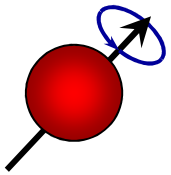
NMR spectroscopy

- vector model – energy levels model
- chemical shift
- J interaction
- equivalence
- interpretation

Nuclear spin and magnetic moment

$\vec{I} = (I_x, I_y, I_z)$ Nuclear angular momentum

intrinsic



$$\left|\vec{I}\right| = \hbar\sqrt{I(I+1)}$$

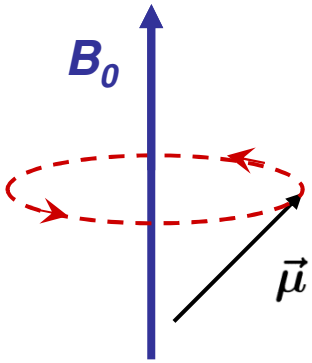
spin number

Magnetic moment $\vec{\mu} = \gamma\vec{I}$

gyromagnetic ratio

Magnetic moment in magnetic field

$\vec{B} = (0, 0, B_0)$



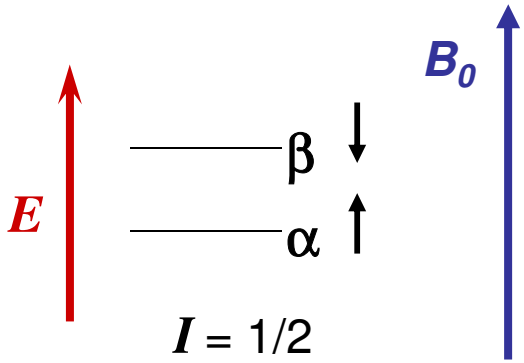
Larmor precession

$$\nu = -\frac{\gamma}{2\pi}B_0$$

Ensemble of spins

Energy of magnetic moment in magnetic field

$$E = -\vec{\mu}\cdot\vec{B}$$



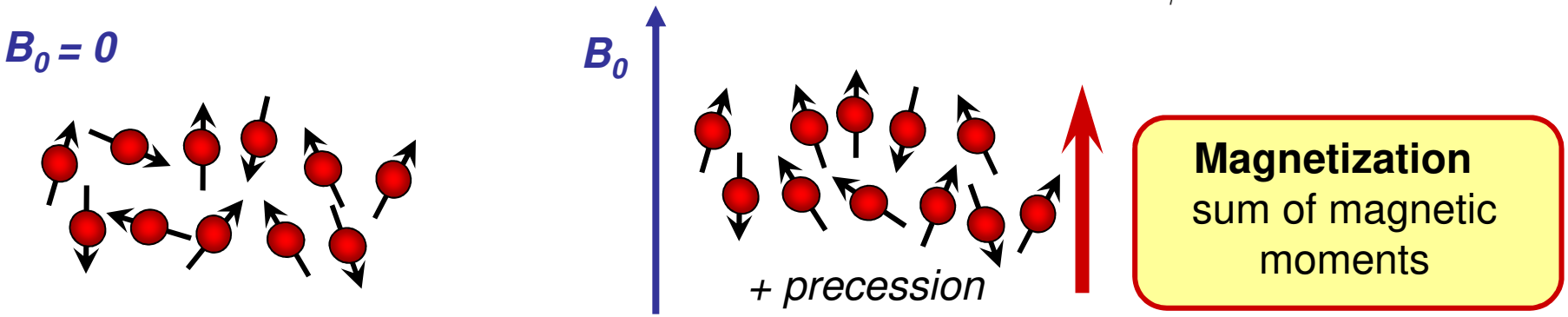
$$\Delta E = \hbar\gamma B_0$$

Boltzman distribution of energies

$$\frac{N_\alpha}{N_\beta} = \exp\left\{\frac{\Delta E}{k_b T}\right\}$$

^{1}H, temperature 300K, magneticfield induction 9.4 T

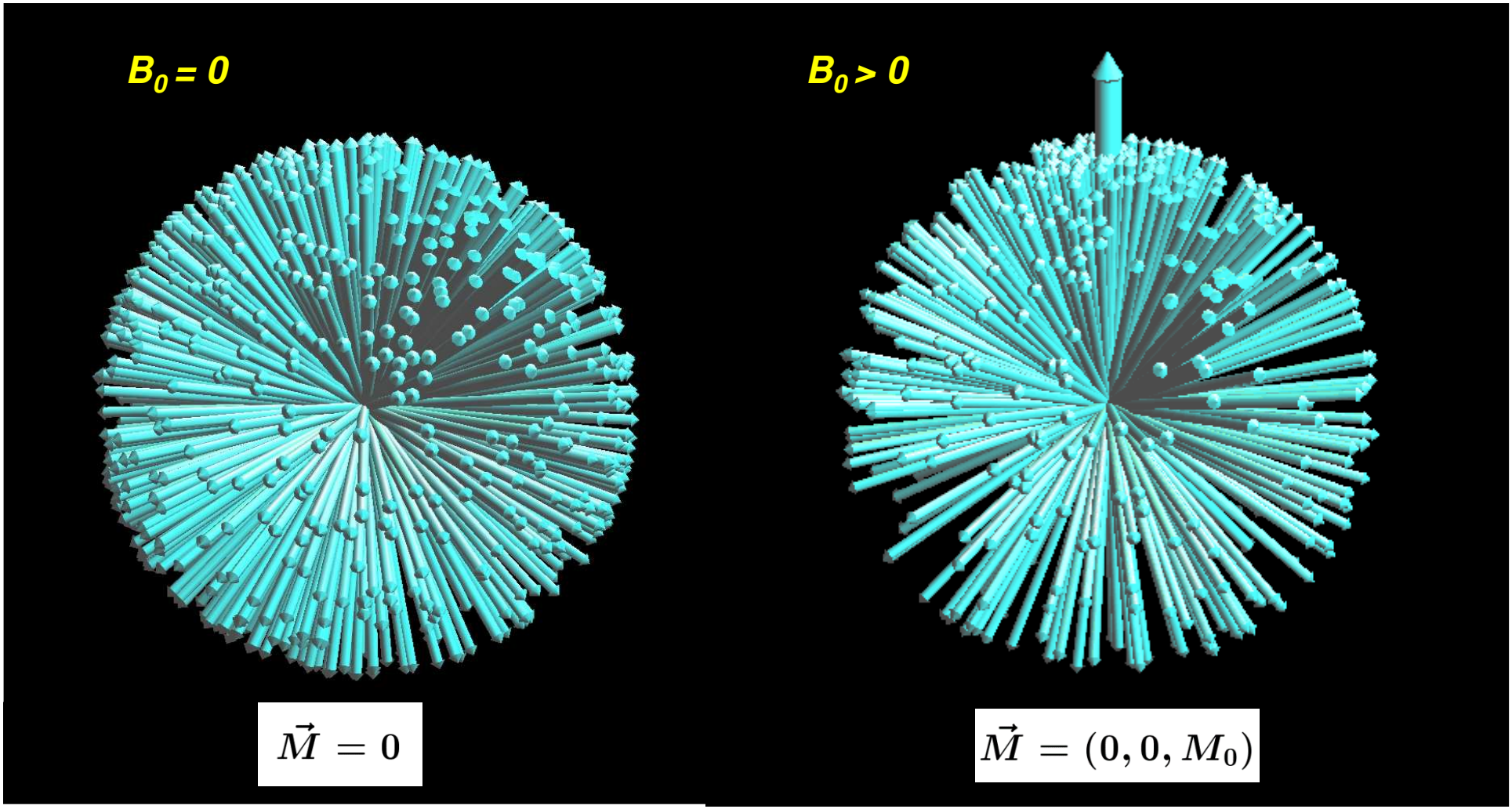
$$\frac{N_\alpha}{N_\beta} = 1.000064$$



Magnetization
sum of magnetic moments

Slight preference of parallel orientation

Ensemble of spins



random orientations

precession and polarization

random initial phase

Bloch equations

Behavior of magnetization in magnetic field (general)

$$\frac{d}{dt}M_z(t) = \gamma\left[\vec{M}(t) \times \vec{B}(t)\right]_z - \frac{M_z(t) - M_0}{T_1}$$

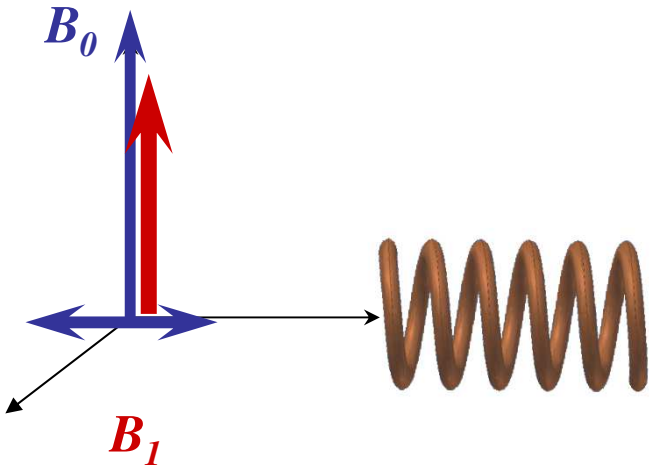
longitudinal

precession *relaxation*

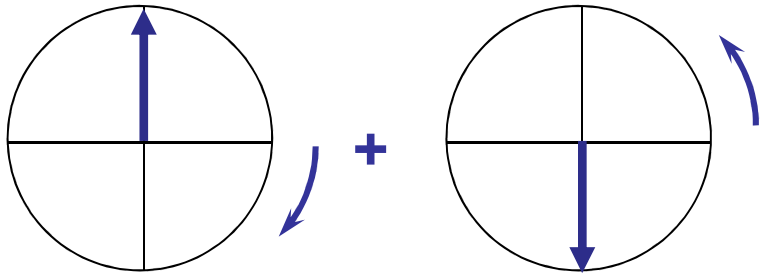
$$\frac{d}{dt}M_{x,y}(t) = \gamma\left[\vec{M}(t) \times \vec{B}(t)\right]_{x,y} - \frac{M_{x,y}(t)}{T_2}$$

transversal

Static and RF fields



Rotating frame
in resonance with Larmor precession

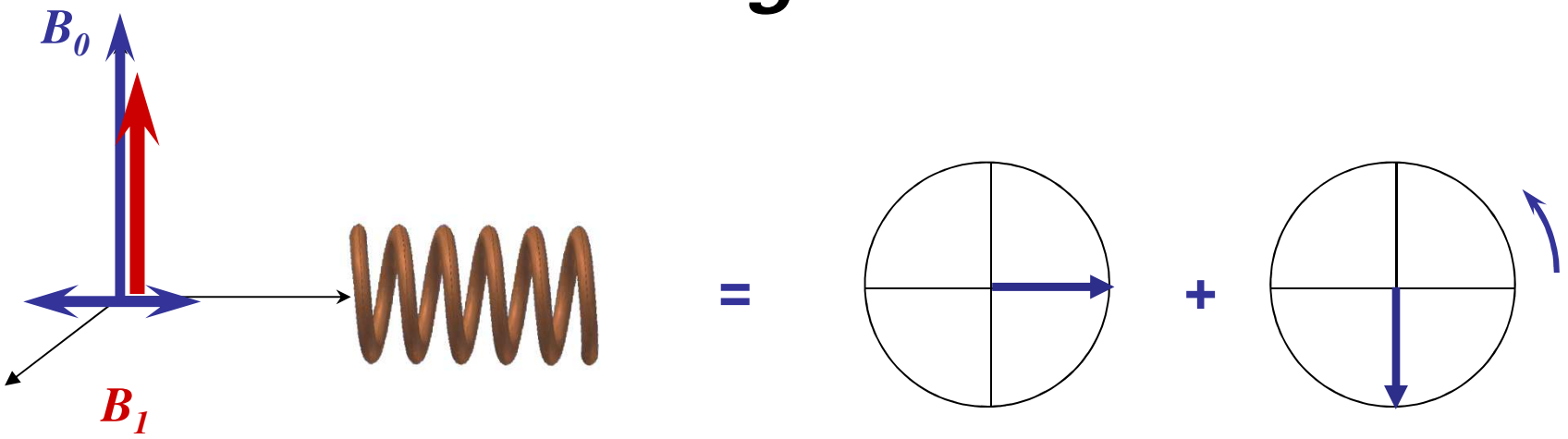


$$(B_1 \cos\omega_{RF}t\,, -B_1 \sin\omega_{RF}t\,, 0)$$

$$(B_1 \cos\omega_{RF}t\,, B_1 \sin\omega_{RF}t\,, 0)$$

$$(2B_1 \cos\omega_{RF}t\,, \quad 0, \quad 0)$$

Rotating frame



non-inertial transformation → fictitious force (Coriolis)

Total magnetic field in rotating frame

$$B = \left(B_1, 0, B_0 - \frac{\omega_{RF}}{\gamma}\right)$$

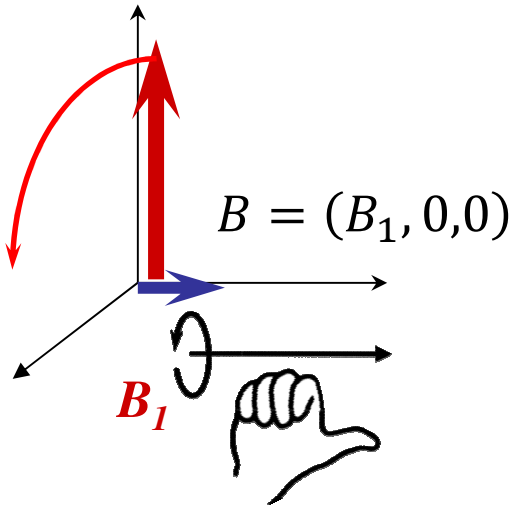
Resonance condition

$$\omega_{RF} = \gamma B_0$$

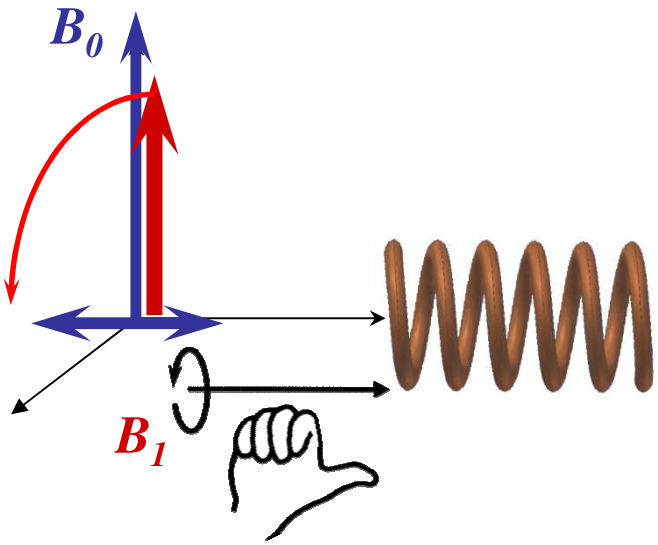
Magnetization feels only static B_1

nutation

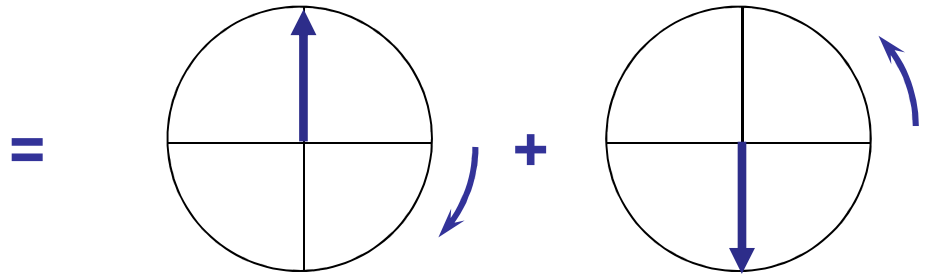
$$\omega_1 = \gamma B_1$$



Effect of radiofrequency field

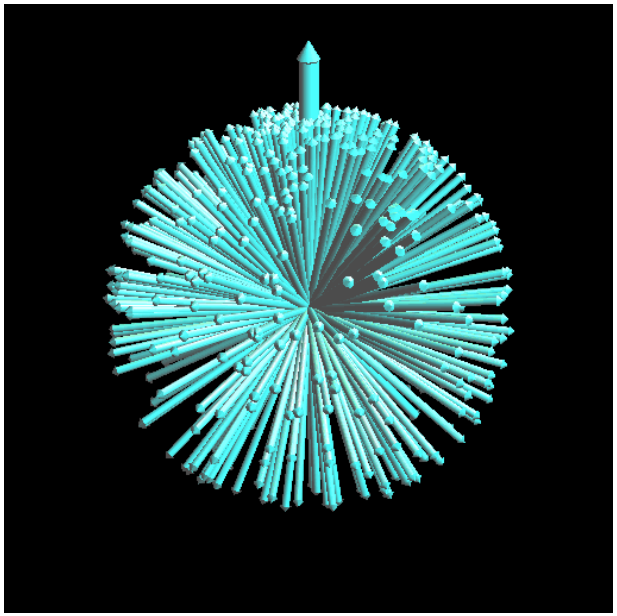


Rotating frame
in resonance with Larmor precession

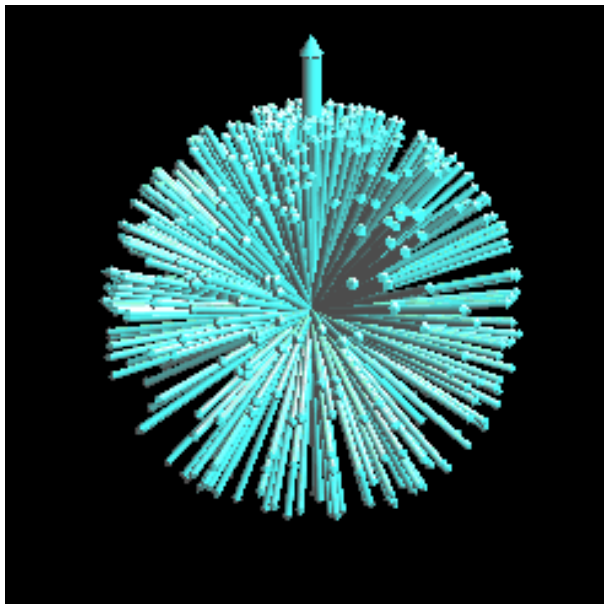


Magnetization feels only static B_1

Has no effect



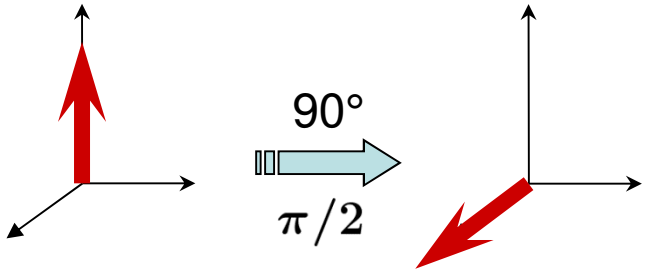
$$\omega_{RF} = \gamma B_0$$

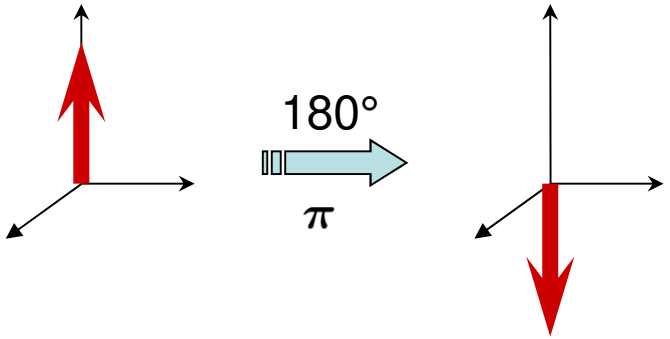


Lars G. Hanson: Bloch Simulator

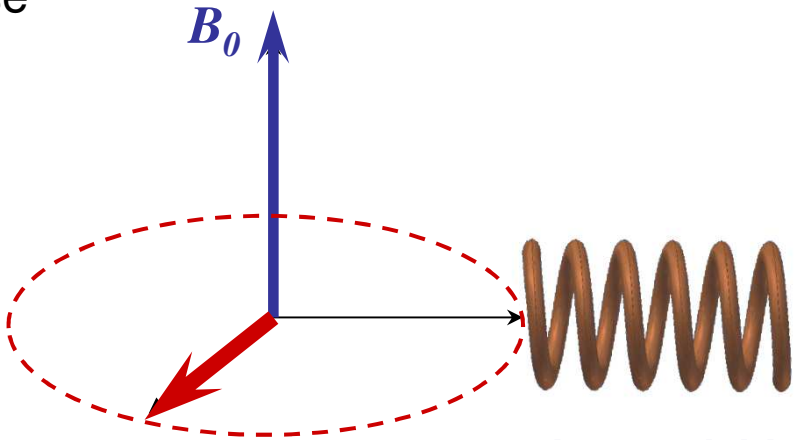
http://www.drcmr.dk/bloch

RF pulses and NMR signal





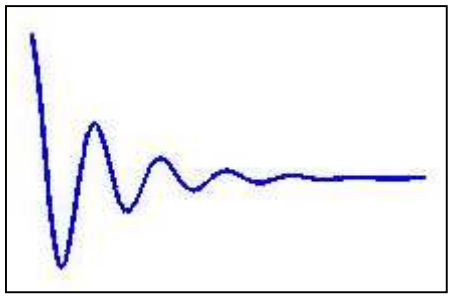
After 90° pulse



Larmor precession

$$\nu = -\frac{\gamma}{2\pi} B_0$$

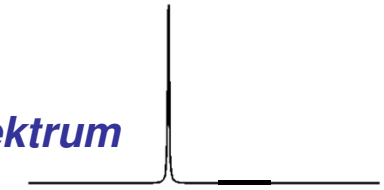
time-variable magnetic flux



Free Induction Decay
FID

Fourier transform

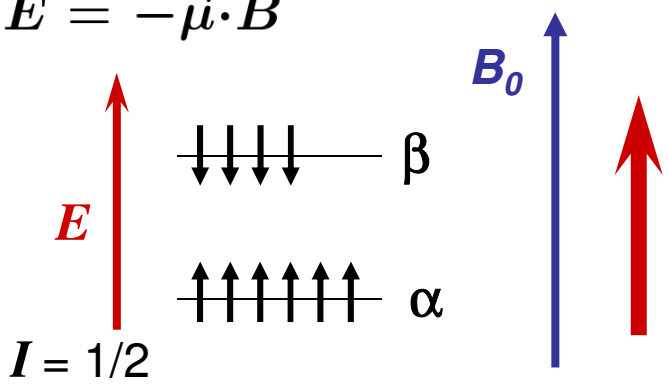
NMR spektrum



Quantum physics view on NMR

Full description, might not always be intuitive

$$E = -\vec{\mu}\cdot\vec{B}$$



$$\Delta E = \hbar\gamma B_0$$

Larmor frequency

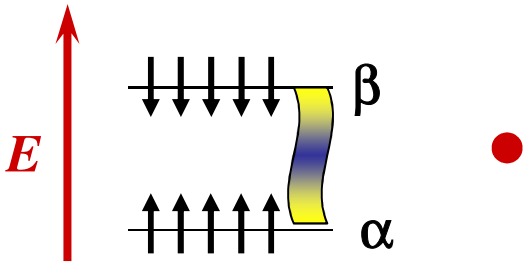
Boltzman distribution of energies

$$\frac{N_\alpha}{N_\beta} = \exp\left\{\frac{\Delta E}{k_b T}\right\}$$

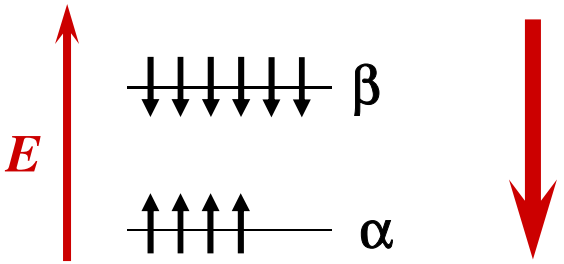
$$\left\|\vec{M}\right\| \propto N_\alpha - N_\beta$$

NMR signal proportional to initial magnetization
– difference of populations on energy levels

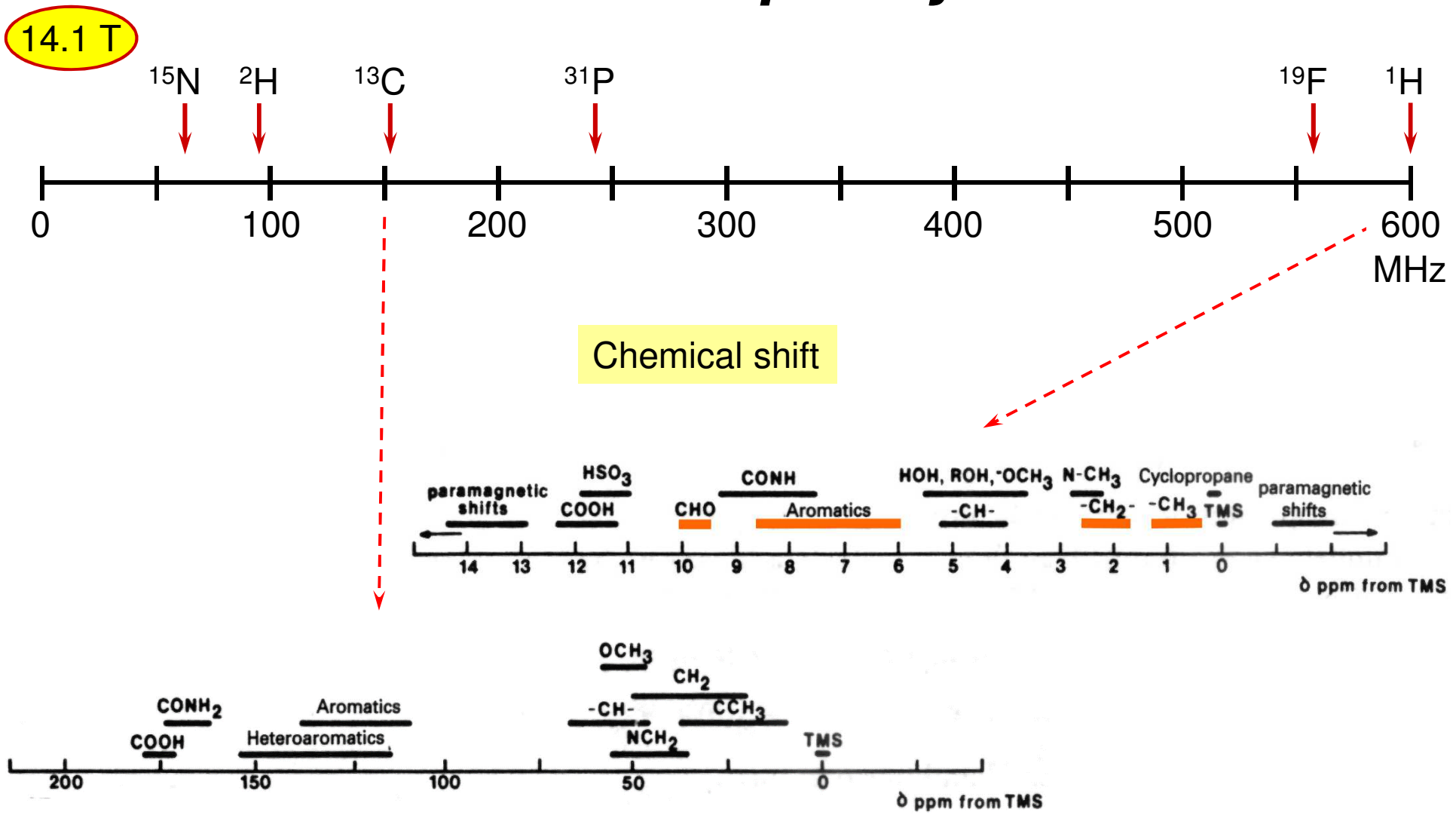
90°-pulse creates a ***coherence***
equalizes populations



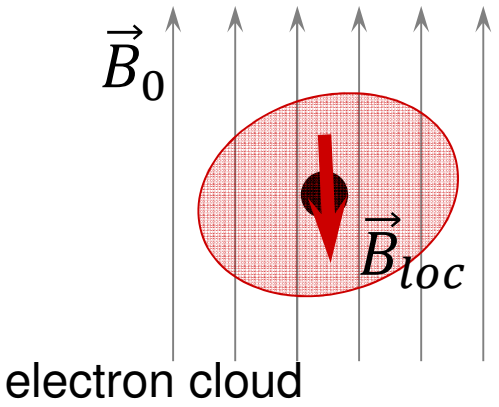
180°-pulse
inversion of populations



NMR frequency

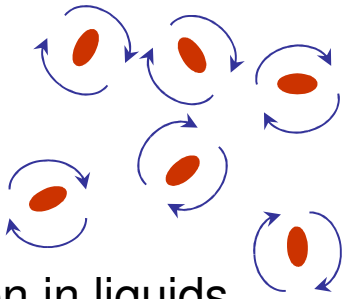


Chemical shielding

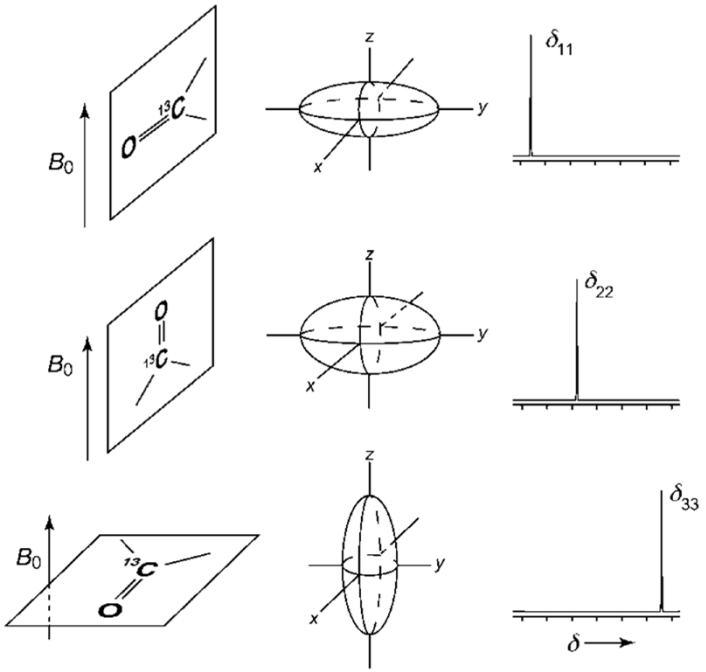


$$\vec{B}_{loc} = -\overleftrightarrow{\sigma}\,\vec{B}_0$$

shielding tensor

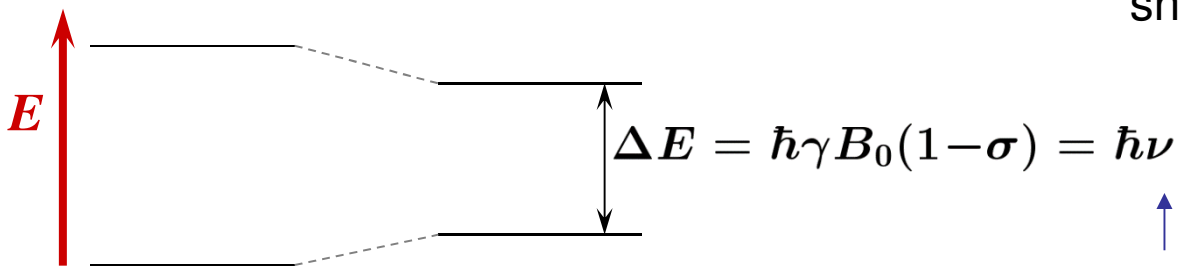


Isotropic rotation in liquids



$$B = B_0 + B_{loc} = B_0(1 - \sigma_{iso})$$

shielding constant



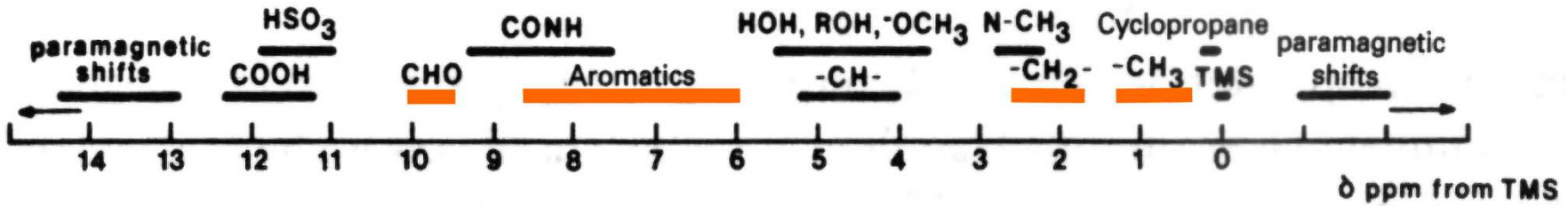
Chemical shift

$$\delta = 10^6 \frac{\nu - \nu_{ref}}{\nu_{ref}}$$

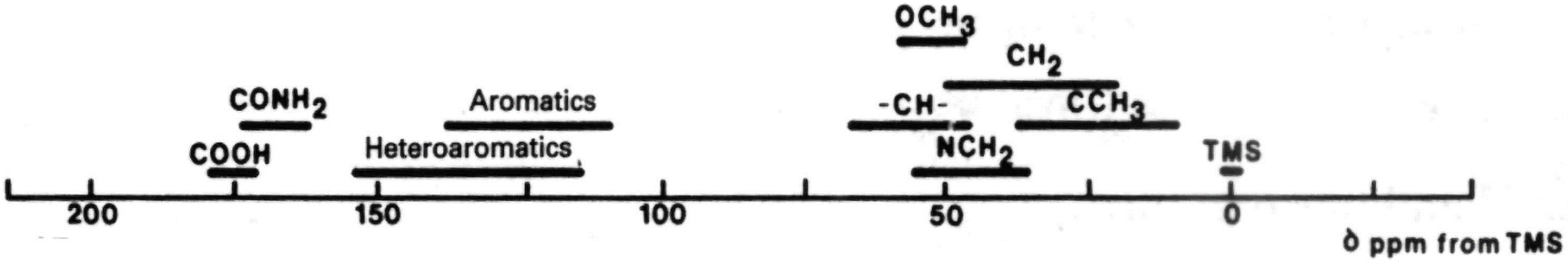
ppm

parts per milion

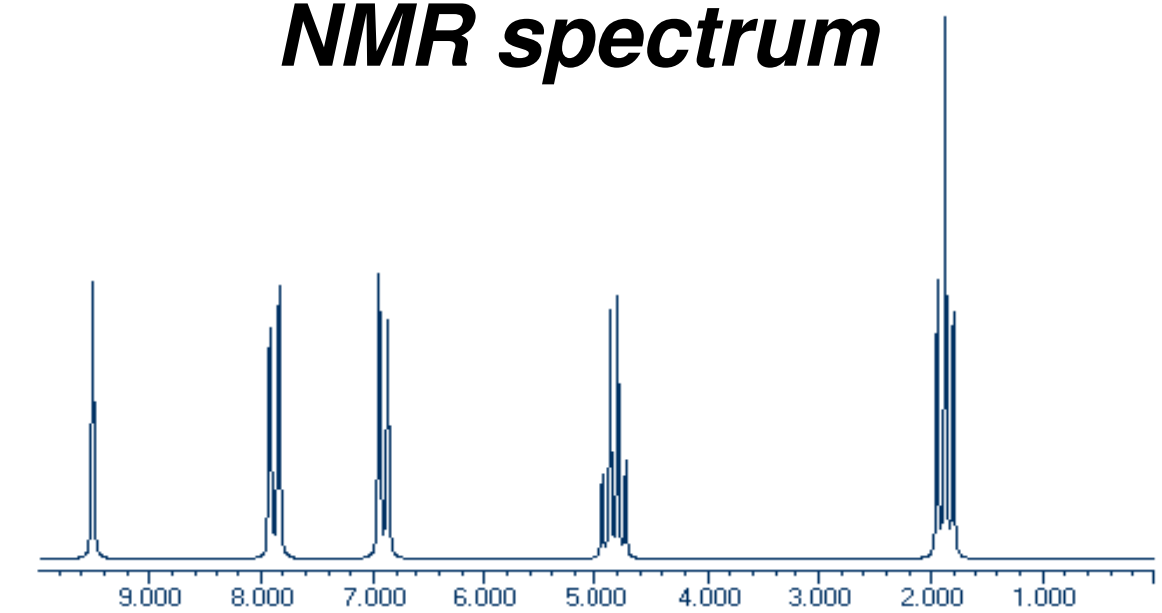
1H



13C



NMR spectrum



ppm, frequency

chemical shielding

high δ	low δ
low field	high field
downfield	upfield
paramagnetic shift	diamagnetic shift
deshielding	shielding

Chemical shielding

$$\sigma = \sigma^{dia} + \sigma^{para} + \sigma^{local}$$

dia	electrons in s-orbitals, decreasing local magnetic field
para	π-electrons and in p-orbitals, increasing local magnetic field
local	influence of surrounding substituents, both positive and negative ***strongest***

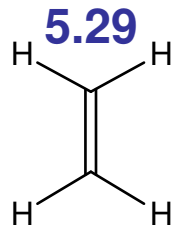
General principle

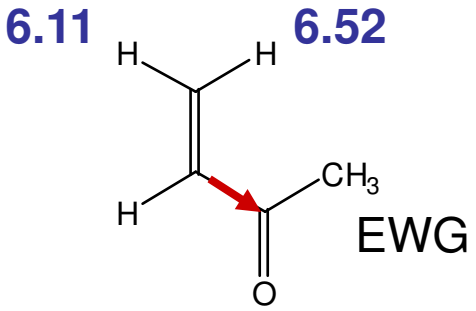
The more electrons around a nucleus the higher shielding and lower chemical shift

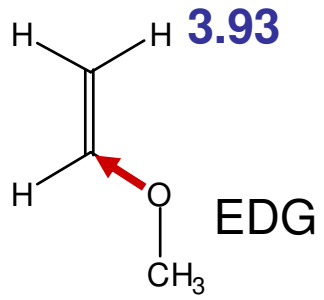
Proton chemical shifts

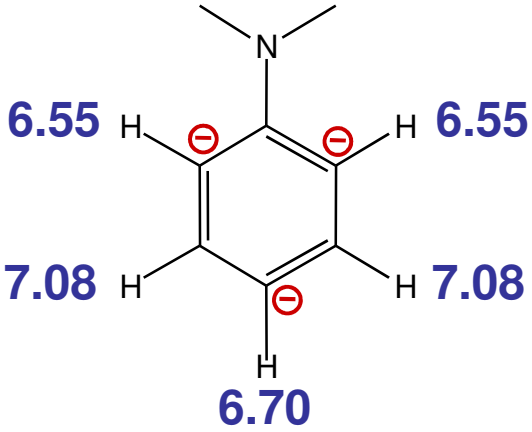
	CH4	CH3I	CH3Br	CH3Cl	CH3F
Electronegativity	2.1	2.5	2.8	3.0	4.0
Shift [ppm]	0.23	1.98	2.45	2.84	4.13

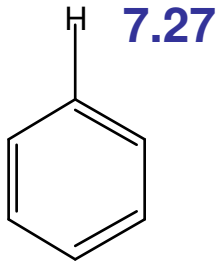
Resonance (mezomeric) effect

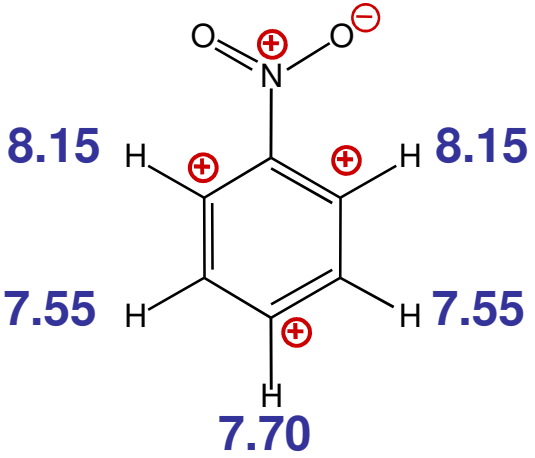






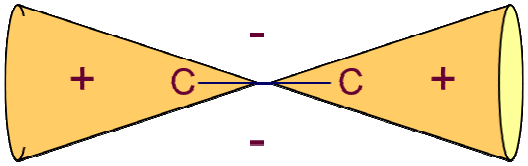






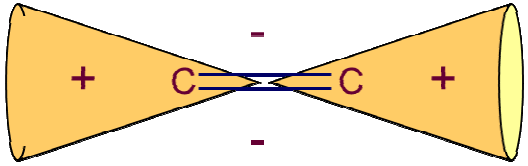
Proton chemical shifts

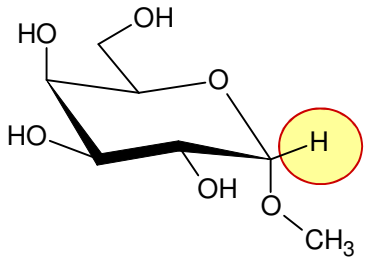
Anisotropic effect



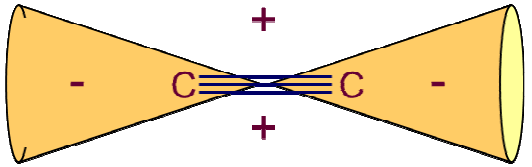
\+ higher δ

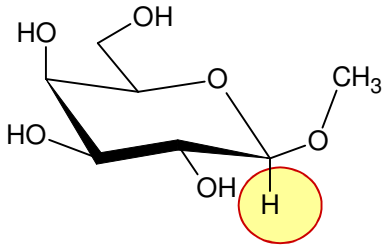
\- lower δ





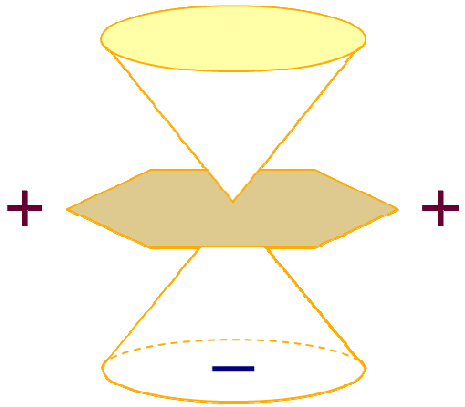
5.18

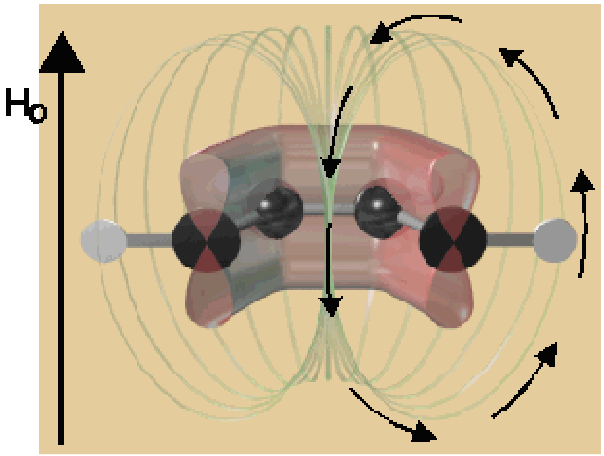


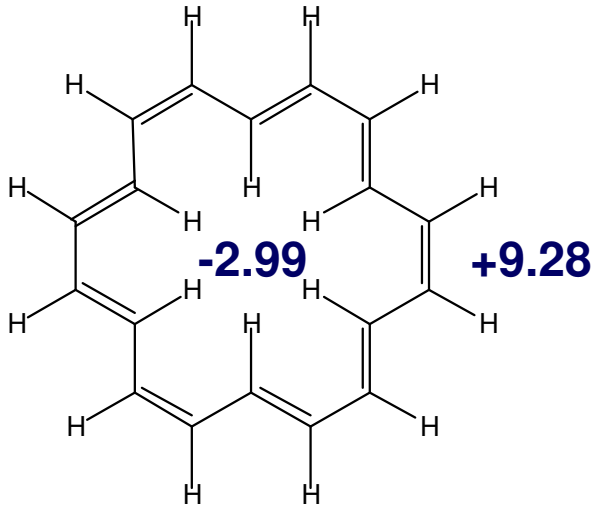


4.69

Ring current effect





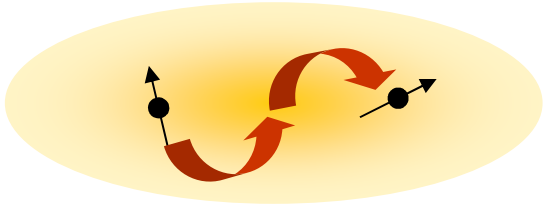


-2.99 **+9.28**

J interaction

Indirect spin-spin coupling

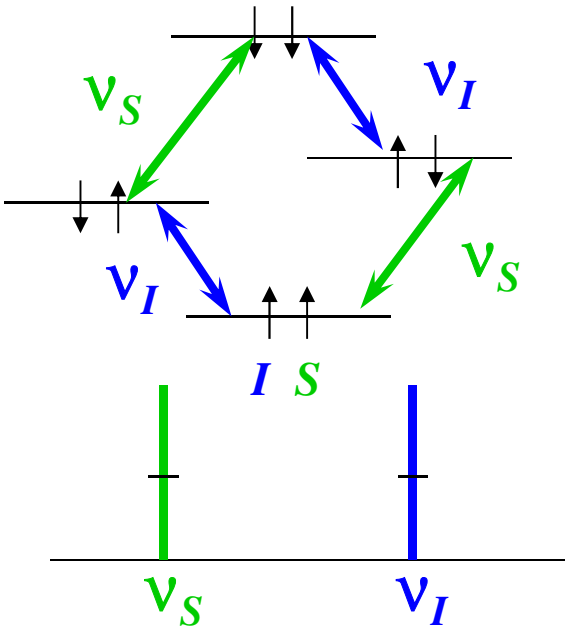
through common electrons



energy contribution

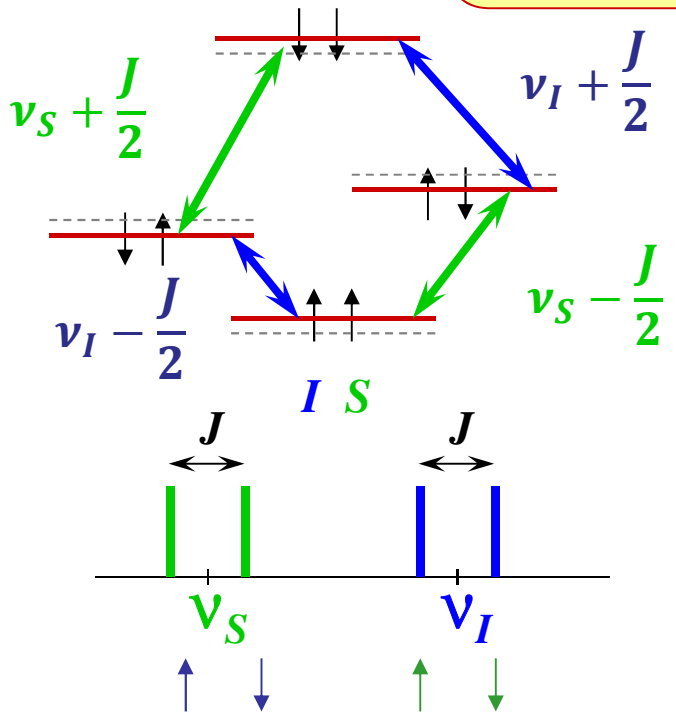
$$E_J = h\, J\, m_I\, m_S$$

Two spins-1/2, no interaction



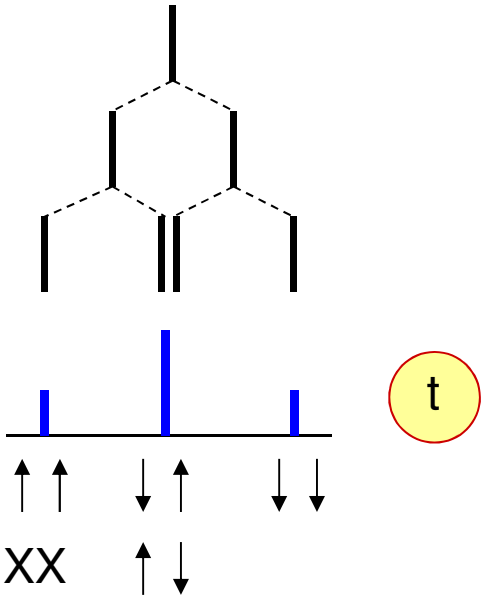
both transitions equal

including J coupling



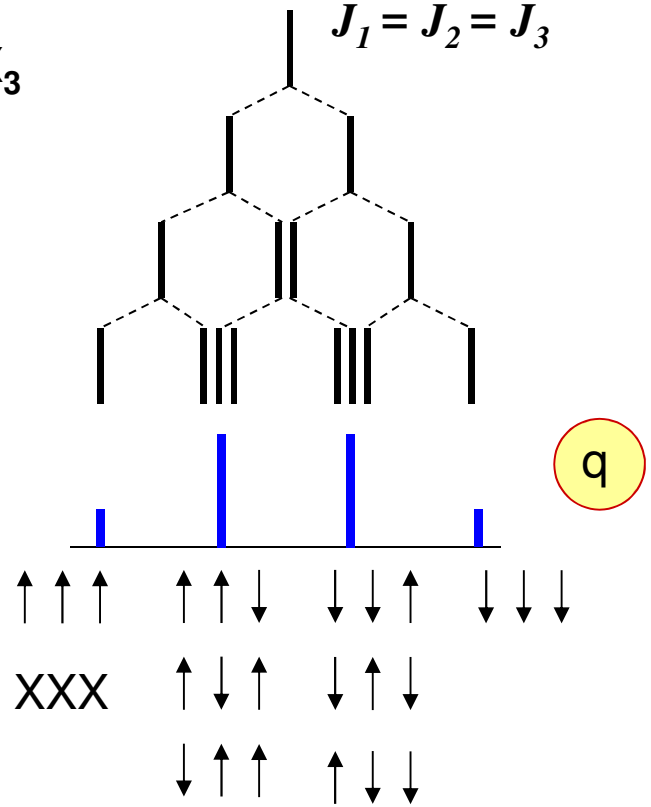
J interaction

AX_2 $J_1 = J_2$



All for spins-1/2

AX_3 $J_1 = J_2 = J_3$



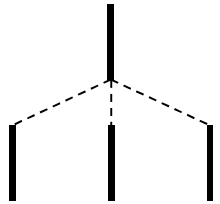
n						
			1			singlet s
1			1	1		doublet d
2			1	2	1	triplet t
3		1	3	3	1	quartet q
4	1	4	6	4	1	pentet p (quintet)

Pascal triangle

+ combinations

J interaction

AX



1 : 1 : 1

$CDCl_3$

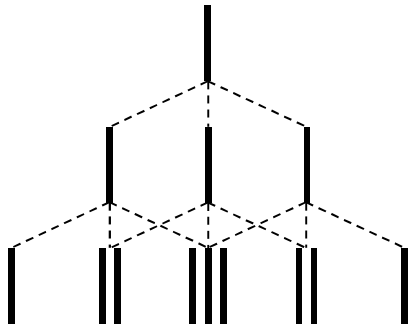
When X is spin-1

possible states

-1, 0, +1

… also for NH_4+

AX_2



1 : 2 : 3 : 2 : 1

CD_2Cl_2

11B (80%) : spin-3/2

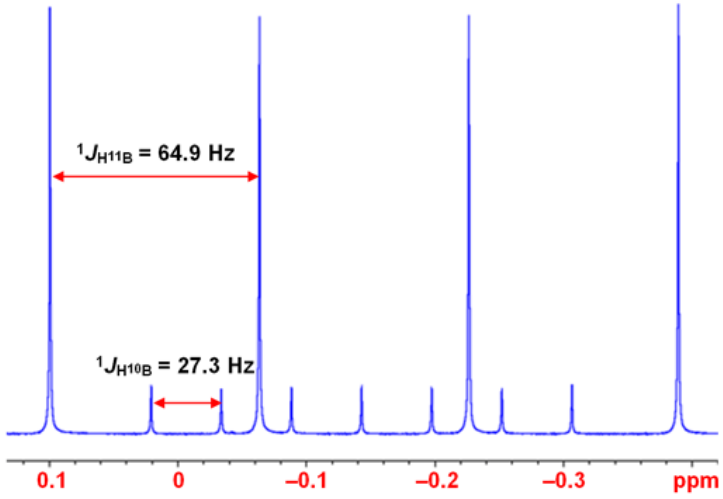
possible states

-3/2, -1/2, +1/2, +3/2

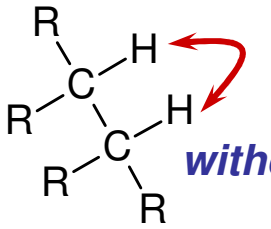
10B (20%) : spin-3

possible states

Proton spectrum of $^{+}BH_4$



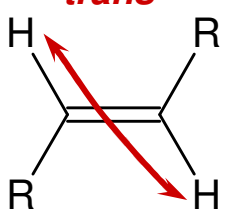
J interaction (proton-proton)



6 – 8 Hz

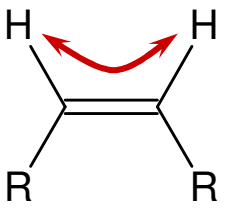
without conformational preference

trans

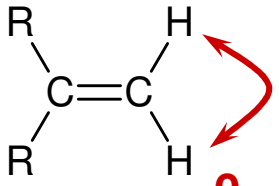


14 – 18 Hz

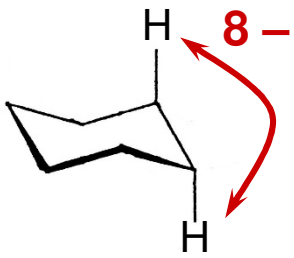
cis



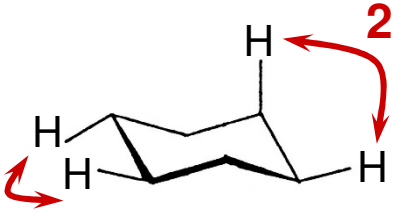
7 – 12 Hz



0 – 2 Hz

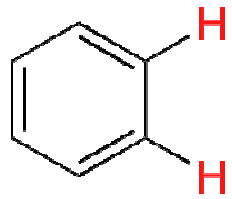


8 – 10 Hz



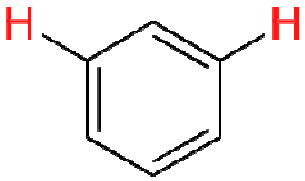
2 – 3 Hz

2 – 3 Hz



ortho-benzylic:

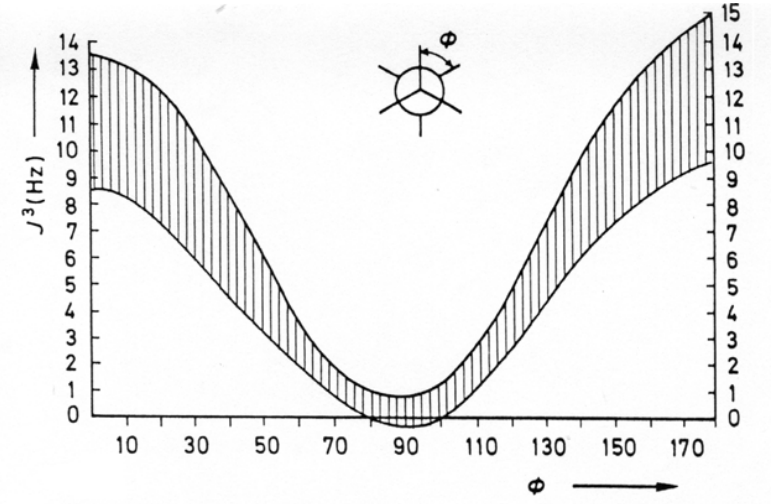
^3J = 6-10 Hz



meta-benzylic:

^4J = 0-4 Hz

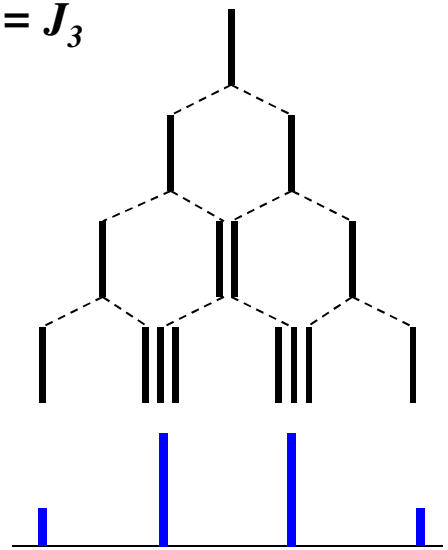
Karplus curve



$$^3J = \begin{cases} 8{,}5\cos^2\phi - 0{,}28 & \text{for } 0 \leqq \phi \leqq 90° \\ 9{,}5\cos^2\phi - 0{,}28 & \text{for } 90° \leqq \phi \leqq 180° \end{cases}$$

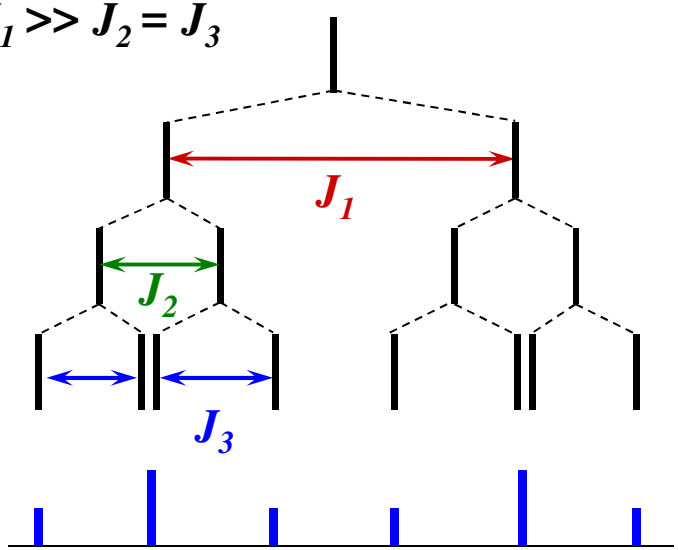
J interaction – multiplet structure

$J_1 = J_2 = J_3$



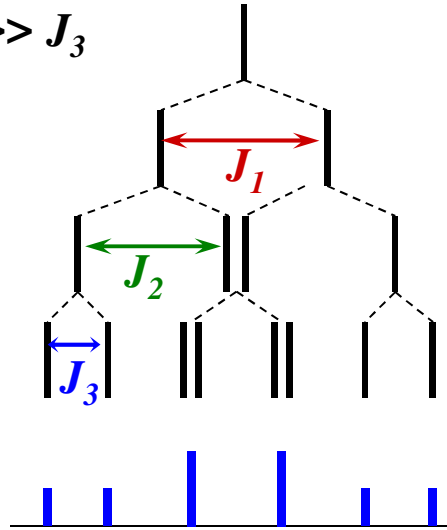
q

$J_1 >> J_2 = J_3$



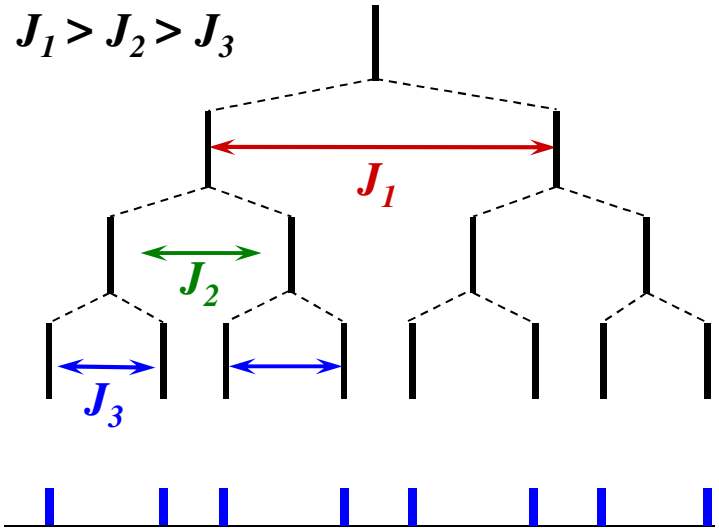
dt

$J_1 = J_2 >> J_3$



td

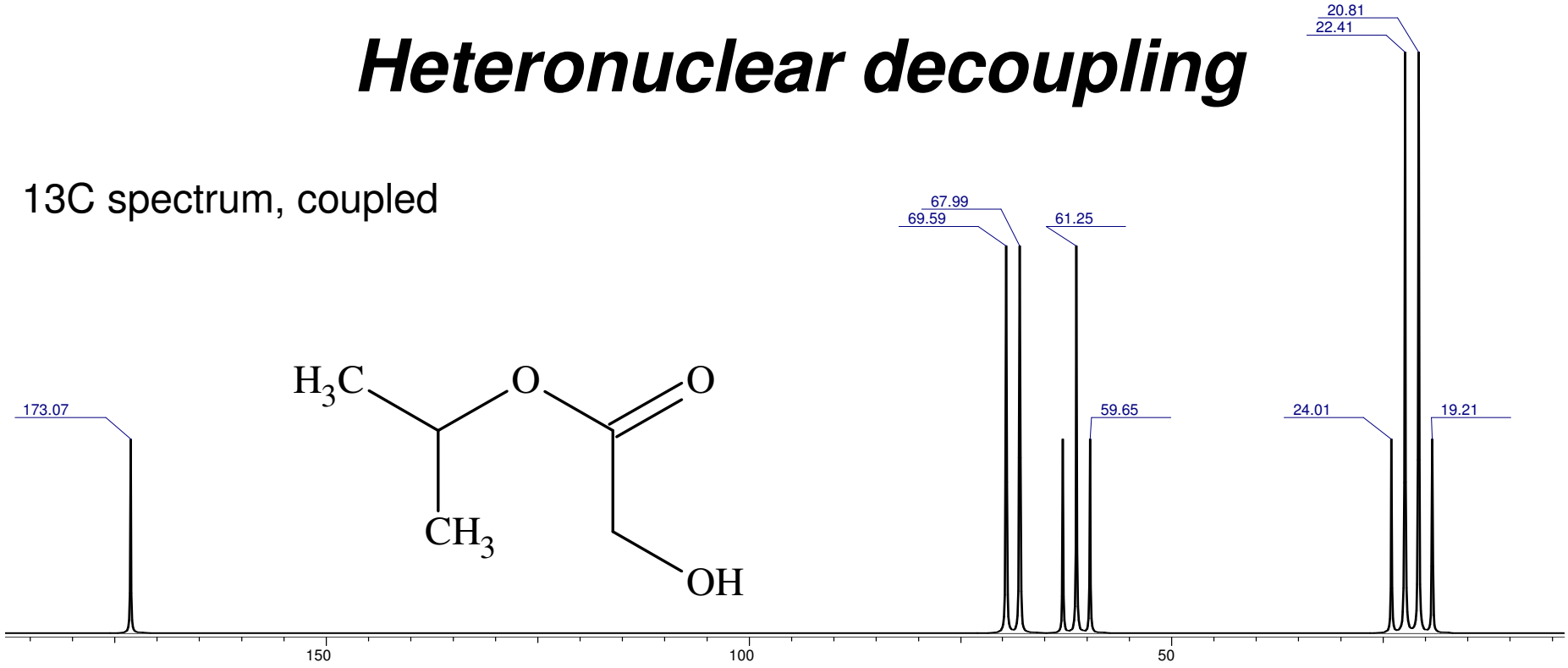
$J_1 > J_2 > J_3$



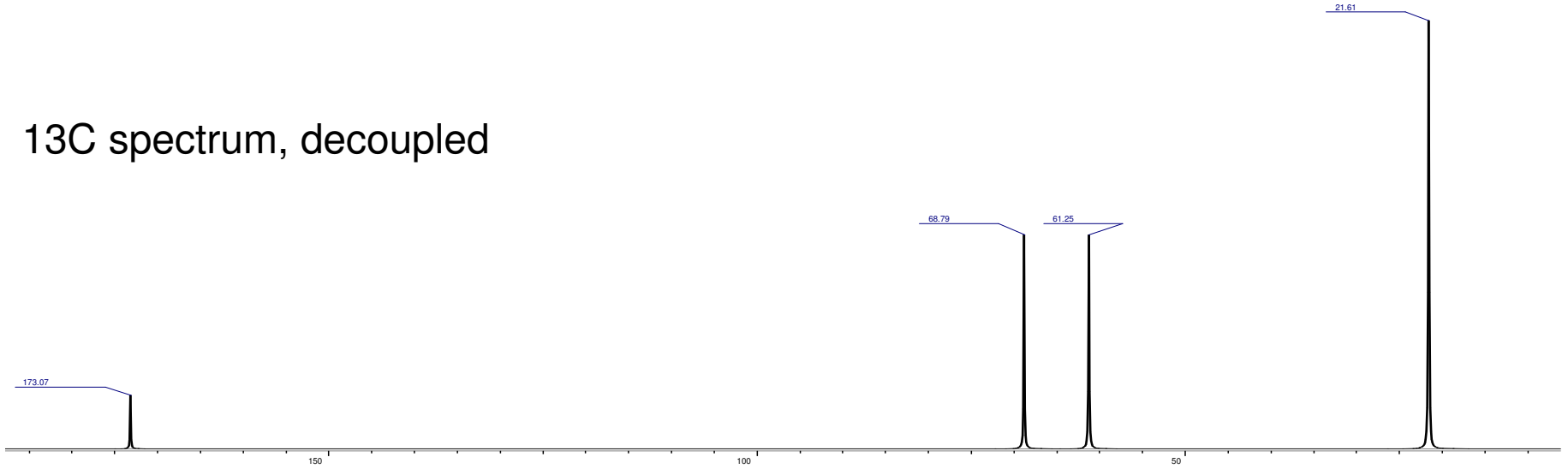
ddd

Heteronuclear decoupling

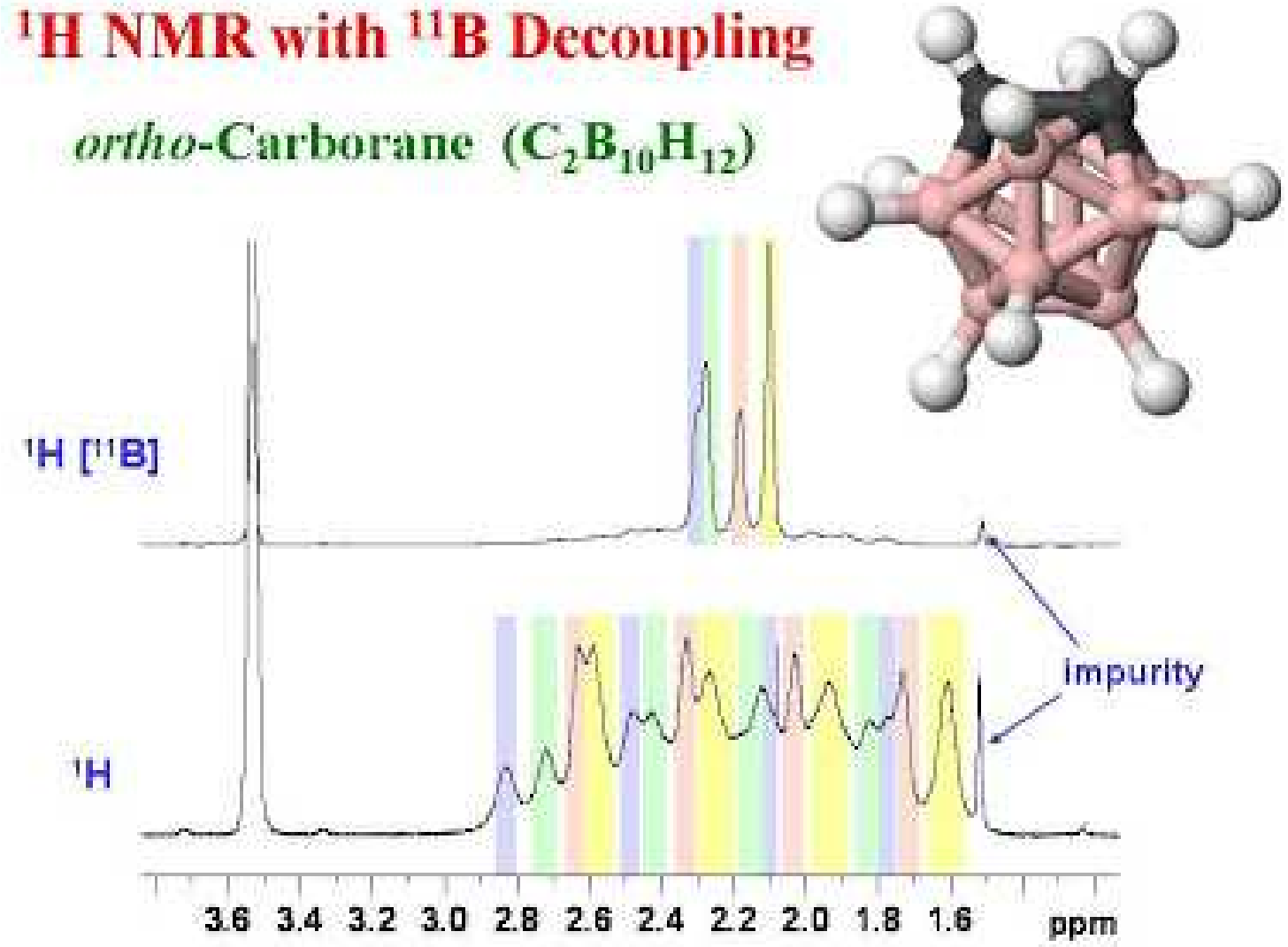
13C spectrum, coupled



13C spectrum, decoupled



Heteronuclear decoupling



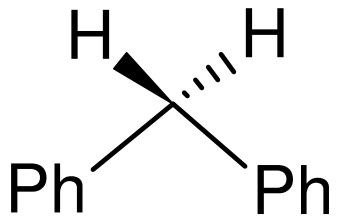
Exercise

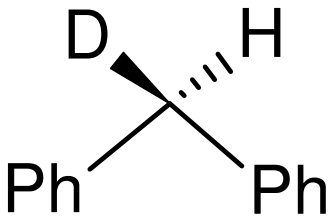
Draw 1H and 13C (both coupled and decoupled) spectra of ethanol

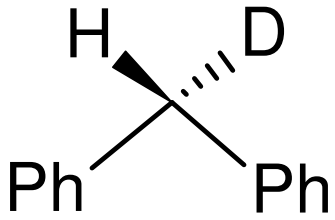
Chemical equivalence

- Nuclei are chemically equivalent if there is asymmetry operation that connects them
- CH_3 protons are equivalent due to fast rotation
- Chemically equivalent nuclei have the same chemical shift

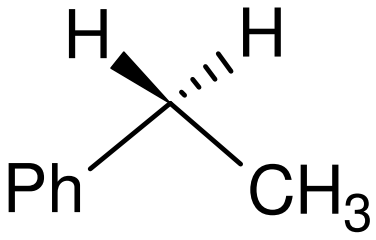
Homotopic

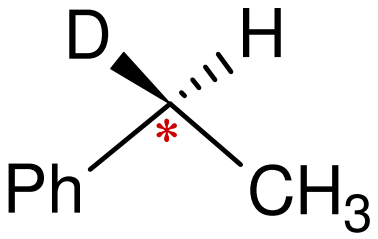


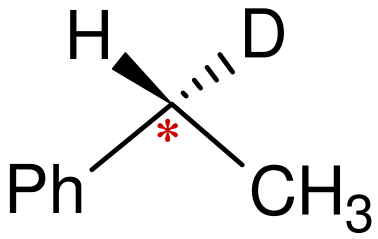




Enantiotopic

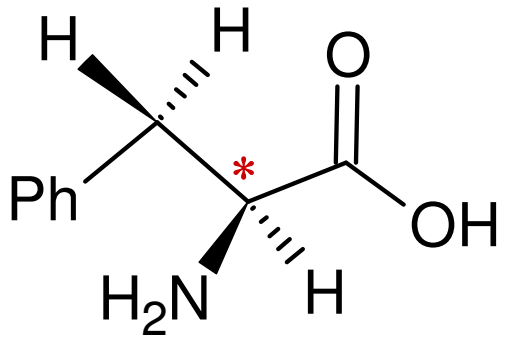


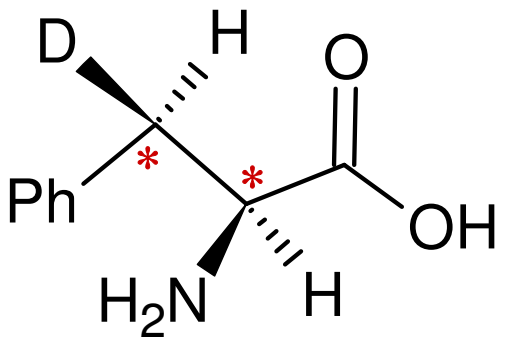


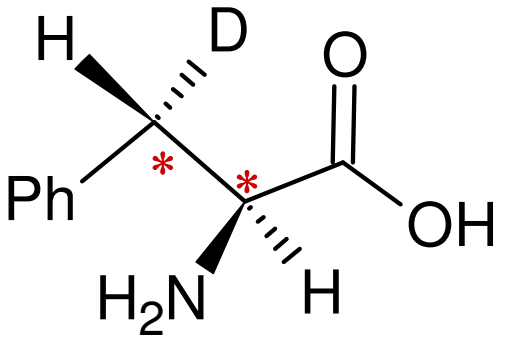


Chemical equivalence

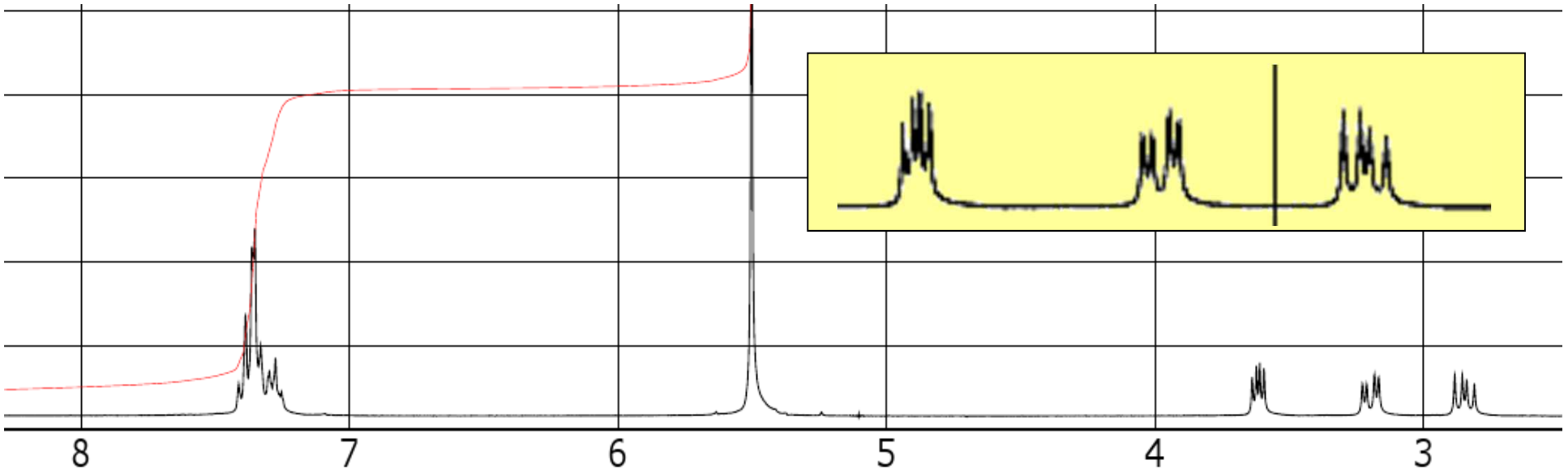
Diastereotopic







NOT chemically equivalent

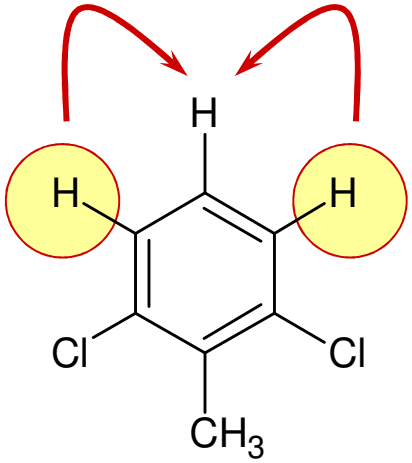


Magnetic equivalence

Nuclei are chemically equivalent

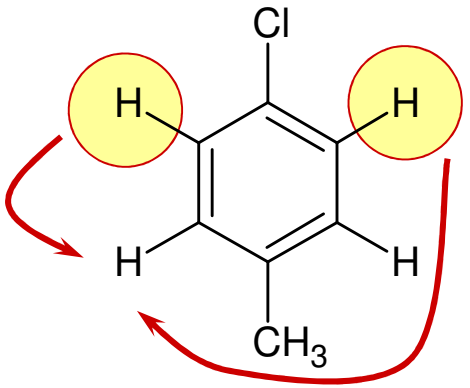
AND

Have the same geometric relation to all other NMR active nuclei
(have the same J interactions with all other NMR active nuclei)



Yes

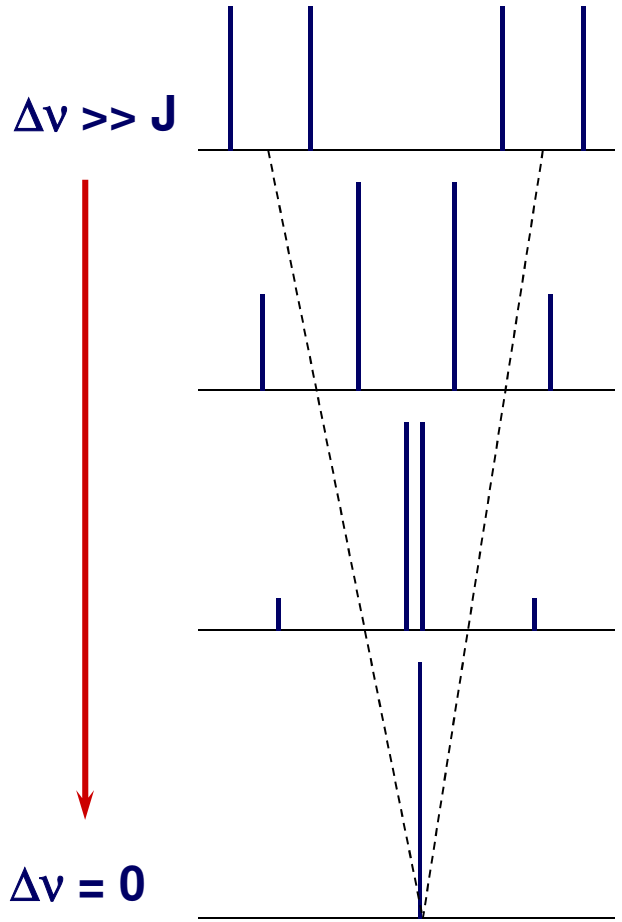
Spectra of magnetic equivalent nuclei are not influenced by J-couplings between them



No

Chemically equivalent but magnetically non-equivalent nuclei provide spectra of higher order (complicated pattern due to J-couplings)

Higher order spectra



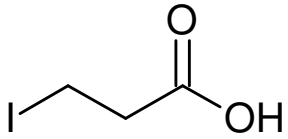
First order

„pseudo-first order“

higher order

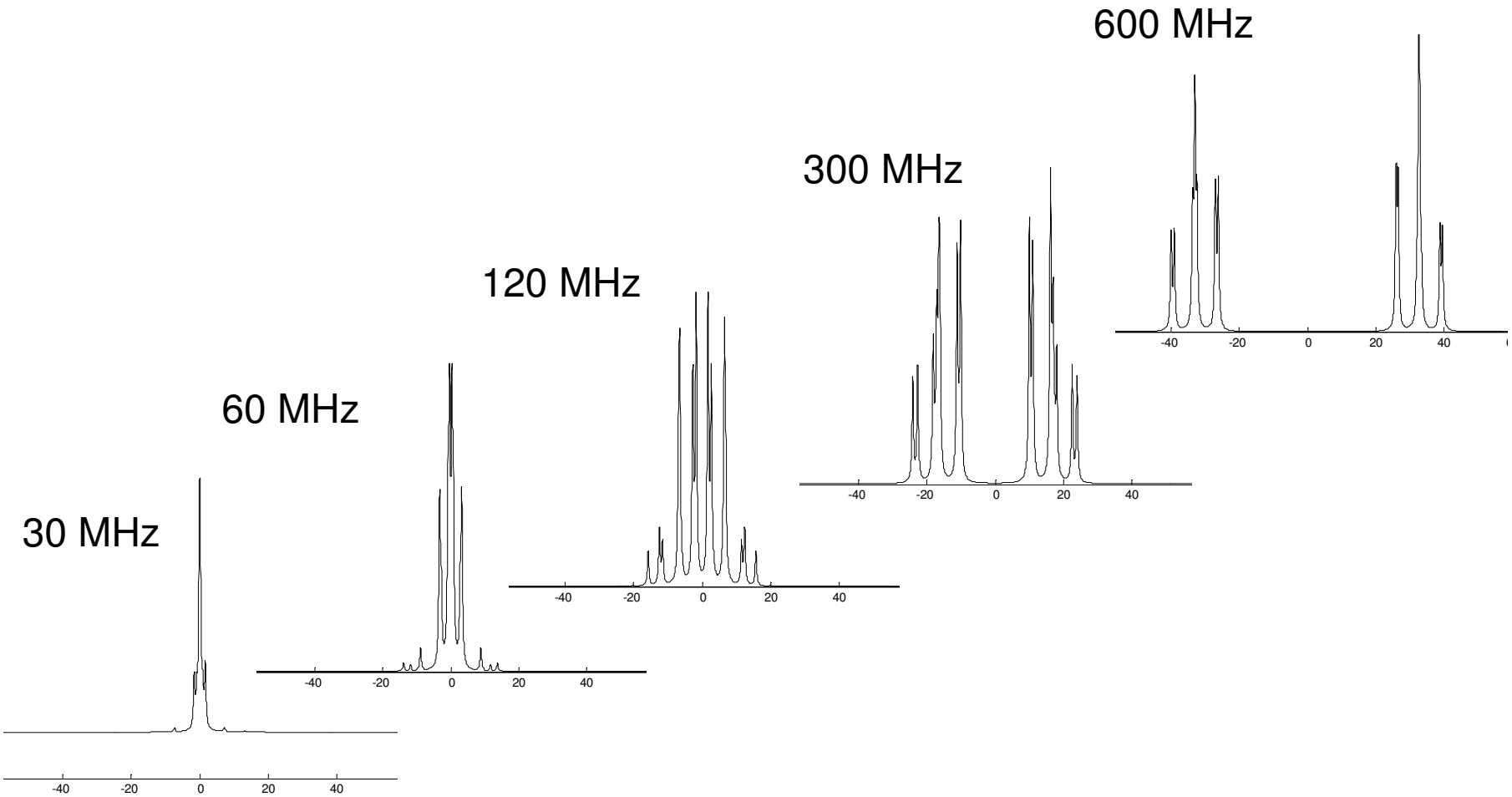
roof effect

Higher order spectra and mag. field



Chemical shift difference 0.11 ppm

J-coupling 7 Hz



Information from ^{1}H spectrum

• Number of signals	***symmetry***
• Intensity	***number of equivalent nuclei***
• Chemical shift	***functional group***
• Fine structure and J-constants	***neighboring protons***

Information from ^{13}C spectrum (decoupled)

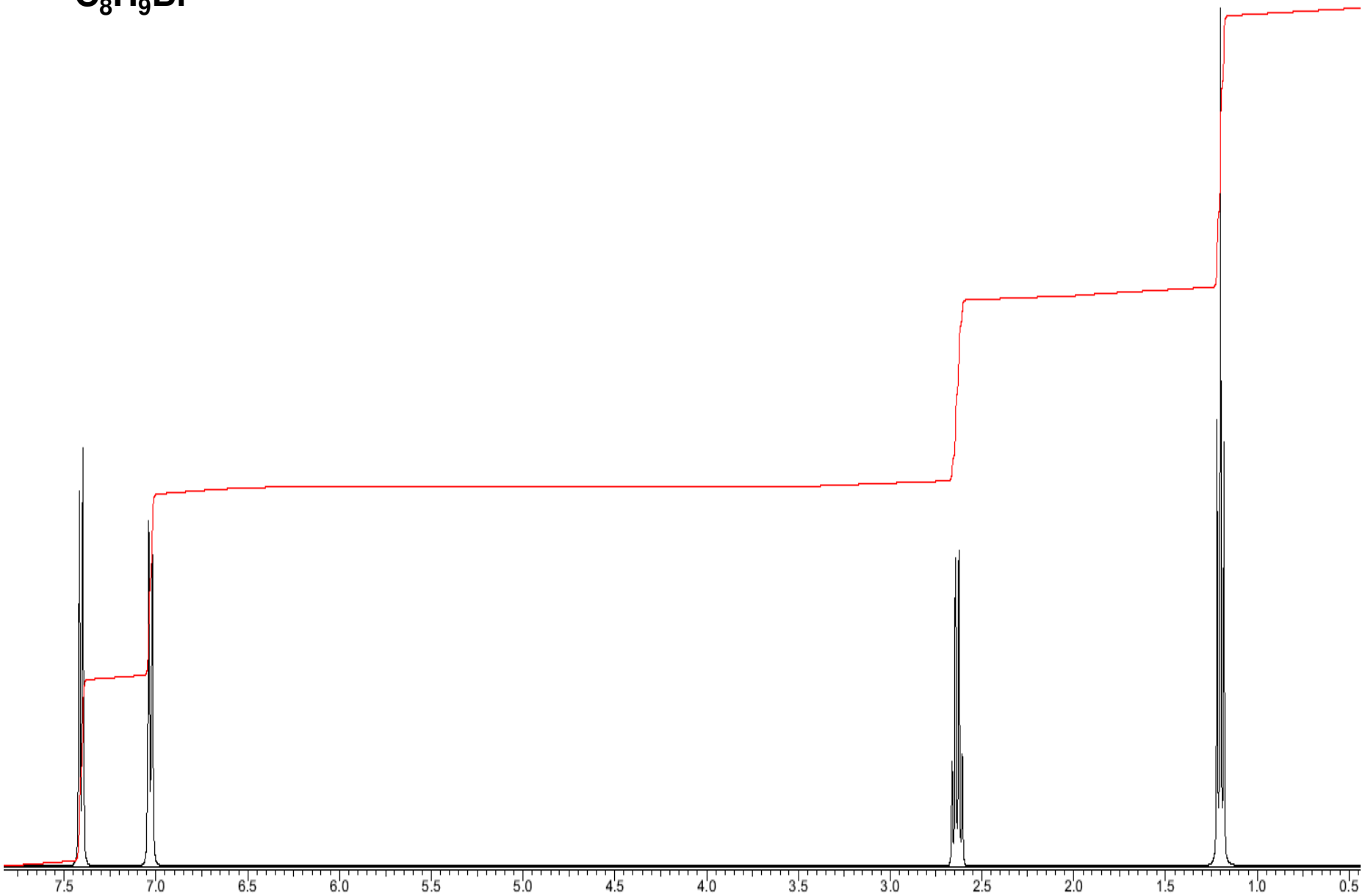
- Number of signals
- Chemical shift
- intensity does not correspond to number of equivalent nuclei

Solving NMR spectra

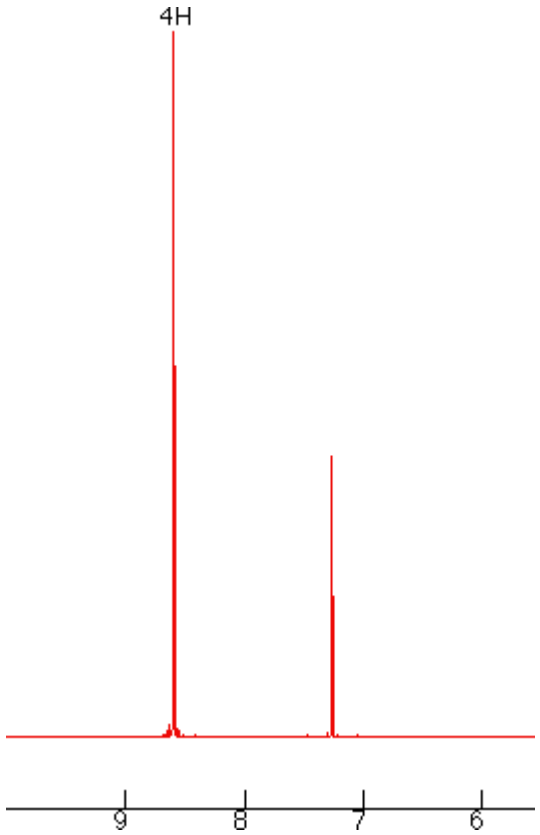
- Read number of signals, their position (shift) and intensity in 1H spectrum
- split protons to corresponding groups
- from splitting patterns decide which groups are neighbors
- guess which functional groups they are according to chem. shifts (and perhaps using additional info like ^{13}C spectrum, APT/DEPT)
- draw possible molecule
- check what spectrum that molecule would give to verify the solution

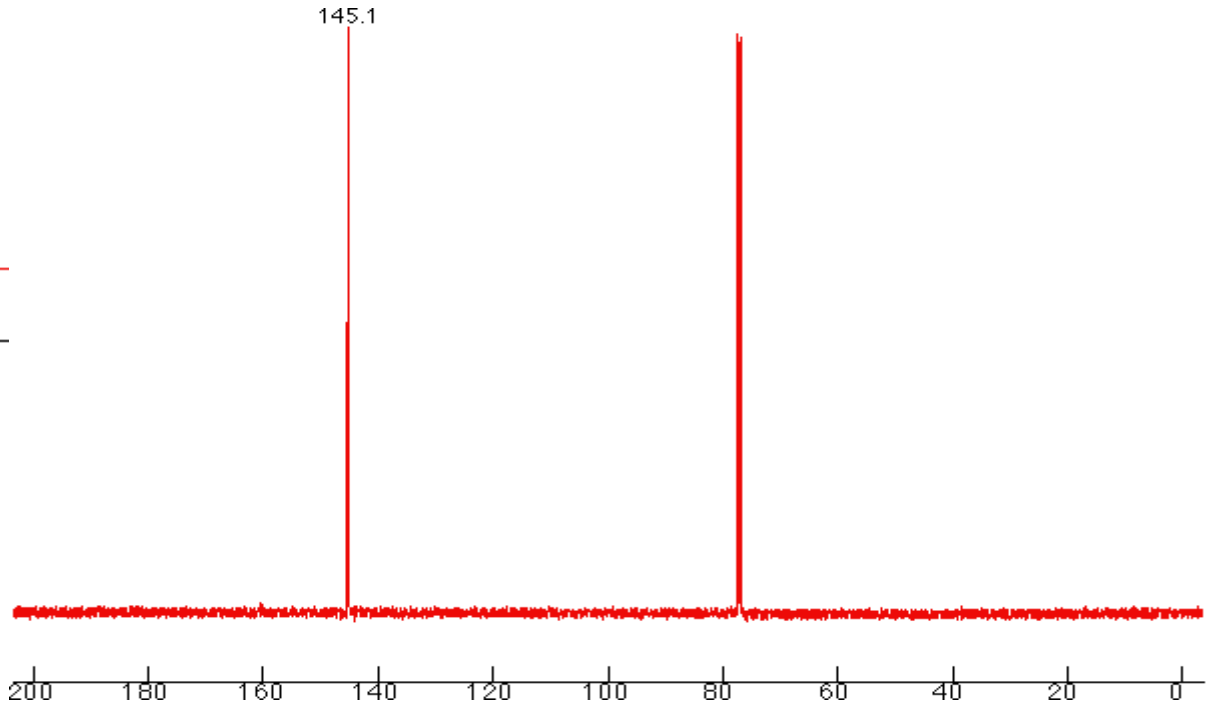
C_8H_9Br

P4



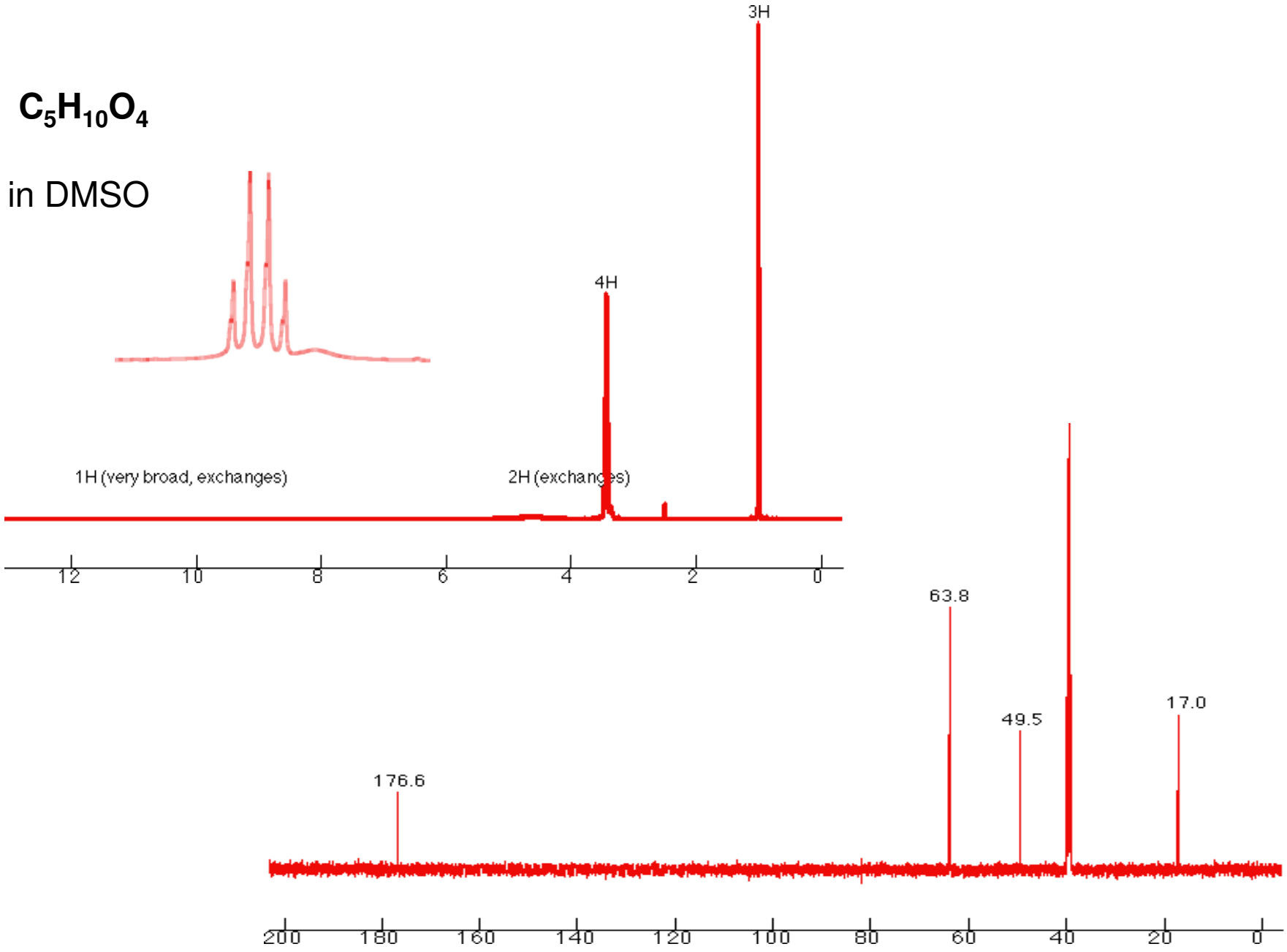
$C_4H_4N_2$ in $CDCl_3$





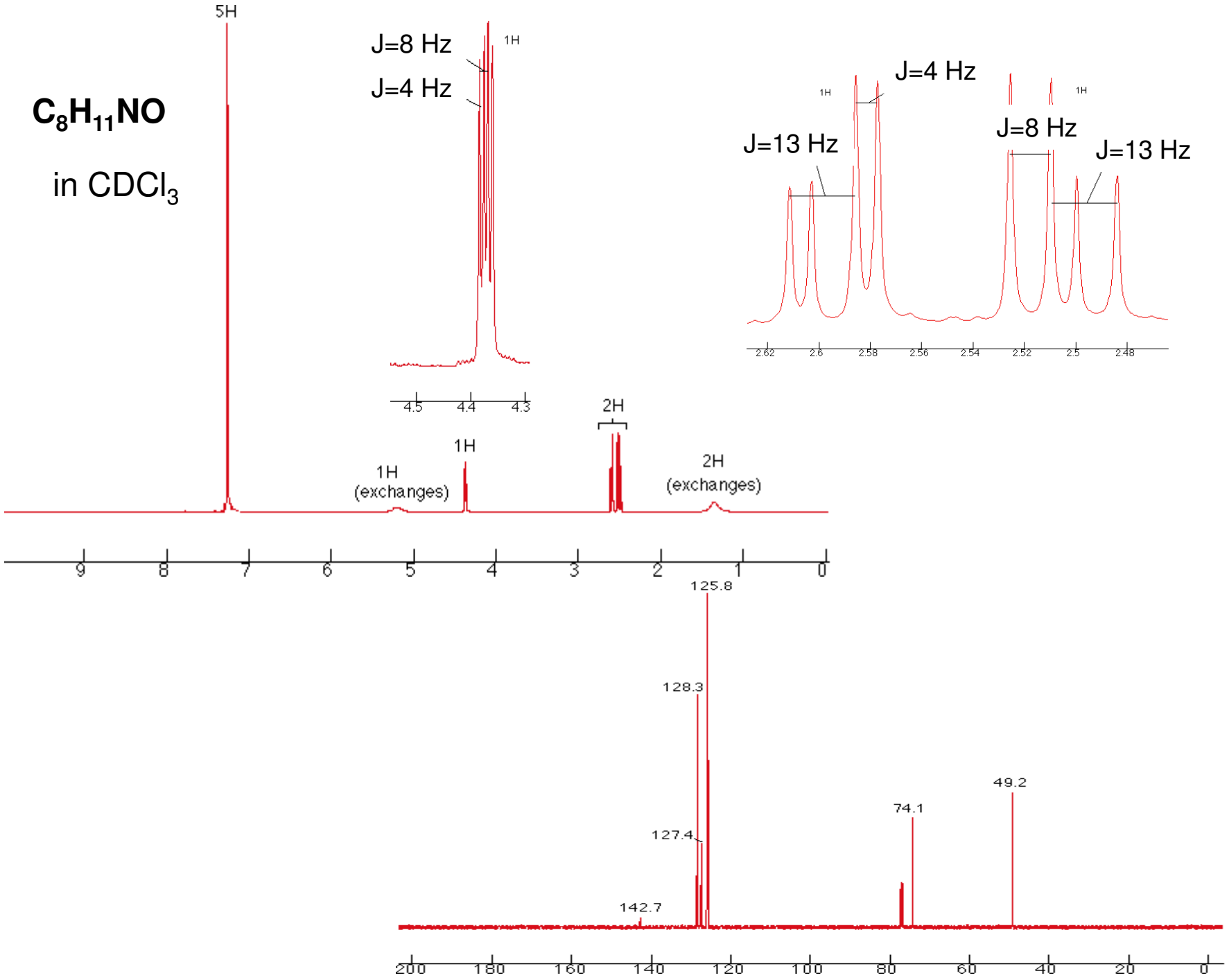
$C_5H_{10}O_4$

in DMSO



$C_8H_{11}NO$

in $CDCl_3$



$C_9H_{13}NO$

in $CDCl_3$