Nuclear magnetic resonance spectroscopy

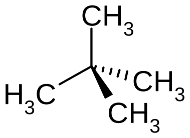
I. ^{1}H NMR

Reading:
Pavia
Chapter 5.8–5.19
Chapter 7.1-7.3, 7.5, 7.6, 7.7 A-C and F, 7.8-7.10
Chapter 8.1, 8.2 A and C

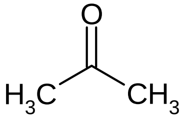
1. Chemical equivalence

- protons in chemically identical environments - are chemically equivalent
  - exhibit the same δ

- equivalence through symmetry considerations

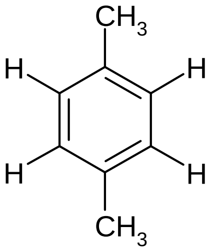


1 signal for 12 ^1H

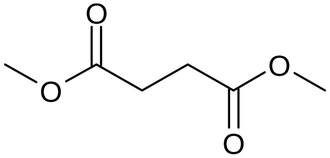


1 signal for 6 ^1H

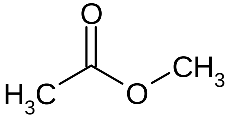
- obvious non-equivalence



2 sets:
1 signal for 6 ^1H in CH_3
1 signal for 4 ^1H in CH



2 sets:
1 signal for 6 ^1H in OCH_3
1 signal for 4 ^1H in CH_2

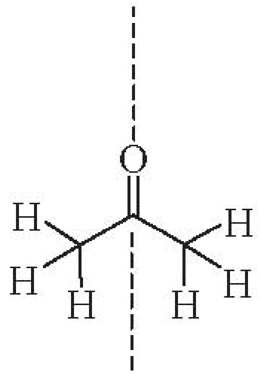


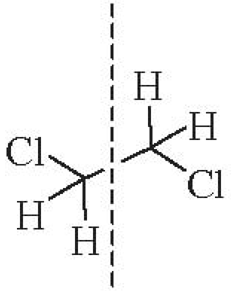
2 sets:
1 signal for 3 ^1H in CH_3
1 signal for 3 ^1H in OCH_3

Example

Chemical and magnetic equivalence: Proton signal is a singlet

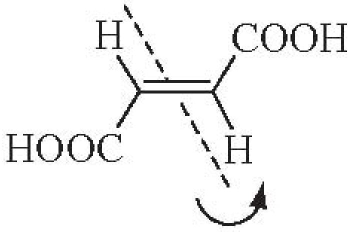
plane of symmetry



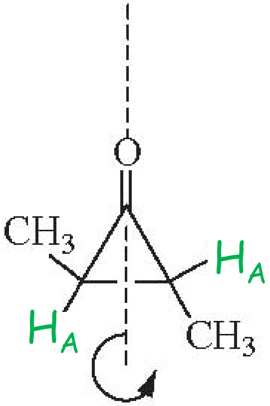


plane of symmetry

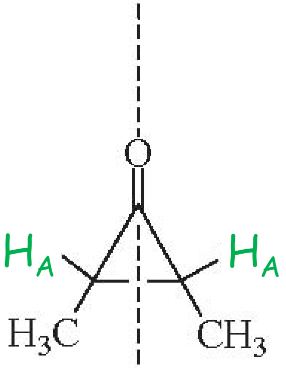
axis of symmetry



fumaric acid

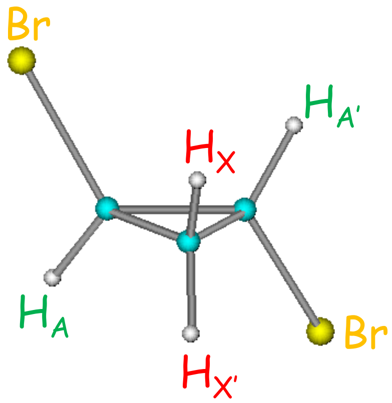


axis of symmetry



plane of symmetry

magnetic inequivalence:



complicated spectrum:
will not discuss!

1. Chemical equivalence continued

- spectral regions
  - chemical environment of the ^1H is important:
    - electronegativity effects
    - hybridization effects
    - H-bonding effects
    - magnetic anisotropy effects

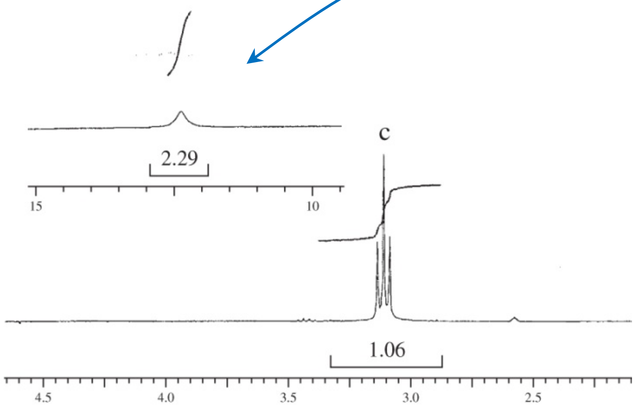
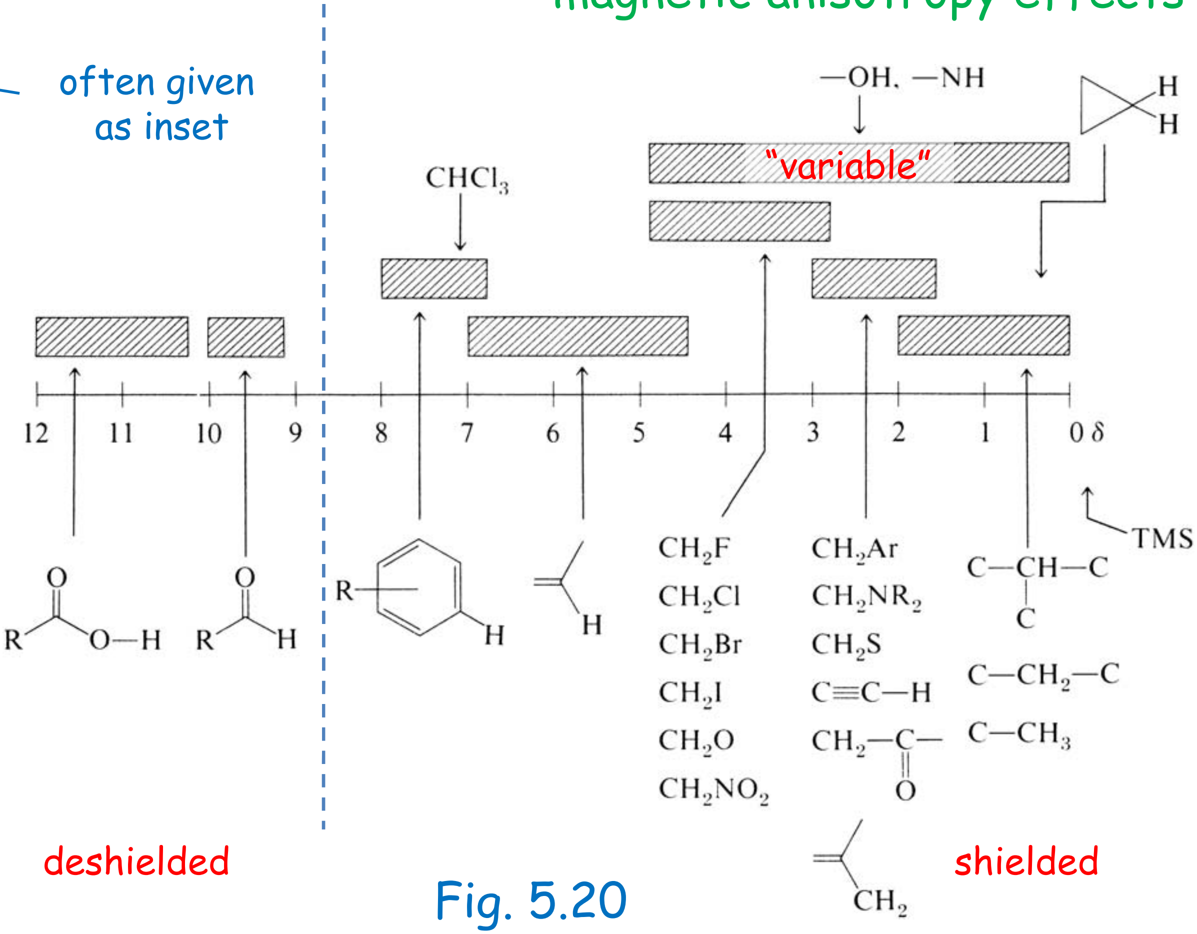


Fig. 5.49

often given as inset



"variable"

deshielded

shielded

Fig. 5.20

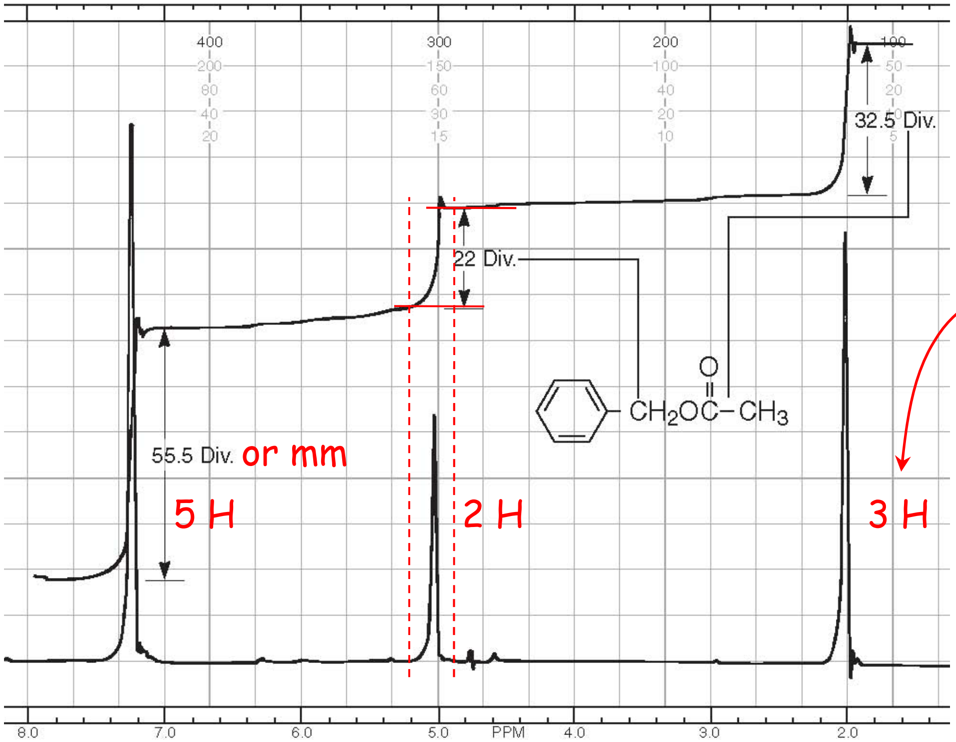
see p. A-8 ff

2. Integration

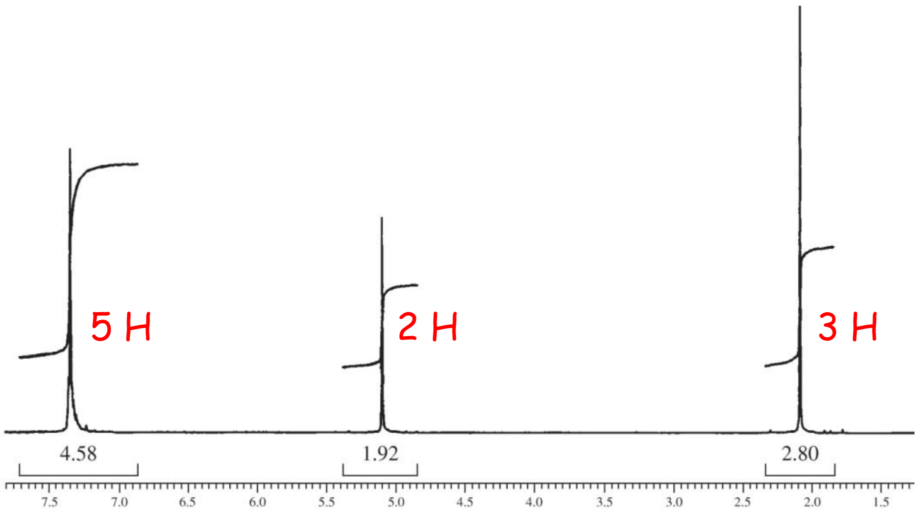
- determines the number of equivalent ^1H for a signal
- determined through the area under the signal
    - given through a step trace (need a ruler!)
- provides first important label

55.5 : 22 : 32.5
2.5 : 1 : 1.5
5 : 2 : 3

⇒ for a total of 10 ^1H!

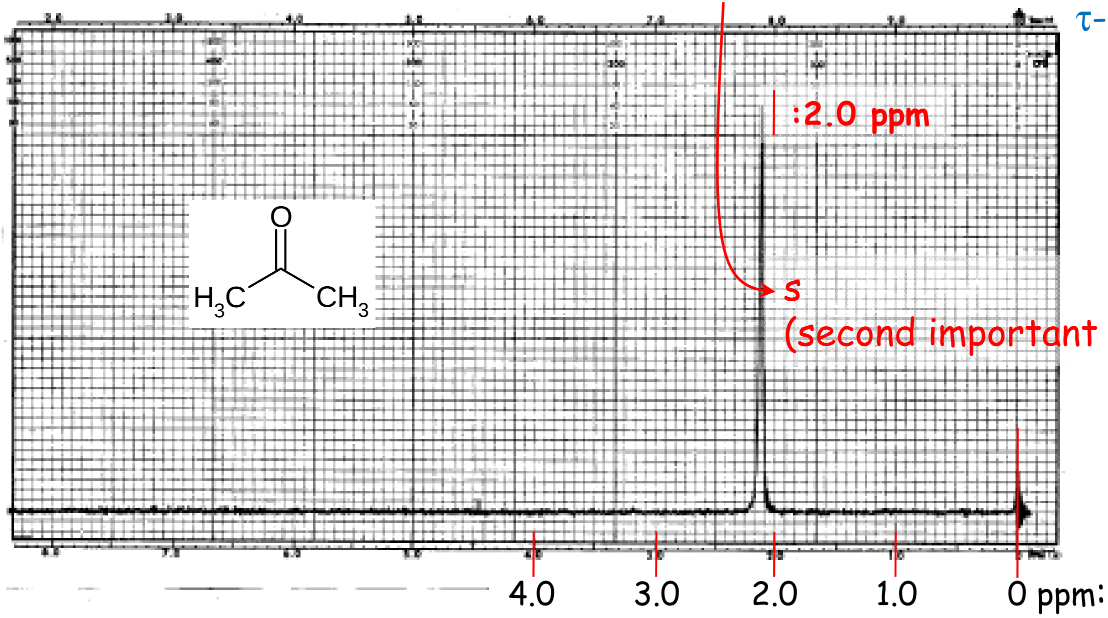


digital information:



3. Simple (singlet) spectra

- signal is only one peak: singlet, s



τ-scale: 10 - δ

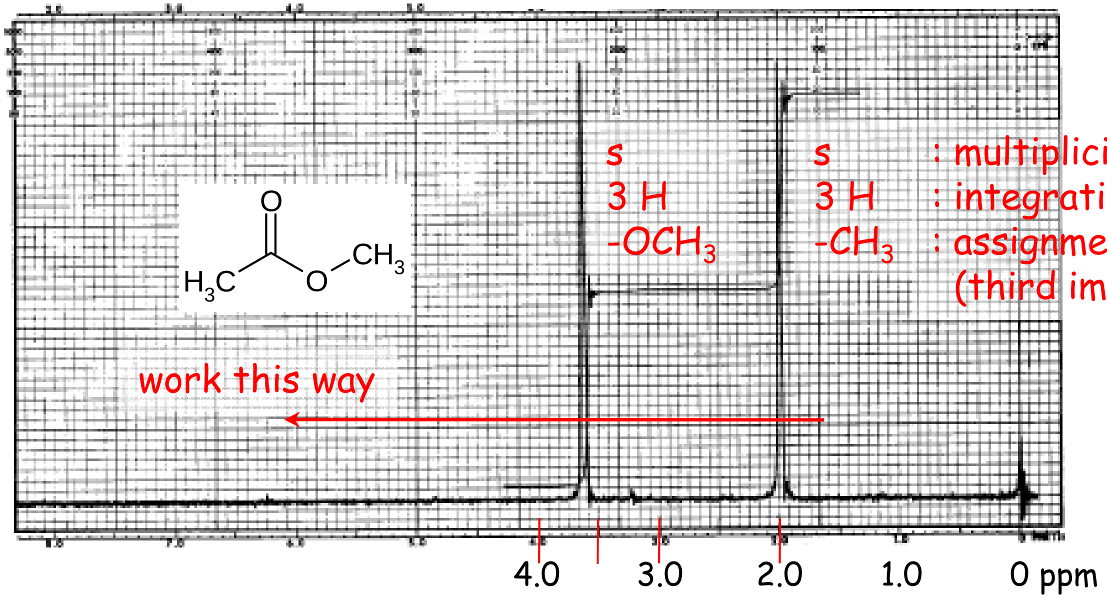
:2.0 ppm

s
(second important label)

δ-scale

reported:
2.1 s (6H)

C_3H_6O



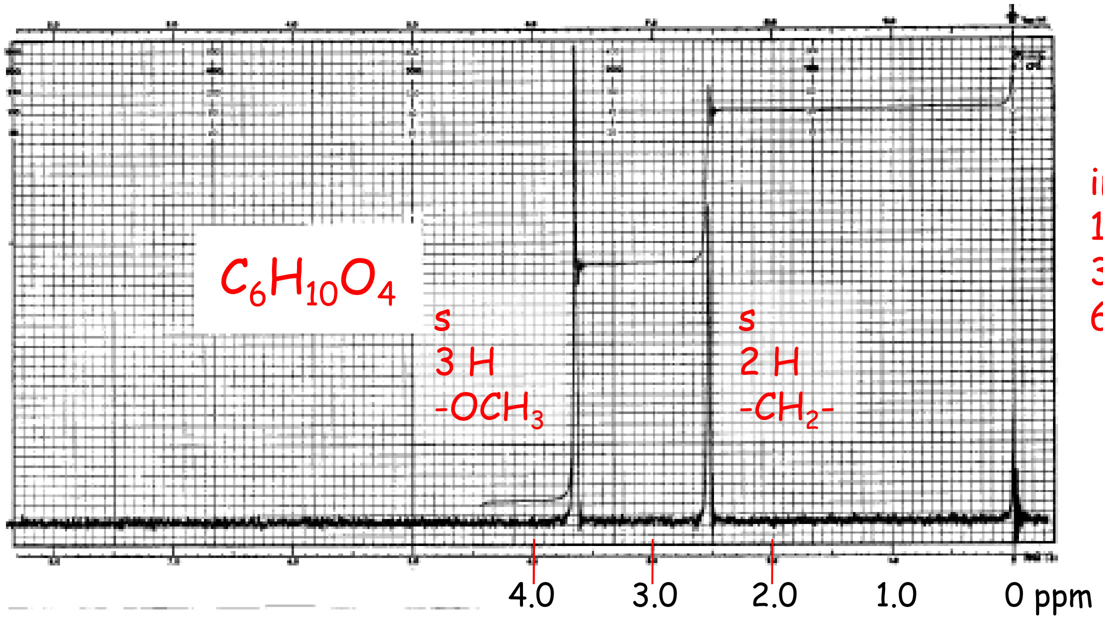
s	s	: multiplicity
3 H	3 H	: integration
$-OCH_3$	$-CH_3$	: assignment (third important label)

work this way

reported:
2.0 s (3H)
3.65 s (3H)

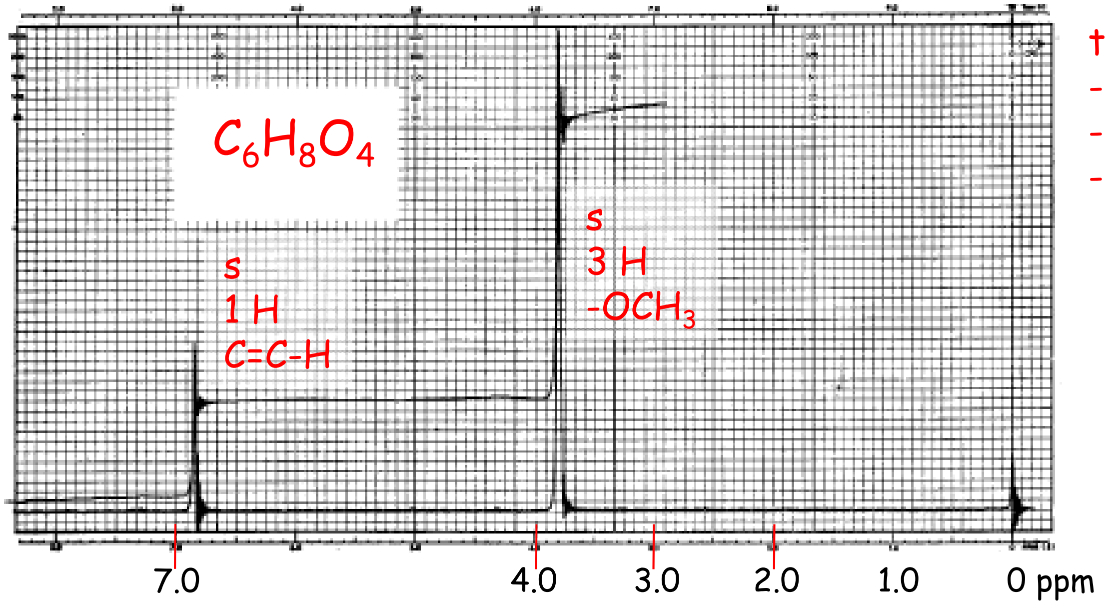
$C_3H_6O_2$

3. Simple spectra continued



integration:
1.5 : 1 or
3 : 2 or revised (!)
6 : 4

reported:
2.55 s 4H
3.65 s 6H
⇒ for a total of 10 ^1H



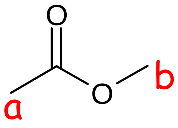
thoughts:
- aromatic?
- U?
- empirical formula?

reported:
3.8 s 6H
6.85 s 2H
⇒ for a total of 8 ^1H

4. Estimation of δ^1H

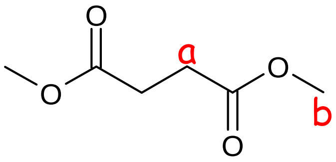
- from increment systems
  - for $X\text{-}CH_2\text{-}Y$ (and $X\text{-}CH_3$, where Y=H adds zero)

δ^1H (ppm) = 0.23 + increments for X and Y substituents see p. A-18



$\delta^1H_a = 0.23 + \underset{\text{COOR}}{1.55} + \underset{\text{H}}{0} = 1.78$ ppm (exp. 2.0 ppm) compare: ok

$\delta^1H_b = 0.23 + \underset{\text{OCOR}}{3.13} + \underset{\text{H}}{0} = 3.36$ ppm (exp. 3.65 ppm) ok

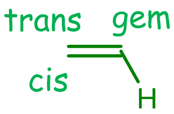


(appropriate?)

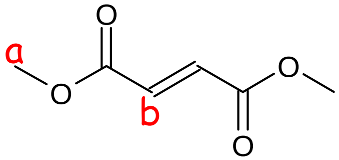
$\delta^1H_a = 0.23 + \underset{\text{COOR}}{1.55} + \underset{\text{R}}{0.47}^{?} = 2.25$ ppm (exp. 2.55 ppm) ok

$\delta^1H_b = 0.23 + \underset{\text{OCOR}}{3.13} + \underset{\text{H}}{0} = 3.36$ ppm (exp. 3.65 ppm) ok

- for



δ^1H (ppm) = 5.25 + increments for gem, trans and cis substituents see p. A-19



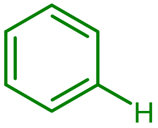
$\delta^1H_a = 0.23 + \underset{\text{OCOR}}{3.13}^{?} + \underset{\text{H}}{0} = 3.36$ ppm (exp. 3.8 ppm) probably too low

$\delta^1H_b = 5.25 + \underset{\substack{\text{gem}\\\text{COOR}}}{0.84} + \underset{\substack{\text{cis}\\\text{COOR}}}{1.15} + \underset{\substack{\text{trans}\\\text{H}}}{0} = 7.24$ ppm (exp. 6.85 ppm) ok

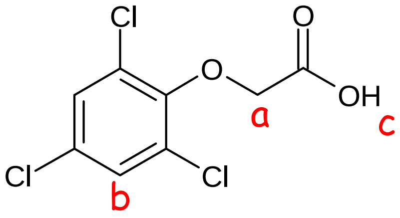
4. Estimation of δ^1H continued

- from an increment system

  - for



δ^1H (ppm) = 7.27 + increments for substituents see p. A-20

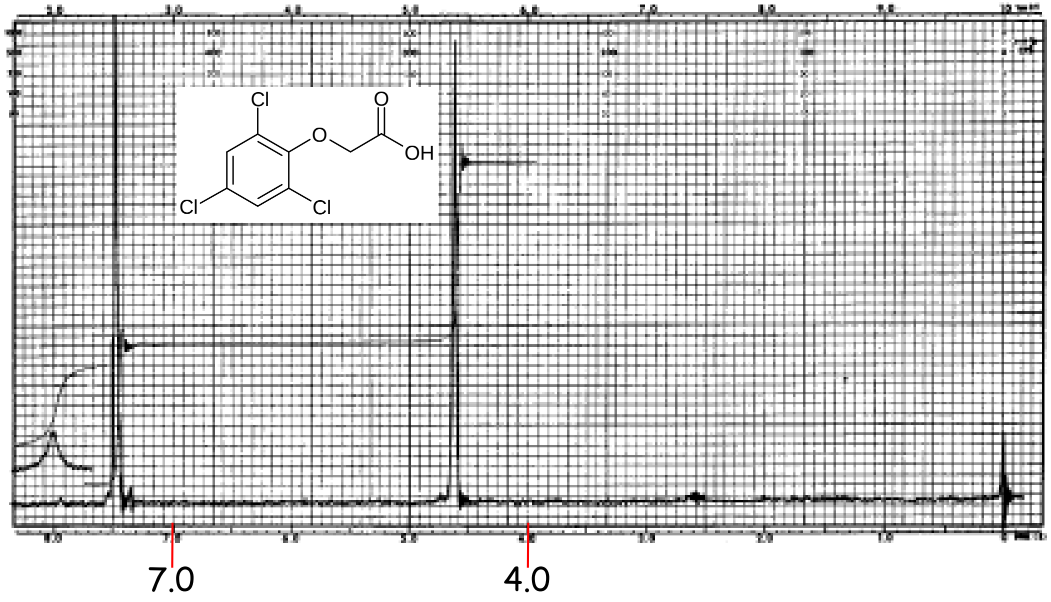


$\delta^1H_a = 0.23 + \underset{COOR}{1.55^?} + \underset{OC_6H_5}{3.23^?} = 5.01$ ppm (exp. 4.6 ppm) ok?

$\delta^1H_b = 7.27 + \underset{o\text{-}Cl}{2 \cdot 0.03} + \underset{p\text{-}Cl}{(-0.09)} + \underset{m\text{-}OR}{(-0.09)} = 7.15$ ppm (exp. 7.5 ppm) ok?

δ^1H_c = 11-12 ppm (no increments; from Table 5.4 or p. A-8)

inset;
problem: →
no scale given!

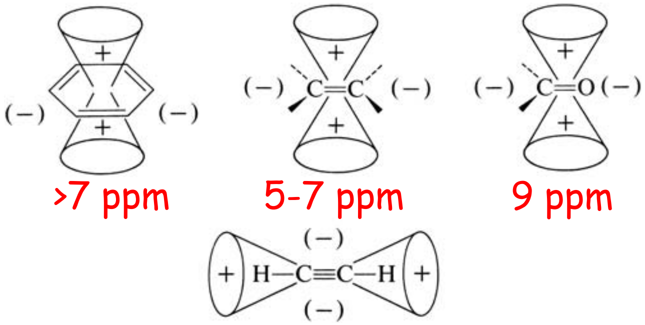


Not overly important for us

5. Magnetic anisotropy

- phenomenon observed for protons on or near π-systems
    - mobile π-electrons create local magnetic fields
    - shielding (+) and deshielding (-) regions
    - unusual chemical shifts

general shielding observations:



>7 ppm

5-7 ppm

9 ppm

2-3 ppm

reasoning:

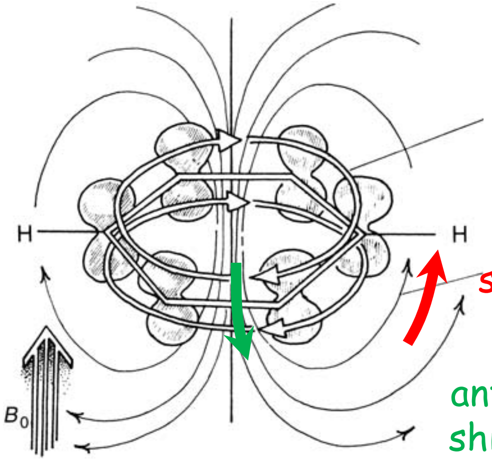
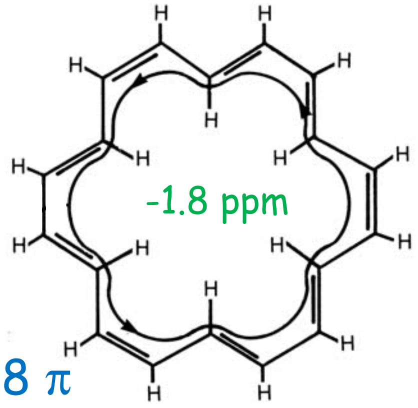


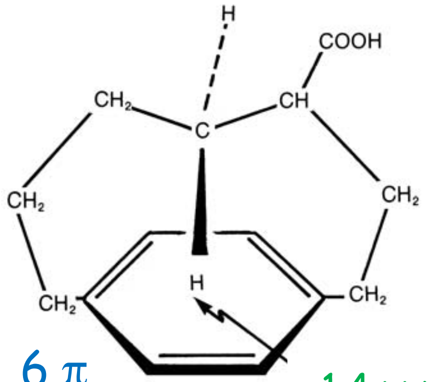
Fig. 5.21

parallel:
deshielding (-)
stronger apparent B_0

antiparallel:
shielding (+)
weaker apparent B_0



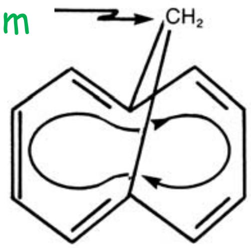
18 π



6 π

-1.4 ppm

-0.5 ppm

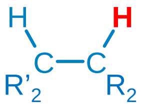


10 π

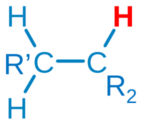
6. Spin-spin coupling

- between sets of chemically equivalent protons: signals are no longer singlets
- signal can be split into:
  - 2 lines: doublet, d
  - 3 lines: triplet, t
  - 4 lines, quartet, q
  - 5 lines, quintet, quint
  - 6 lines, sextet, sext
  - 7 lines, septet, sept

# of lines depends on the number of neighbouring ^{1}H:
n+1 rule:
n+1 lines in the signal for n equivalent neighbouring ^{1}H



: d signal

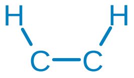


: t signal

- protons can couple over
  - 2 bonds: ^{2}J coupling

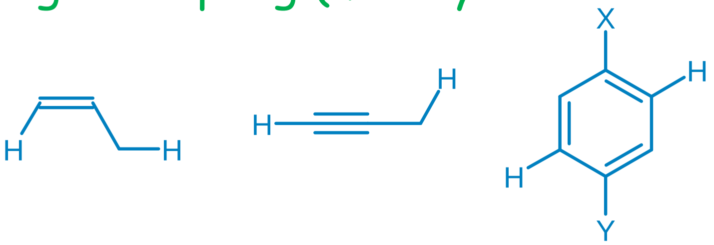
Will get back to this in detail later

  - 3 bonds: ^{3}J coupling



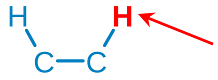
  - 4 bonds or more: ^{4}J, ^{5}J coupling or "long-range" coupling (mostly not observed)

but observed across multiple bonds:



6. Spin-spin coupling continued

- signal multiplicity (number of lines) explained:

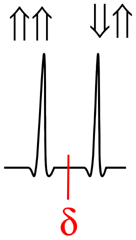

signal observed for this ^{1}H

⇑ ⇑

⇓ ⇑

^{1}H sees ***one*** ^{1}H on the next carbon atom:

- total of 2 different spin situations: ⇑⇑ and ⇓⇑
- signal for ^{1}H splits into 2 lines: doublet

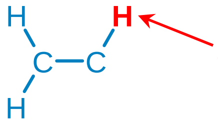


equal probability

⇒ same area/height

⇒ intensity ratio in signal 1:1

total spin observed by ^{1}H: $+\frac{1}{2}$ $-\frac{1}{2}$


signal observed for this ^{1}H

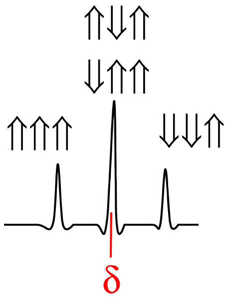
⇑⇑ ⇑

[⇑⇓ ⇑
⇓⇑ ⇑]

⇓⇓ ⇑

^{1}H sees ***two*** ^{1}H on the next carbon atom:

- total of 3 different spin situations
- signal for ^{1}H splits into 3 lines: triplet



⇒ intensity ratio in signal 1:2:1

total spin observed by ^{1}H: +1 0 -1

6. Spin-spin coupling continued

- for I = $\frac{1}{2}$, intensities of the lines within a signal follow the binomial distribution
- Pascal's triangle (easily constructed)

1 one line only

1 1 two lines, equal intensities

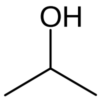
1 2 1 three lines, intensity ratio 1:2:1

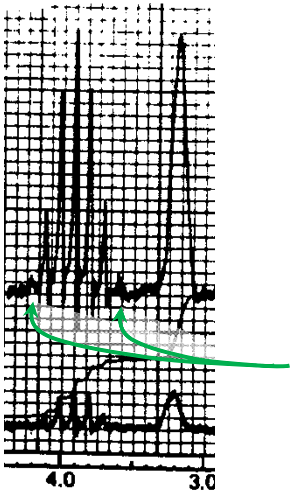
1 3 3 1

1 4 6 4 1

1 5 10 10 5 1

1 6 15 20 15 6 1 septet, outer lines often tough to detect!





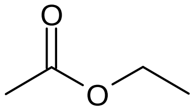
looks like only 5 lines

don't miss the outer lines!

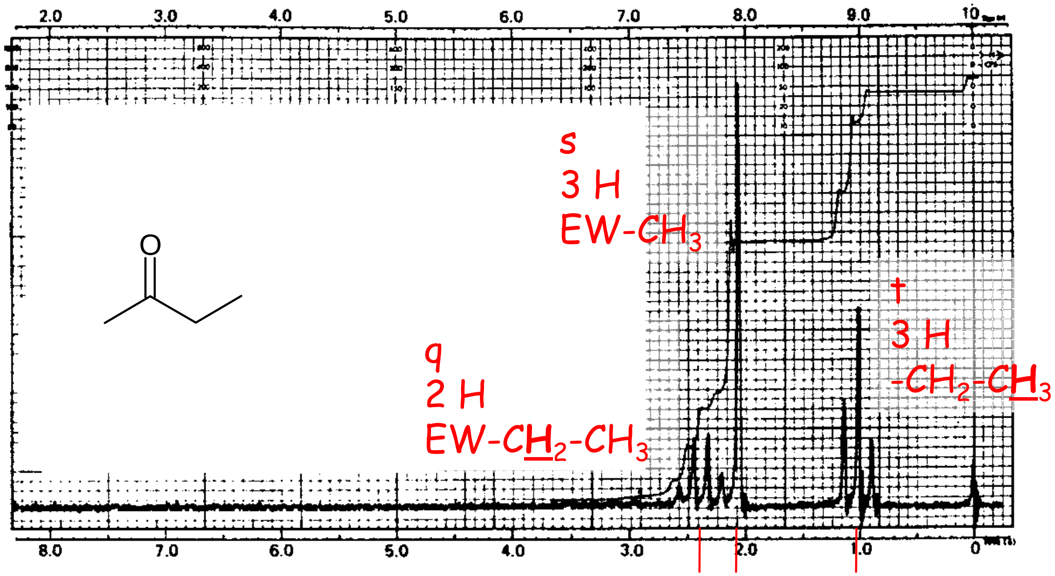
now we can predict ^{1}H spectra

Example

Better than problem 5.13!

Predict (draw) the ^{1}H NMR spectrum for  .
Consider (list!) δ, multiplicity and integration.

7. Spectra with simple multiplets



Do not forget that you need all three labels on a signal!

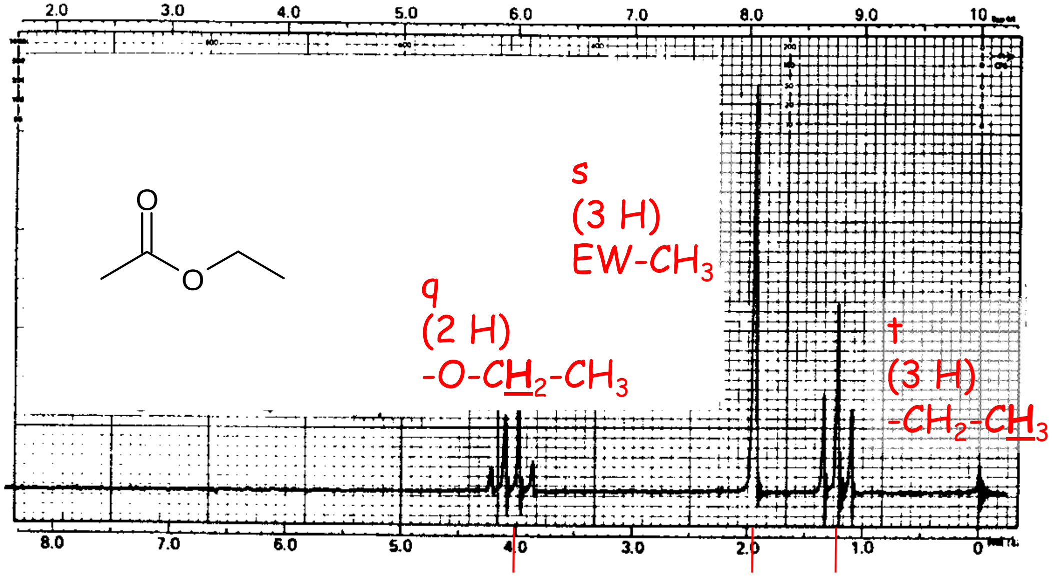


Table 5.8: examples of splitting patterns

7. Spectra with simple multiplets continued

- multiplet issues

I. Multiplicity

$ClCH_2CH_2CH_2CH_3$

quint sext

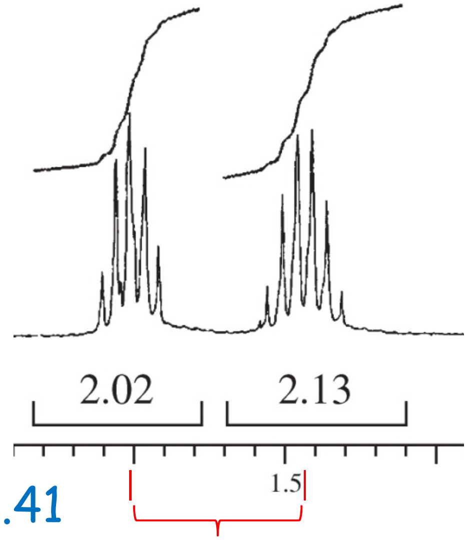


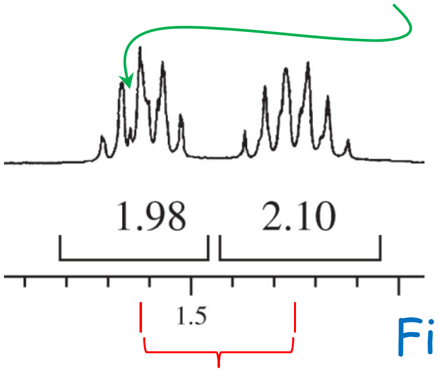
Fig. 5.41

Δδ 0.25 ppm

$CH_3OCH_2CH_2CH_2CH_3$

quint? sext?

Or both rather “mult”?



Δδ 0.15 ppm

Fig. 5.43

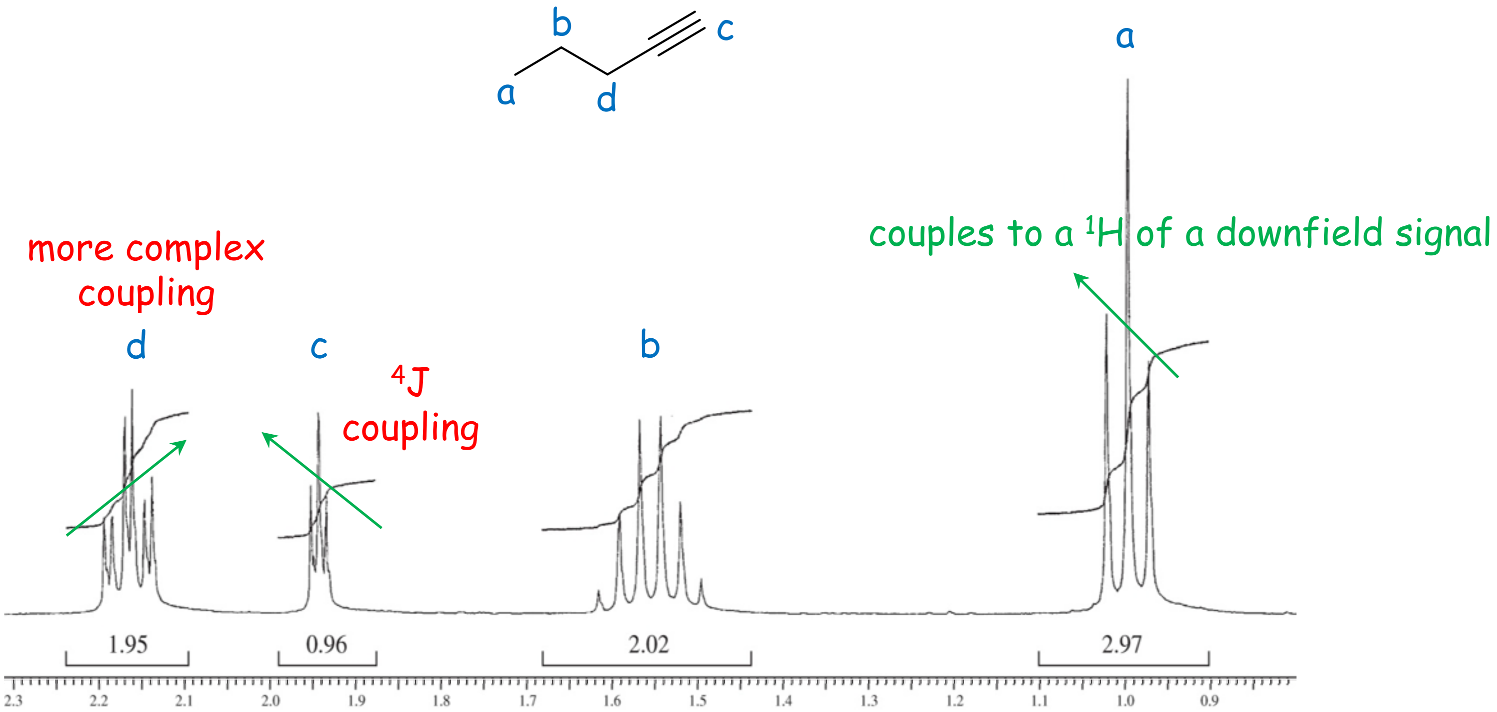
Will discuss later in more detail, but for our purposes, these are still quint and sext!

7. Spectra with simple multiplets continued

- multiplet issues

II. Skewing in multiplets

- first information on which protons are coupled



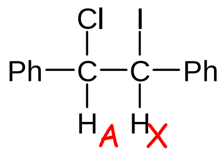
more complex coupling

^4J coupling

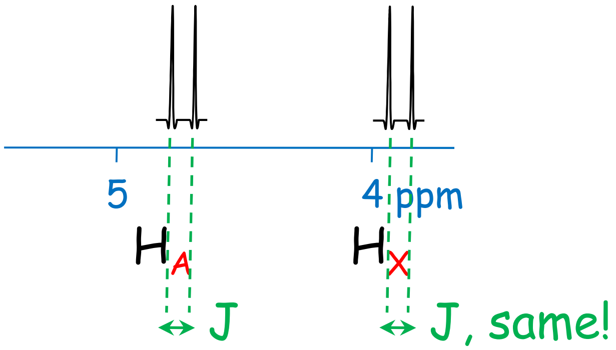
couples to a ^1H of a downfield signal

8. Coupling constant, J

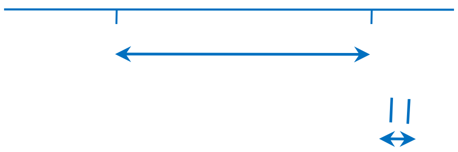
- number assigned to the spread of the lines in a multiplet
  - more reliable information on which protons are coupled than skewing
  - for two multiplets from coupling protons, J is the same



$\mathrm{Ph{-}C(Cl)(H_A){-}C(I)(H_X){-}Ph}$



if this spectrum was taken at 60 MHz:



1 ppm or 60 Hz

0.1 ppm ⇒ ^3J 6 Hz

AX spin system:

- Pople notation
- two chemically different protons, $\Delta\delta$ is (relatively) large

8. Coupling constant, J, continued

ICH_2CH_3

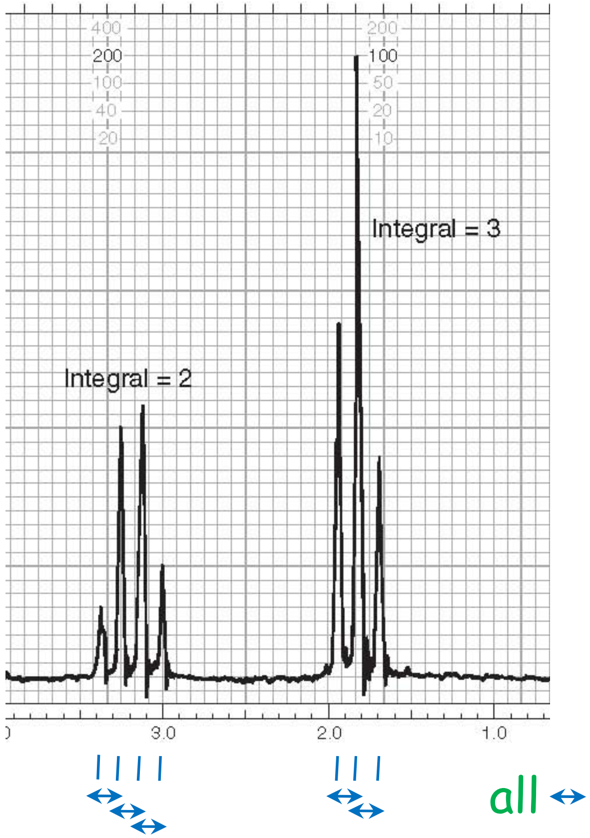


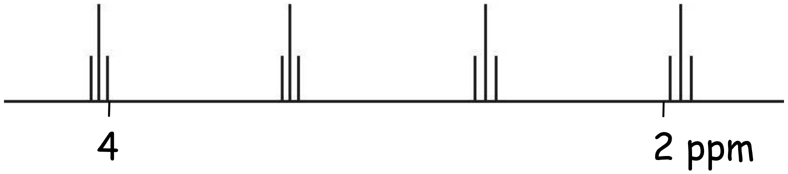
Table 5.9:
generalized J values
and
A-13 ff

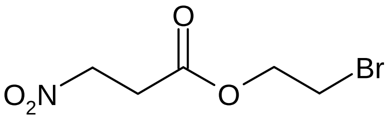
all ↔ spacings are the same,
^3J 7.5 Hz

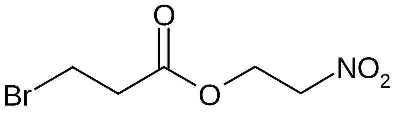
A_2X_3 spin system:
- Pople notation
- two sets of chemically different protons, $\Delta\delta$ is (relatively) large

Example

Assuming that ^3J is greater upon Br-substitution, which structure is correct?







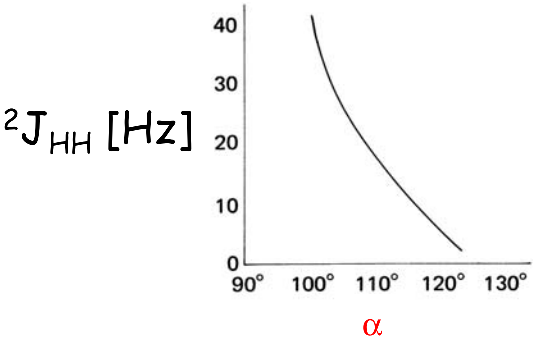
8. Coupling constant, J, continued

- origin of the coupling: via the electrons in the bonds

: interaction between spins of nuclei and electrons

size of J depends on the geometry:

- ^2J depends on the HCH bond angle: larger J with smaller angle (better interaction of σ-orbitals)



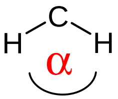
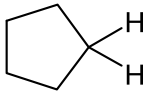
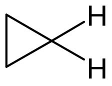


Fig. 7.4

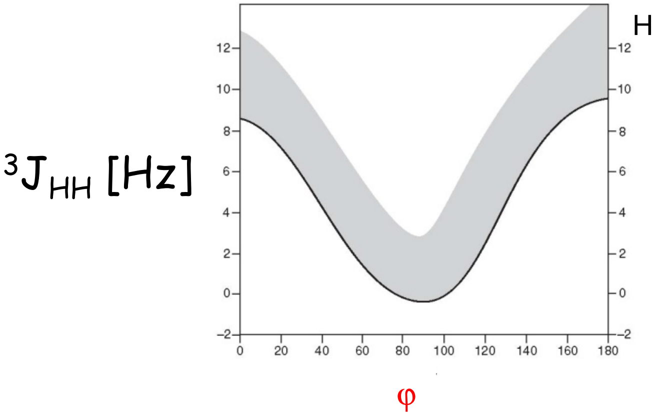


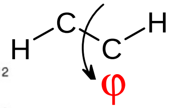
α 109°
^2J 12 Hz



α 118°
^2J 5 Hz

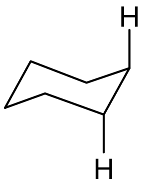
- ^3J depends on the HCCH torsion angle: minimum function at 90° (no interaction of σ-orbitals)



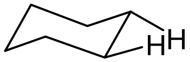


Karplus curve

Fig. 7.7



φ 180°
^3J 12 Hz

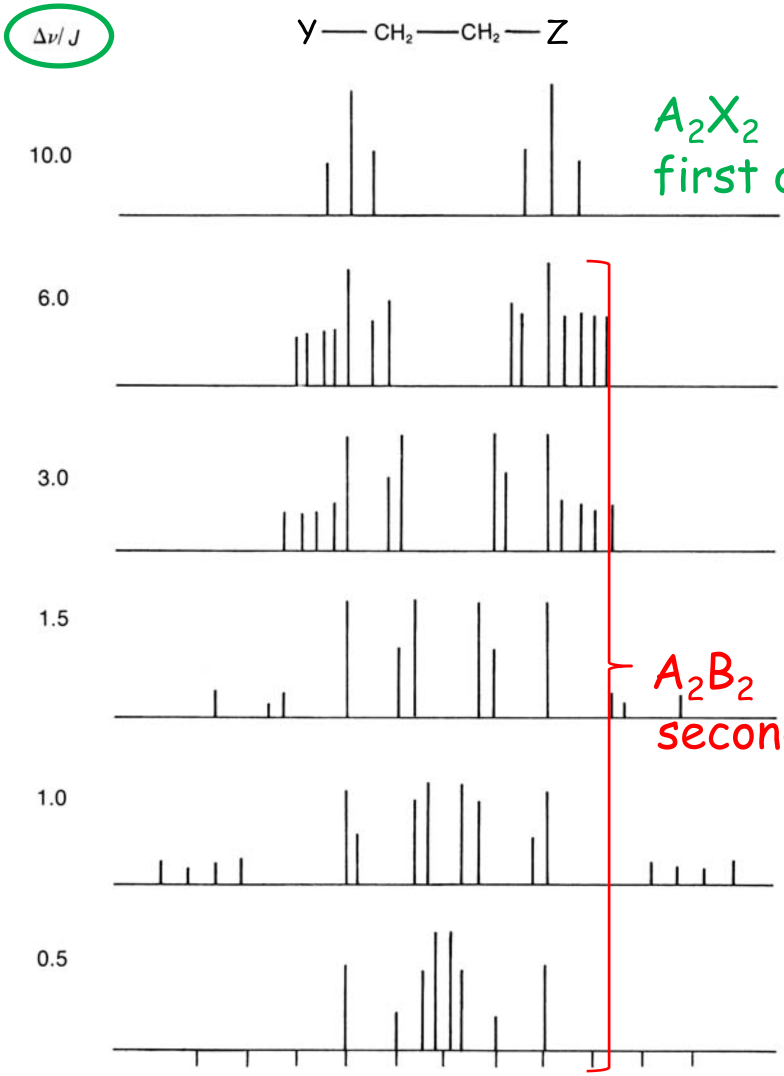


φ 60°
^3J 4 Hz

9. First and second order spectra

- Second-order spectra are found for sets of nuclei if Δν/J is too small

both in Hz



A_2X_2
first order

A_2B_2
second order

Fig. 7.44

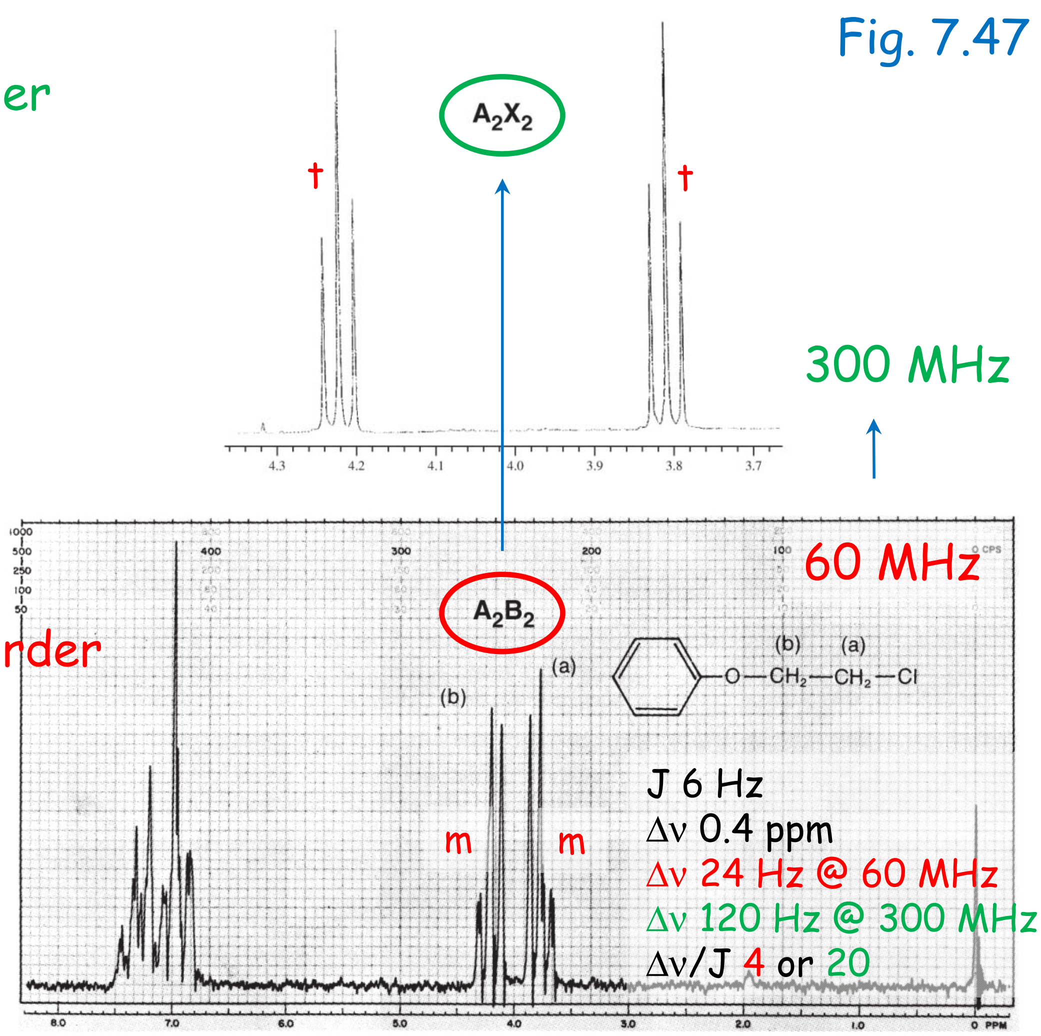


Fig. 7.47

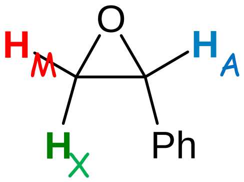
300 MHz

60 MHz

J 6 Hz
Δν 0.4 ppm
Δν 24 Hz @ 60 MHz
Δν 120 Hz @ 300 MHz
Δν/J 4 or 20

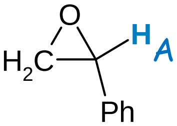
10. Non-equivalence within a group

- coupling within a group (CH_2, e.g.) when protons are ***not*** chemically equivalent



all three ^1H are chemically different

⇒ all will couple amongst each other

⇒this is ***not***  , H_A does ***not*** couple into a triplet!

- observed coupling here: $^3J_{AM} \neq {}^3J_{AX}, {}^2J_{MX}$
- we expect - three different coupling constants
  - signals of different multiplicity than so far

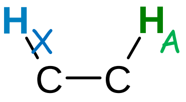
- we can analyse – coupling constants
  - appearance of a signal

through tree-diagrams

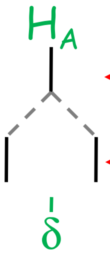
10. Non-equivalence within a group continued

- analysis with a tree-diagram

simple system:
coupling to one type of ^{1}H

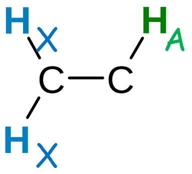


⇒ doublet for H_A

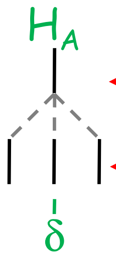


← undisturbed signal

← signal split by H_X



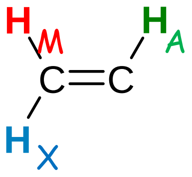
⇒ triplet for H_A



← undisturbed signal

← signal split by H_X

advanced system:
coupling to two types of ^{1}H



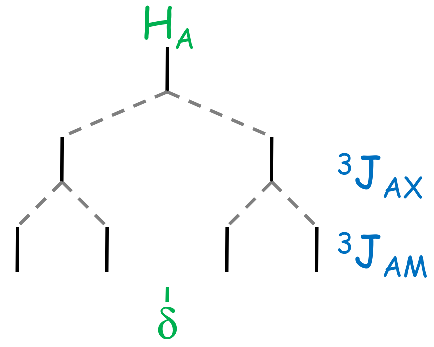
AMX system

⇒ one doublet for H_A with H_M, one doublet for H_A with H_X

⇒ doublet of doublets for H_A, dd

doublet with H_X →

doublet with H_M →



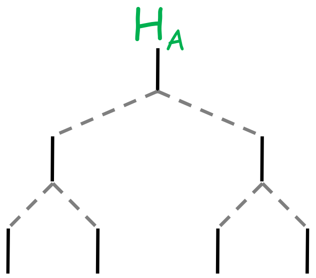
⇒ 1 signal, 4 lines

10. Non-equivalence within a group continued

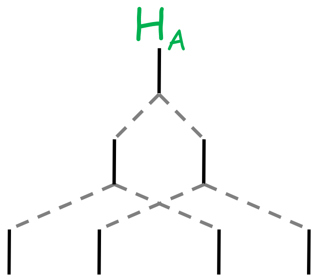
- two uses of a tree-diagram

towards a spectrum: what does the signal look like?

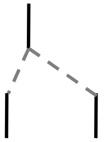
- use larger J first



not like this:



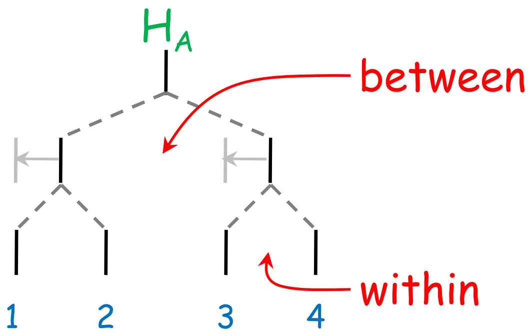
- stay symmetrical



: not like this, either!

from a spectrum: what are the coupling constants?

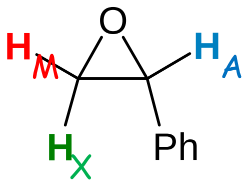
- take distance ***within*** and ***between*** the “individual multiplets”

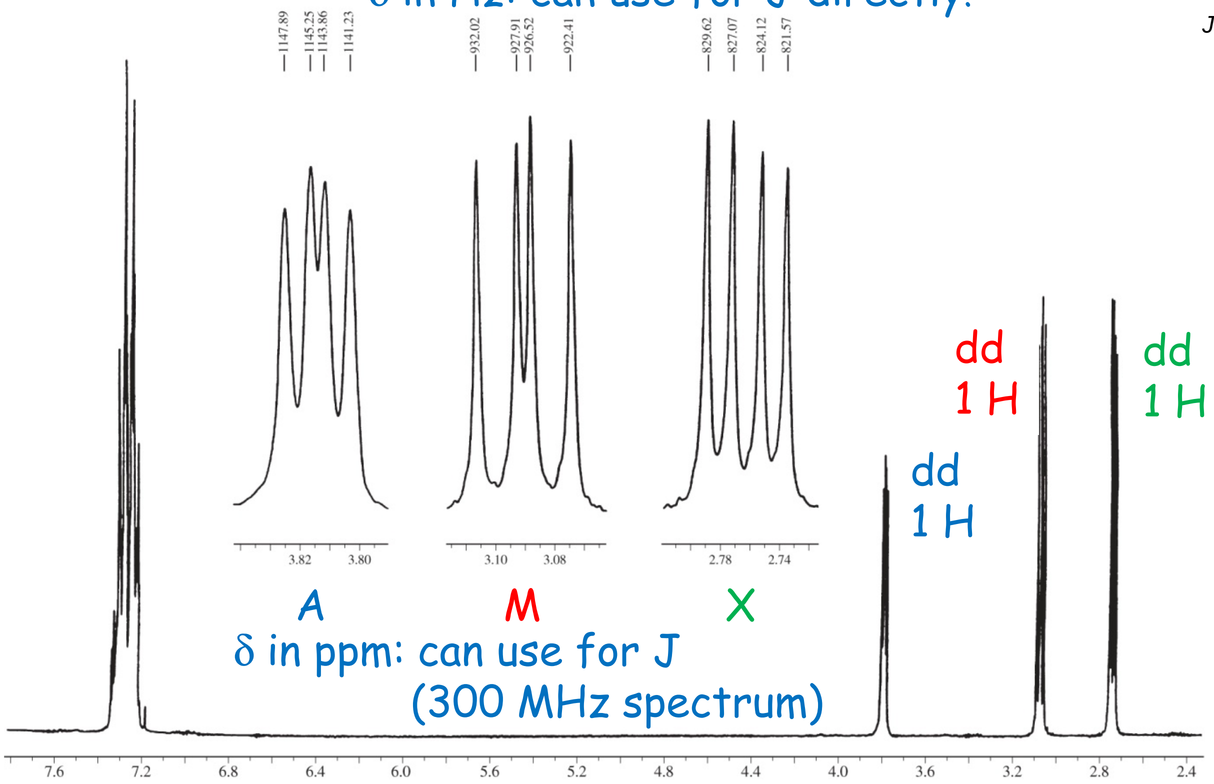


for a dd, measure
“within”: distance of lines 1 and 2 or 3 and 4
“between”: distance of lines 1 and 3 or 2 and 4

10. Non-equivalence within a group continued

- appearance of the spectrum





δ in Hz: can use for J directly!

dd
1 H

dd
1 H

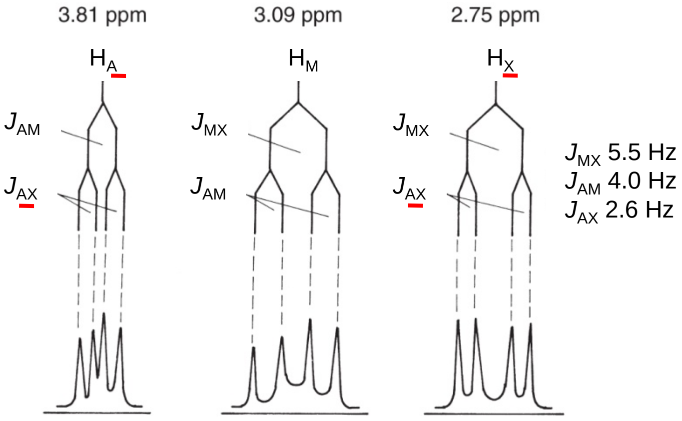
dd
1 H

A M X

δ in ppm: can use for J
(300 MHz spectrum)

Fig. 7.31

tree-diagram
analysis



J_{MX} 5.5 Hz
J_{AM} 4.0 Hz
J_{AX} 2.6 Hz

example:

J_{AX} appears twice:

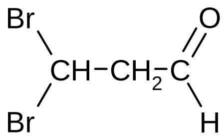
- in the signal for H_A
- in the signal for H_X

summarize as:

$^3J_{AX}$ 2.6 Hz
$^3J_{AM}$ 4.0 Hz
$^2J_{MX}$ 5.5 Hz

10. Non-equivalence within a group continued

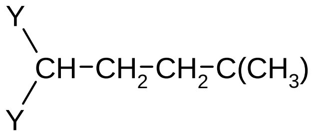
- two practice patterns



spin system:

multiplicities:

tree-diagram (assume $J_1 > J_2$):



spin system:

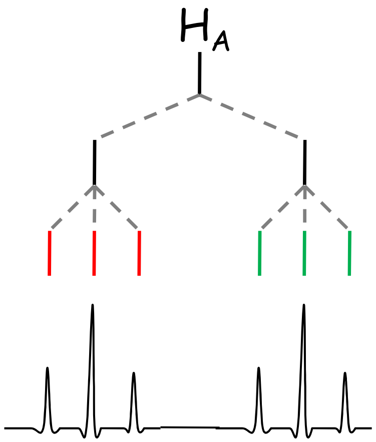
multiplicities:

tree-diagram:

How do you determine which J is which?

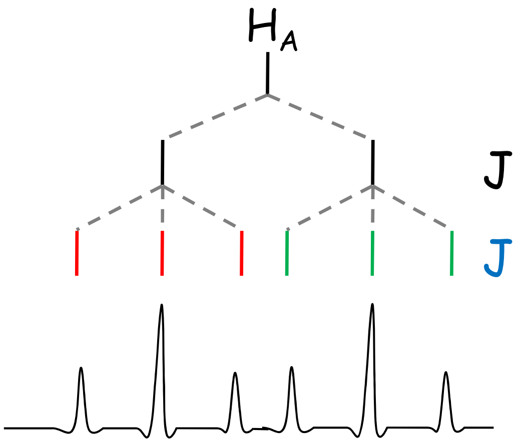
10. Non-equivalence within a group continued

- the appearance of a dt as J changes



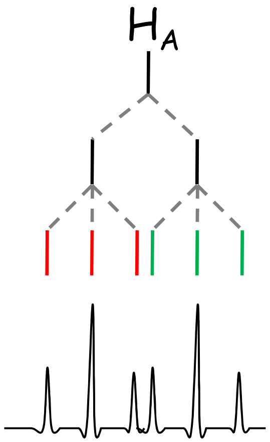
J_1 14 Hz

J_2 3 Hz



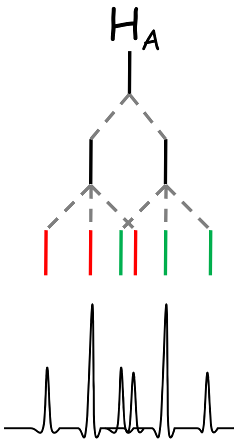
J_1 14 Hz

J_2 6 Hz



J_1 8 Hz

J_2 3 Hz

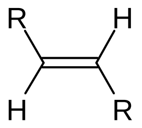


J_1 6 Hz

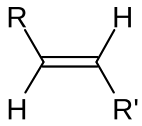
J_2 3 Hz

10. Non-equivalence within a group continued

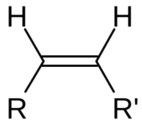
- coupling examples in alkenes



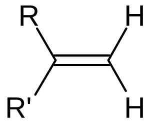
^1H are chemically and magnetically equivalent
⇒ s, 2H, no splitting



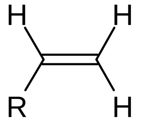
2 d, ^3J ~ 16 Hz (large)



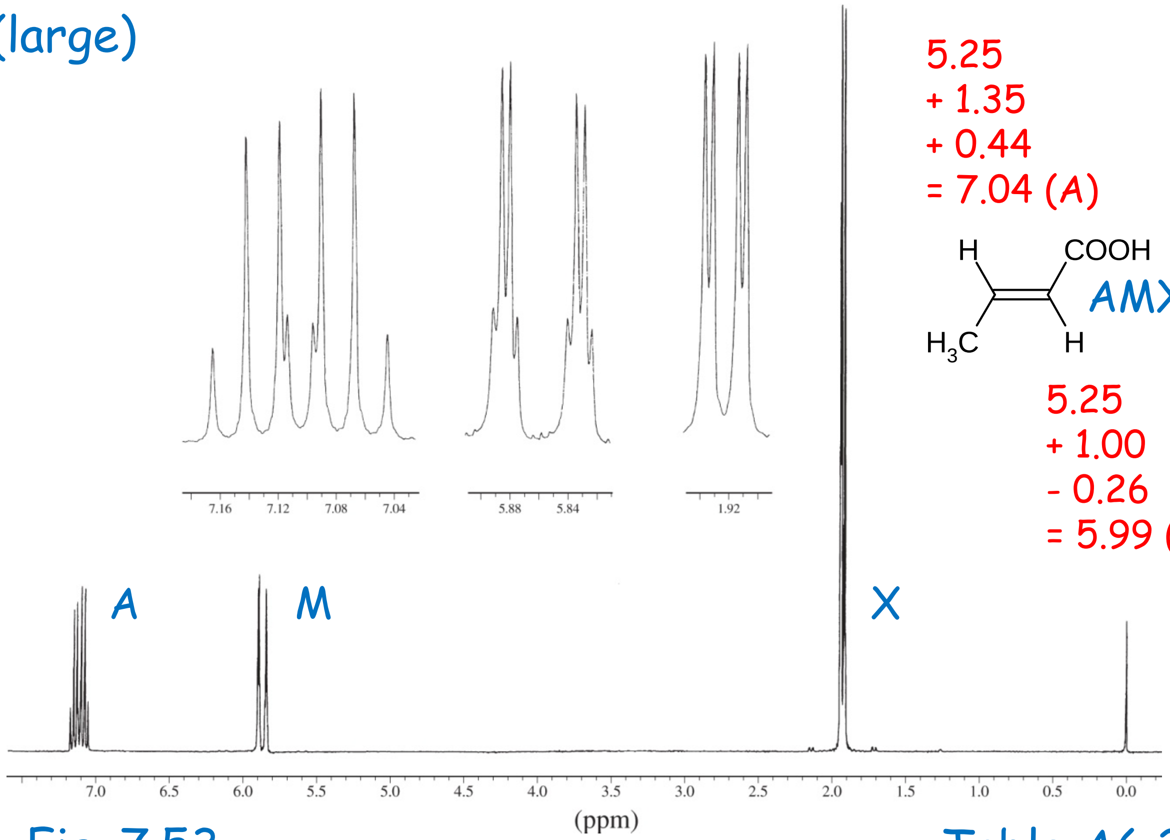
2 d, ^3J ~ 8 Hz



2 d, ^2J ~ 0-5 Hz



3 dd



5.25
+ 1.35
+ 0.44
= 7.04 (A)

AMX_3

5.25
+ 1.00
- 0.26
= 5.99 (M)

Fig. 7.53

Table A6.2

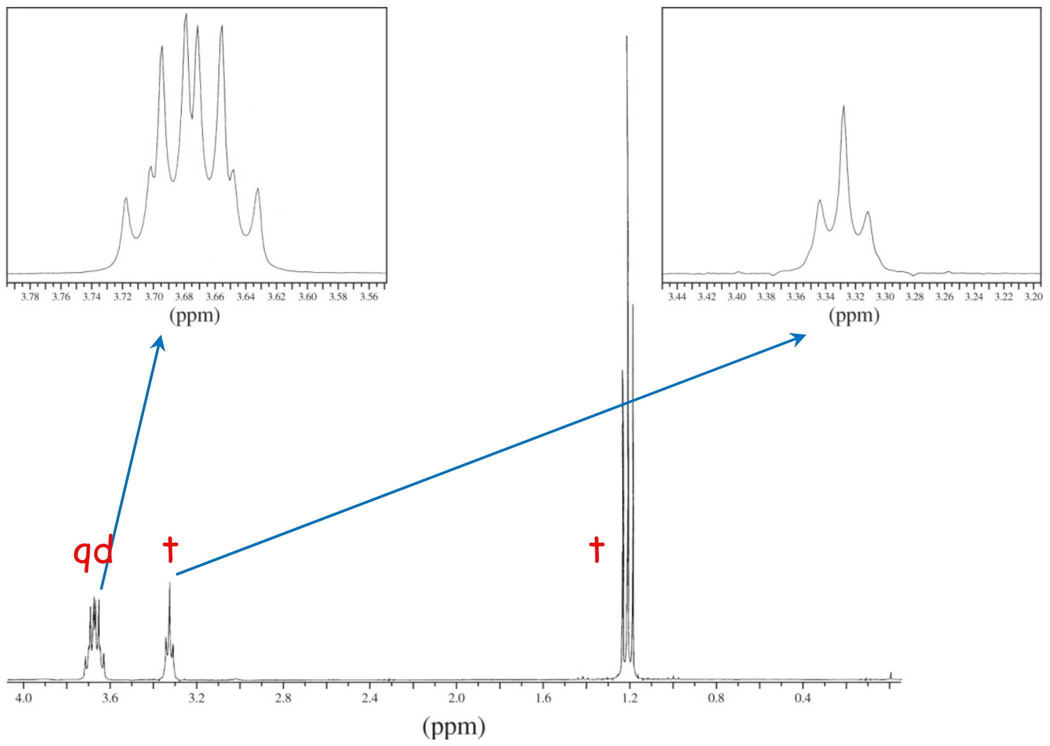
11. Protons on oxygen

- 2 issues

I. Lack of coupling

CH_3CH_2OH

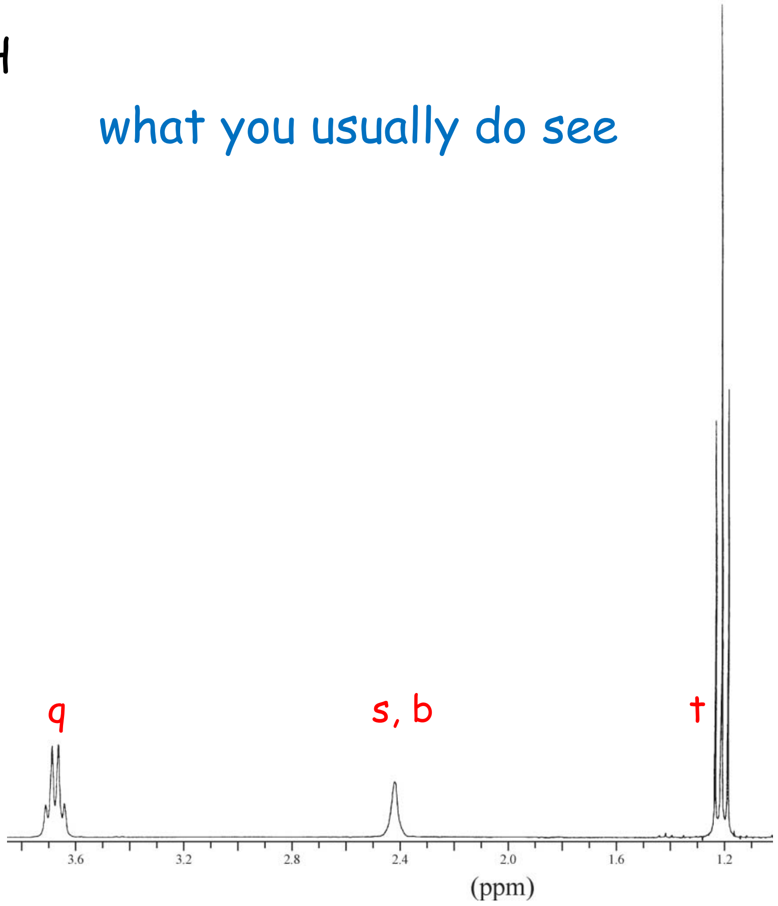
what you might expect to see



- ultrapure sample
- coupling to the OH proton observed

Fig. 8.3

what you usually do see



- ordinary sample
- coupling to the OH proton ***not*** observed

Fig. 8.2

11. Protons on oxygen continued

- Reason that coupling to protons on oxygen is not observed:
    - exchange takes place with other ROH, H_2O, traces of acid…
    - OH proton is not attached long enough for coupling to be recorded
    - rate of exchange is too great

Examples of fast exchange (high rate):

$CH_3OH + H_3O^+ \rightleftharpoons CH_3OH_2^+ + H_2O$ 10^8 L/mol·s

$RSH + R'S^- \rightleftharpoons RS^- + R'SH$ $6 \cdot 10^5$ L/mol·s

Example of a slow exchange (low rate):

$CH_3OH + H^*OH \rightleftharpoons CH_3OH^* + H_2O$ 3 L/mol·s

- for coupling to be observed,

  rate of exchange (1/s) ≈ coupling constant J (Hz)

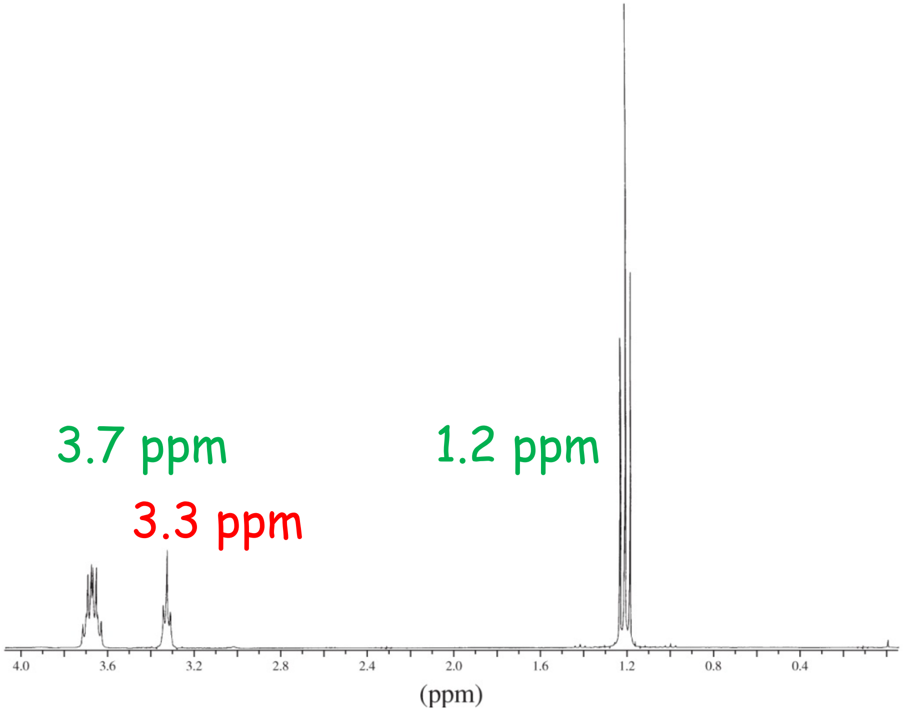
How would you slow down the rate of exchange?
Cooling?
H-bonding?

11. Protons on oxygen continued

- 2 issues

II. Variability in δ

CH_3CH_2OH



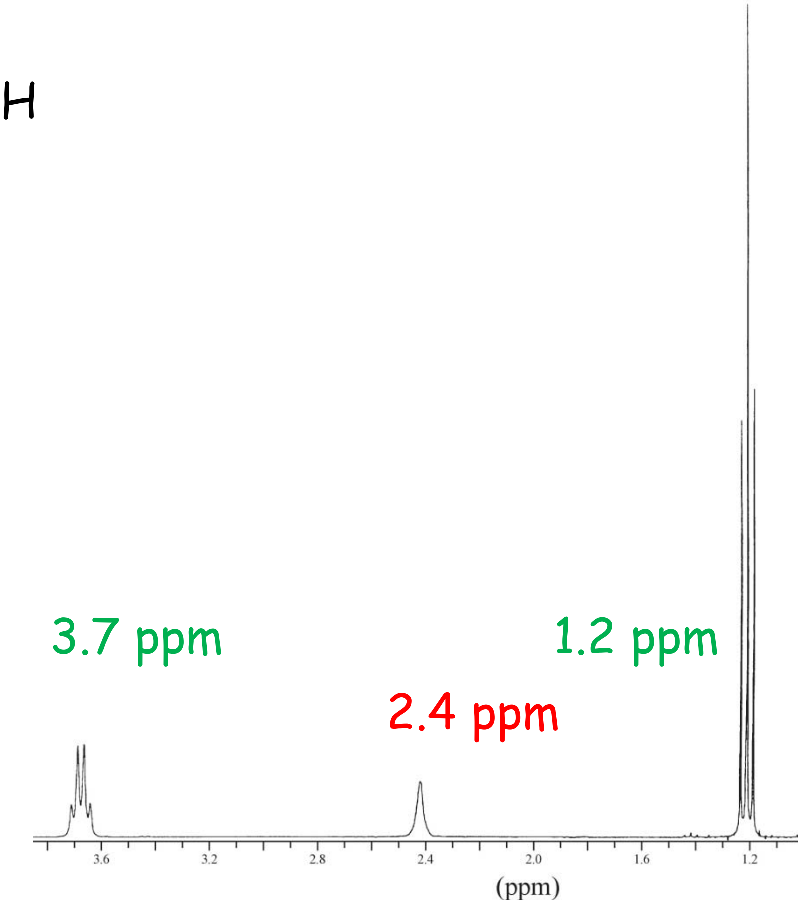
3.7 ppm

3.3 ppm

1.2 ppm

- ultrapure sample

Fig. 8.3



3.7 ppm

2.4 ppm

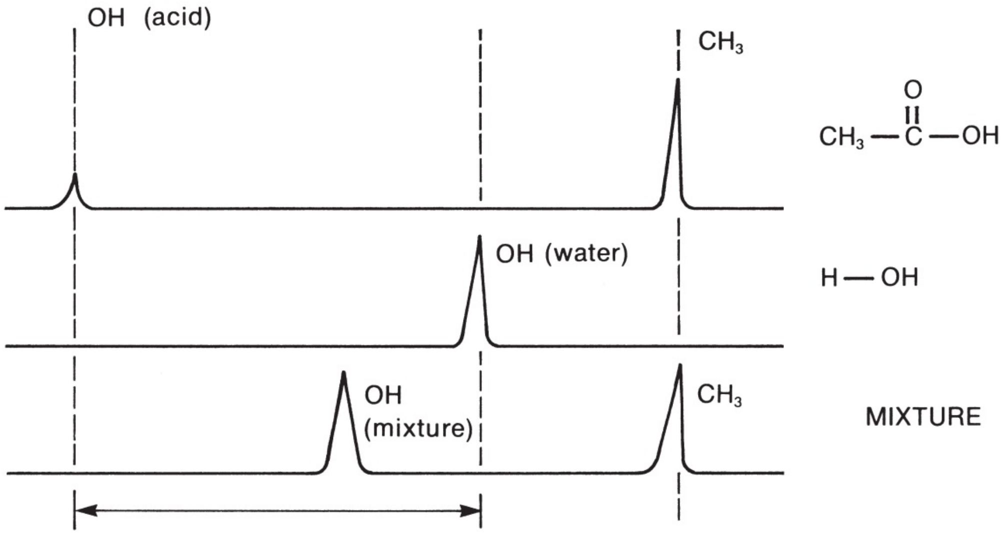
1.2 ppm

- ordinary sample

Fig. 8.2

11. Protons on oxygen continued

- Reason for the variable δ:
    - rapid exchange with H_2O… (again)
    - OH signal position becomes the weighted average



exact position depends on the amount of water

Fig. 8.4