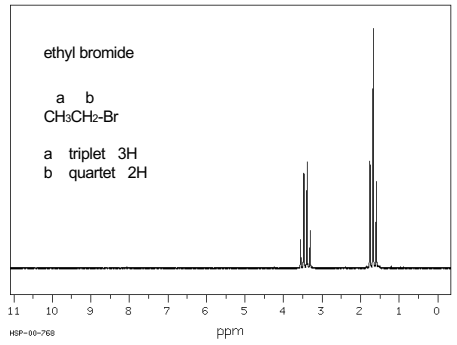
45

45



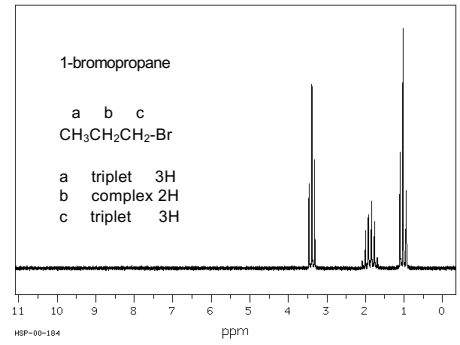
46

46



47

47



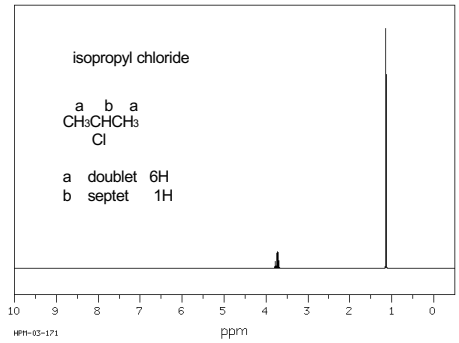
48

48

isopropyl chloride

a b a
CH_3CHCH_3
Cl

a doublet 6H
b septet 1H



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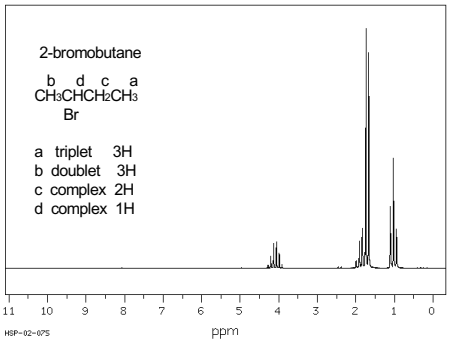
49

2-bromobutane

b d c a
$CH_3CHCH_2CH_3$
Br

a triplet 3H
b doublet 3H
c complex 2H
d complex 1H

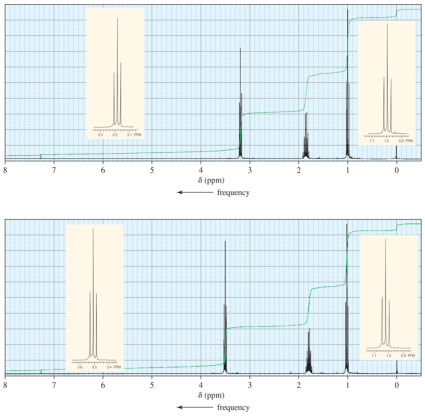


50

50

Which NMR corresponds to:

1-iodopropane
1-chloropropane



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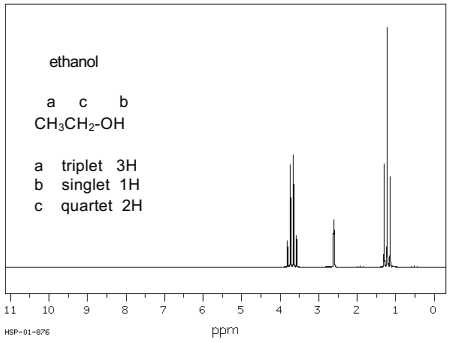
ethanol

a c b
CH_3CH_2-OH

a triplet 3H
b singlet 1H
c quartet 2H



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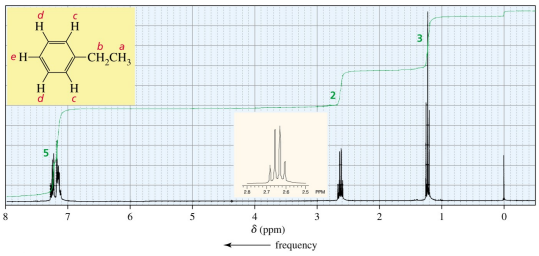
52

ethylbenzene



The signals for protons *c*, *d*, and *e* overlap because in this case, the electronic effect of an ethyl substituent is similar to that of a hydrogen.

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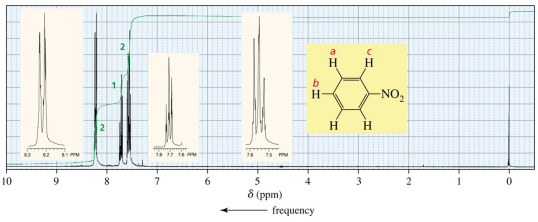
p-diethylbenzene



The signals for protons *a*, *b*, and *c* do not overlap because the nitro group is strongly electron withdrawing.

54

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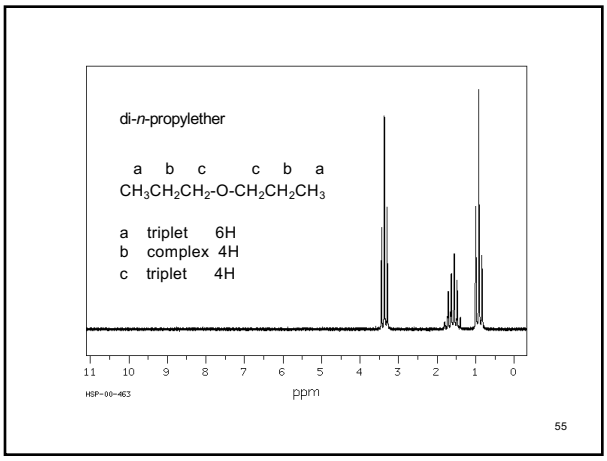
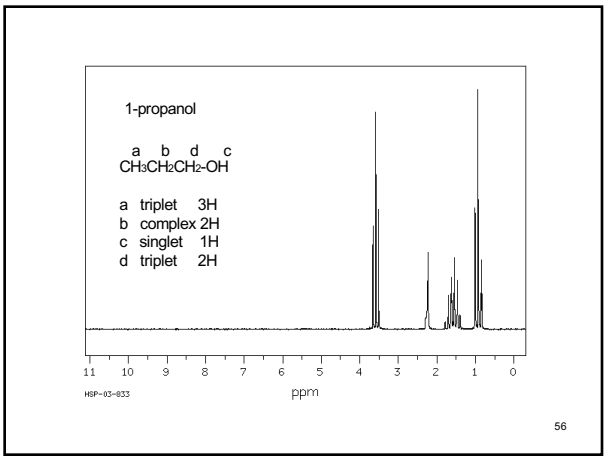
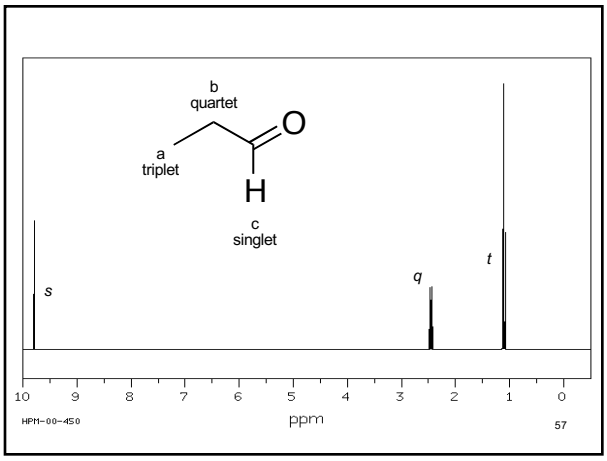


55



56



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Sample problem:

There are a lot of isomers with molecular formula: $C_5H_{10}O$

Using the ^{1}H-NMR and ^{13}C-NMR spectra in the next slides, identify the structure of the compound.

This could be an alcohol, ether, ketone, or aldehyde.

Look for those characteristics in the spectra.

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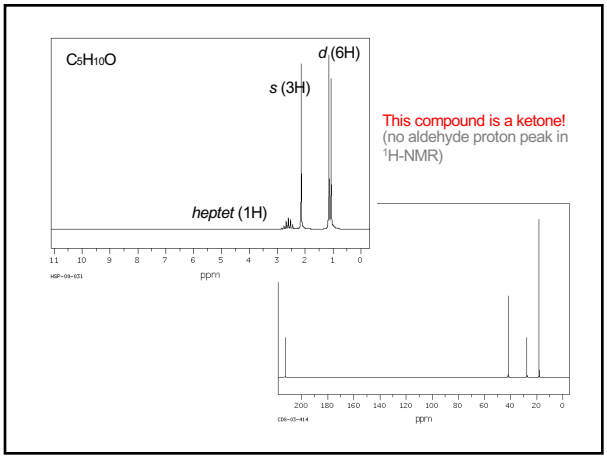

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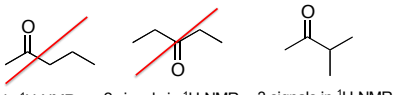
From ^{1}H-NMR: no aldehyde

^{13}C-NMR: confirms carbonyl (peak around 212 ppm)

This compound is a ketone!

That leaves 3 isomers:



4 signals in ^{1}H-NMR
5 signals in ^{13}C-NMR

2 signals in ^{1}H-NMR
3 signals in ^{13}C-NMR

3 signals in ^{1}H-NMR
4 signals in ^{13}C-NMR

On your own, assign the peaks to both NMR spectra

60

60