Spectroscopic Identification of Organic Molecules

^{1}H NMR Spectroscopy

Exclusively for the summer course at
East China University of Science and Technology

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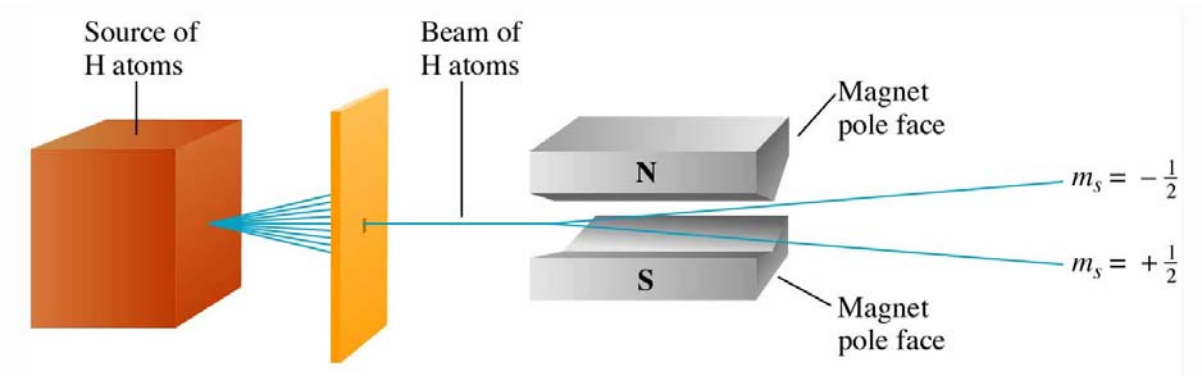
^{1}H NMR Spectroscopy

1. Basic Theory of NMR

1.1 Magnetic Properties of Nuclei

Experiment by Stern-Gerlach: A beam of H-atoms splits into two by a magnetic field.



Spin angular momentum (P):

$\underline{\mathbf{P}} = \underline{\mathbf{I}} \cdot \hbar \qquad (\hbar = h/2\pi)$

I: spin quantum number,

$|\underline{\mathbf{I}}| = [I \cdot (I+1)]^{1/2}$

Magnetic moment (μ):

$\underline{\boldsymbol{\mu}} = \gamma \cdot \underline{\mathbf{P}}$

γ: gyromagnetic ratio

$\gamma = \underline{\boldsymbol{\mu}}/\underline{\mathbf{P}} = \mu / [\{I \cdot (I+1)\}^{1/2} \cdot \hbar]$

= magnetic moment / angular momentum

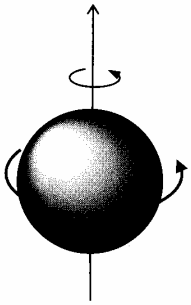


FIGURE 3.1 Spinning charge on proton generates magnetic dipole.

TABLE 3.1 Type of nuclear spin number, *I*, with various combinations of atomic mass and atomic number.

I	Atomic Mass	Atomic Number	Example of Nuclei
Half-integer	Odd	Odd	$^{1}_{1}H(\frac{1}{2})$, $^{3}_{1}H(\frac{1}{2})$, $^{15}_{7}N(\frac{1}{2})$, $^{19}_{9}F(\frac{1}{2})$, $^{31}_{15}P(\frac{1}{2})$
Half-integer	Odd	Even	$^{13}_{6}C(\frac{1}{2})$, $^{17}_{8}O(\frac{1}{2})$, $^{29}_{14}Si(\frac{1}{2})$
Integer	Even	Odd	$^{2}_{1}H(1)$, $^{14}_{7}N(1)$, $^{10}_{5}B(3)$
Zero	Even	Even	$^{12}_{6}C(0)$, $^{16}_{8}O(0)$, $^{34}_{16}S(0)$

1.2 Spinning Nuclei in a Magnetic Field

A spinning nucleus (I = 1/2) in a uniform magnetic field (Bo):

Precessional motions along side (α, +1/2) and the opposite side (β, –1/2) to the applied magnetic field. Precessional angle → 54.5°.

Precessional frequency (ω): Larmor frequency,

$\omega = (1/2\pi)\cdot\gamma\cdot B_0 = \{\mu / (I\cdot h)\}\cdot B_0$ $\because \gamma = \mu / p = \mu / (I\cdot\hbar) = 2\pi\mu / (I\cdot h)$

Zeeman Level (ΔE) = $2\mu\cdot B_0$

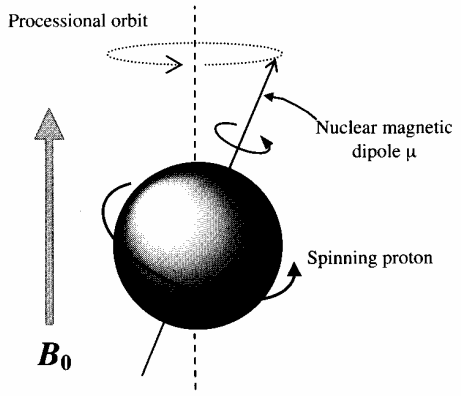


FIGURE 3.3 Classical representation of a proton precessing in a magnetic field of magnitude B_0 in analogy with a precessing spinning top.

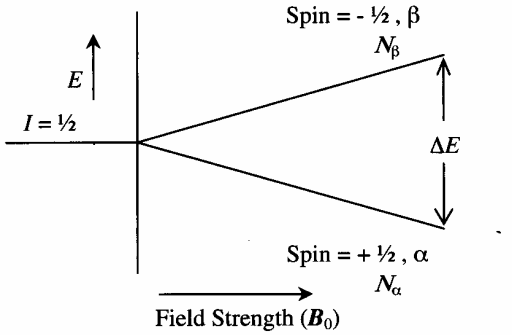


FIGURE 3.2 Two proton energy levels in a magnetic field of magnitude B_0. N is population of spins in the upper (N_β) and lower (N_α) energy states. The direction of the magnetic field (B_0) is up, parallel to the ordinate, and field strength (B_0) increases to the right. Larger (B_0) fields increase ΔE.

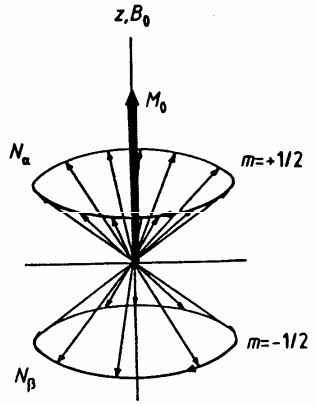
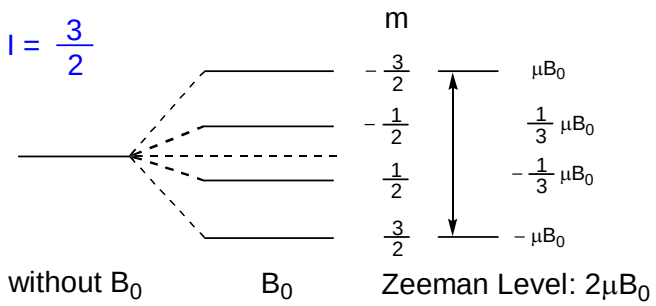


Figure 1-5.
Distribution of the precessing nuclear dipoles (total number N ($= N_\alpha + N_\beta$) around the double cone. As $N_\alpha > N_\beta$ there is a resultant macroscopic magnetization M_0.

In general, nuclear spin I can have 2I + 1 energy levels (I, I-1, I-2, ----, -I), and each level is separated by $(\mu/I)\cdot B_0$.



$$\frac{N_\beta}{N_\alpha} = e^{-\Delta E/k_B T} \approx 1 - \frac{\Delta E}{k_B T} = 1 - \frac{\gamma\hbar B_0}{k_B T} \quad \text{(1-10)}$$

where k_B is the Boltzmann constant ($= 1.3805 \times 10^{-23}$ J K^{-1}) and T is the absolute temperature in K.

Example)

B_0 = 1.41 T (60 MHz) at 300 K (27 ℃),

$\Delta E \approx 2.4 \times 10^{-2}$ J/mole

$N_\beta \approx 0.9999904 N_\alpha$

For 300 MHz,

$N_\beta \approx 0.99995 N_\alpha$

1.3 NMR Experiment

Alternating magnetic field B_1, which is perpendicular to B_0 is applied to the sample to induce the transition between the Zeeman levels.

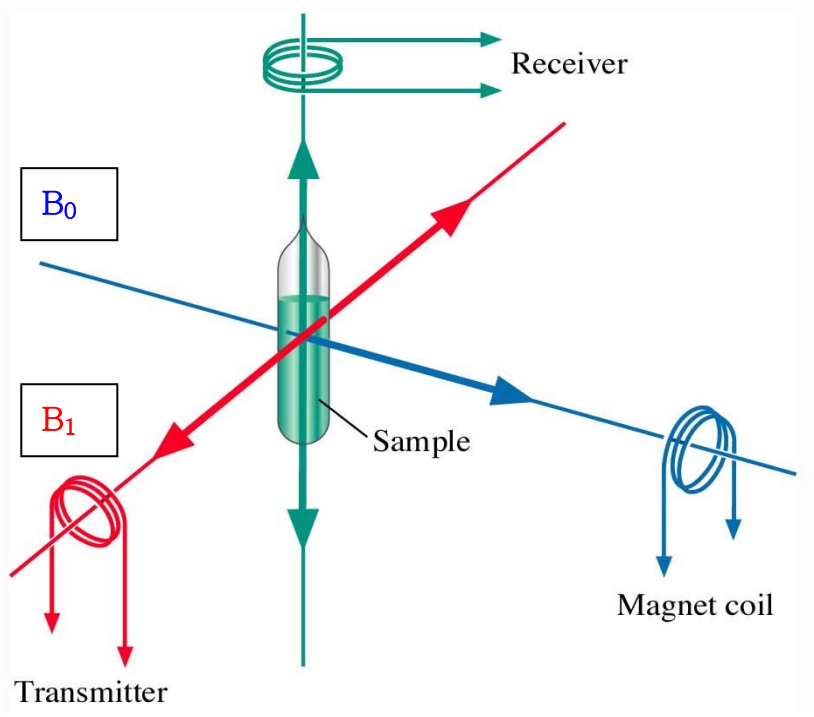
$\Delta E = h\nu = (\mu/I)\cdot B_0$, allowed transition: $\Delta m = \pm 1$.

ν of B_1:

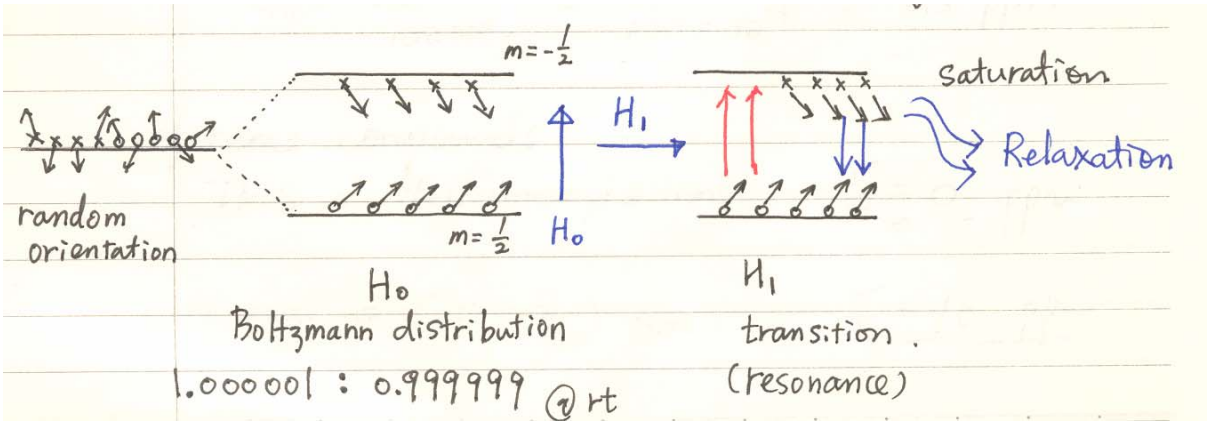
B_0 = 9,395 gauss
then, ν of B_1 = 40 MHz

B_0 = 14,095 gauss
then, ν of B_1 = 60 MHz

B_0 = 23,490 gauss
then, ν of B_1 = 100 MHz



Relaxation:



Spin-lattice relaxation:

Photon without radiation, giving energy to the vibrational system.

Photon with radiation (minor effect)

Relaxation time: T_1

Spin-Spin relaxation time:

Spin exchange

Relaxation time: T_2

$B_{effective} = B_0 - \alpha \cdot B_0 = B_0 \cdot (1 - \alpha)$

α: diamagnetic shielding constant – reflects chemical and magnetic environments of the nuclei.

α: 10^{-5} (proton) ~ 10^{-2}, if B_0 = 15 Kgauss (~ 60 MHz), then $B_0 \cdot \alpha$ = 0.15 gauss = ~ 600 Hz.

2. Chemical Shift δ (ppm): Dimensionless parameter, independent of B_0

Chemical shifts have their origin in **diamagnetic and paramagnetic shielding effects** produced by circulation of both bonding and non-bonding electrons in the neighborhood of the nuclei.

$\delta_{AB} = (\nu_A - \nu_B)/B_0$

Example)

B_0: 300 MHz, $\nu_A - \nu_B$ = 150 Hz

δ_{AB} = 150 Hz / 300 MHz = 150 Hz / 300 x 10^6 Hz = 0.5 ppm

B_0: 600 MHz, $\nu_A - \nu_B$ = 300 Hz

δ_{AB} = 300 Hz / 600 MHz = 300 Hz / 600 x 10^6 Hz = 0.5 ppm

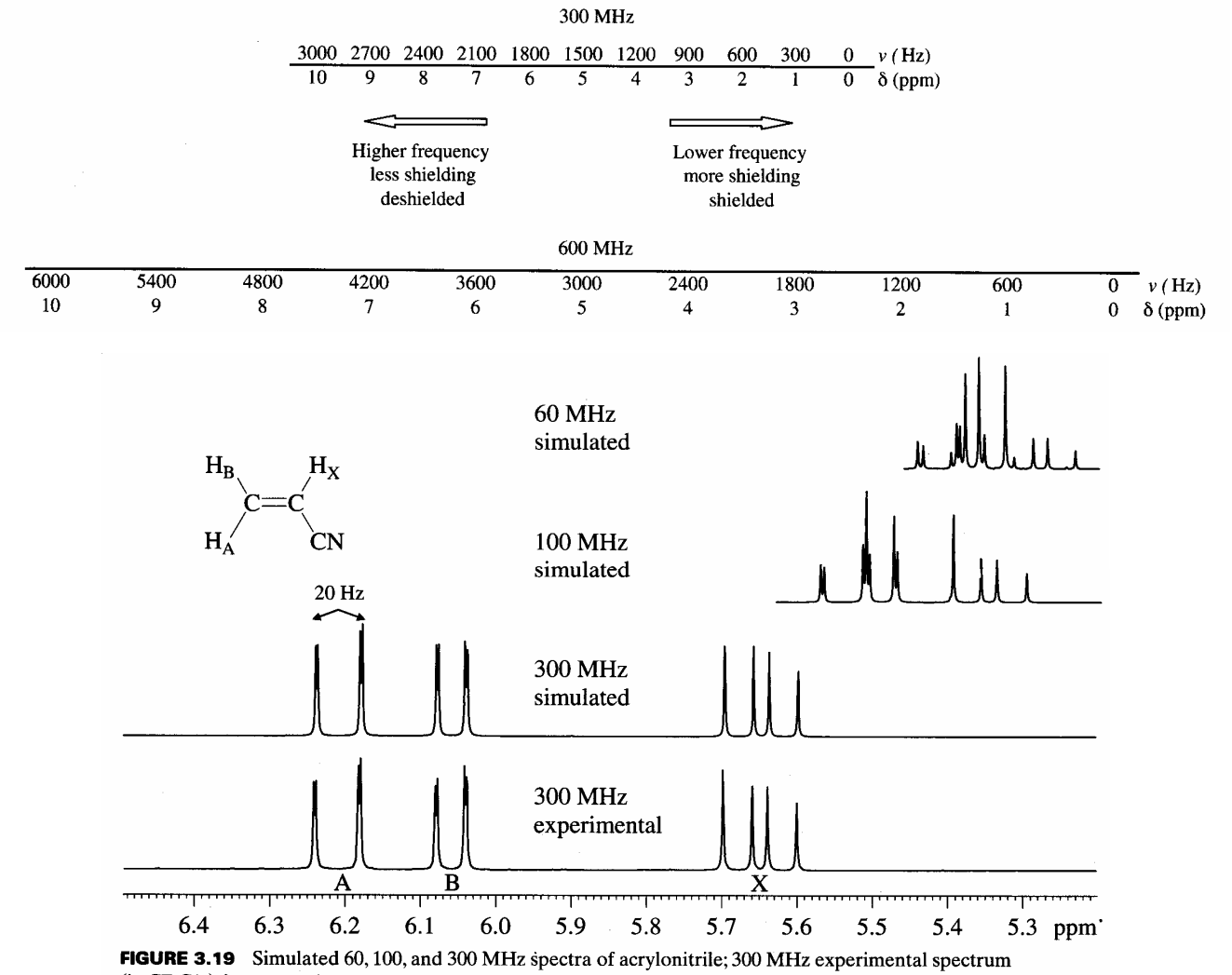
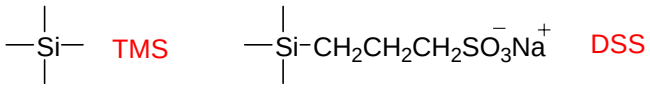


FIGURE 3.19 Simulated 60, 100, and 300 MHz spectra of acrylonitrile; 300 MHz experimental spectrum (in $CDCl_3$) for comparison.

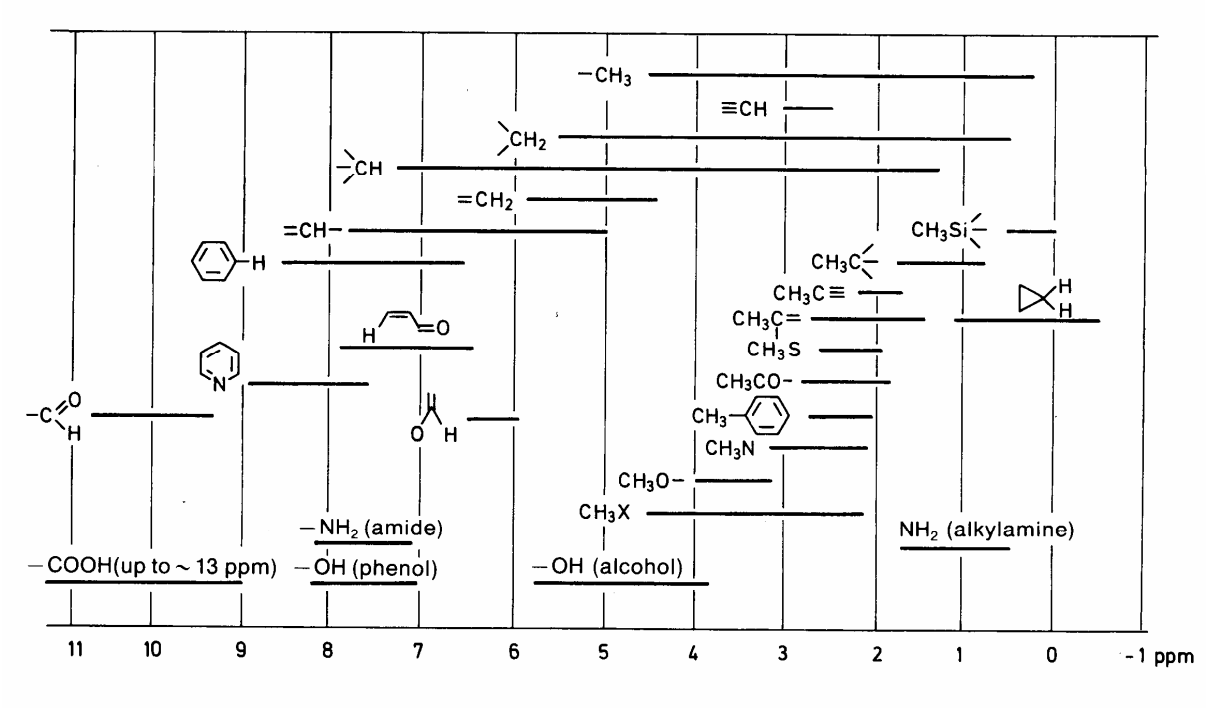
Reference compound δ = 0 ppm.

(1) TMS (tetramethylsilane)

(2) DSS (sodium 2,2-dimethyl-2-silapentane-5-sulfonate)



Chemical shifts referred to DSS or TMS agree within ~0.02 ppm. The sharp singlet is not influenced by pH changes. The multiplet of CH_2 in DSS are not significant at concentrations < 1%.



► Empirical Additive Rules

(1) Dailey, Shoolery's Rule

(*J. Am. Chem. Soc.* **1955**, *77*, 3977)

X–CH_2–Y

$\tau = 9.77 - \sum S(\delta)$ **$\delta = 10 - \tau$**

$\delta = 0.23 + \sum S(\delta)$

(2) Electronegativity of X

CH_3–CH_2–X

E.N. (X) = $0.684 \cdot (\delta_{CH2} - \delta_{CH3}) + 1.78$

Table 4.3 Substituent constants, *S*(δ), for proton resonances in substituted methanes

Substituent	*S*(δ) (ppm)
Cl	2.53
Br	2.33
I	1.82
NRR′	1.57
OR	2.36
SR	1.64
CR−O	1.70
CR=CR′R′	1.32
C≡CH	1.44
C≡N	1.70
CH_3	0.47
Phenyl	1.85
OH	2.56
OCOR	3.13
COOR	1.55
CF_3	1.14

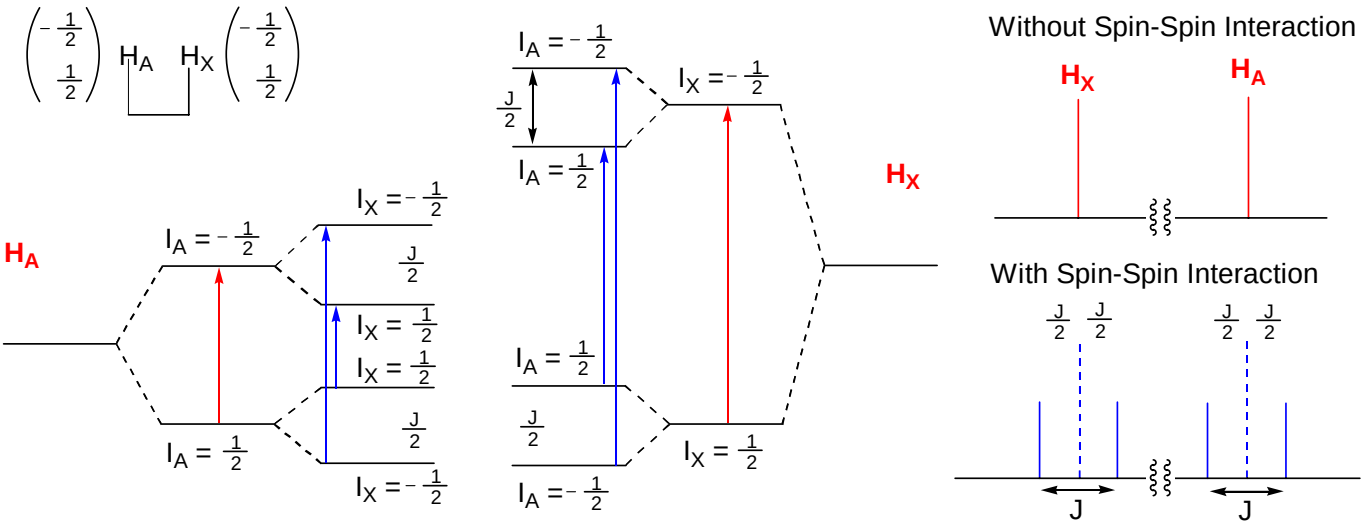
3. Spin-Spin Coupling Constants (J)

Nuclei changes the local magnetic field (effective magnetic filed) of each nucleus by **attractive or repulsive interaction of each magnetic quantum number**. Since nuclear magnetic moments are **independent of the applied field B_0**, so is the coupling constant J.

AX system: $\delta_{AB} \cdot B_0 / J \geq 10$

Since $\delta_{AX} = (\nu_A - \nu_B) / B_0$, then $(\nu_A - \nu_B) / J \geq 10$

AX System



H_A–C–CH_2 and **H_A–C–CH_3**

CH_2 group	m_T	CH_3 group	m_T
$\alpha\alpha$	+1	$\alpha\alpha\alpha$	$+\frac{3}{2}$
$\alpha\beta$ $\beta\alpha$	0	$\alpha\alpha\beta$ $\alpha\beta\alpha$ $\beta\alpha\alpha$	$+\frac{1}{2}$
$\beta\beta$	−1	$\alpha\beta\beta$ $\beta\alpha\beta$ $\beta\beta\alpha$	$-\frac{1}{2}$
		$\beta\beta\beta$	$-\frac{3}{2}$

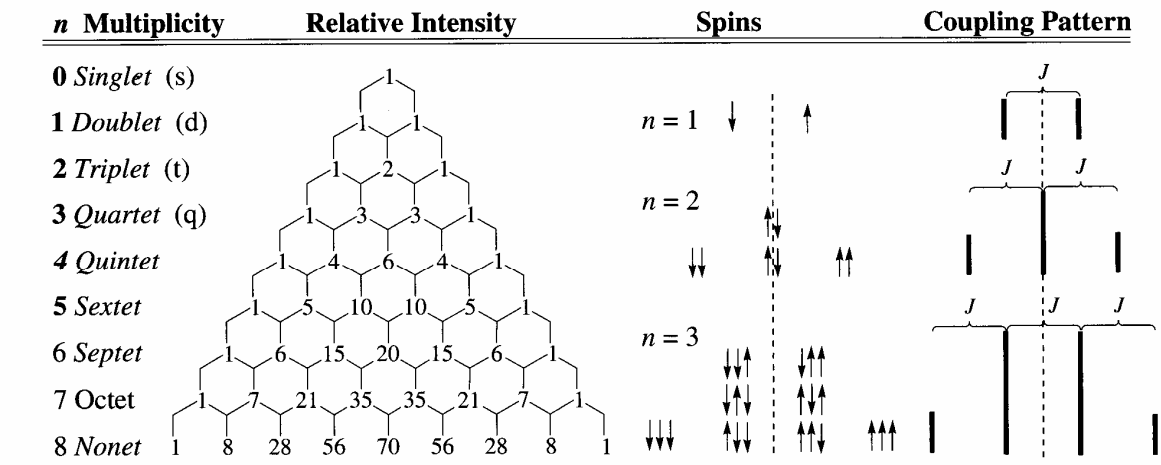
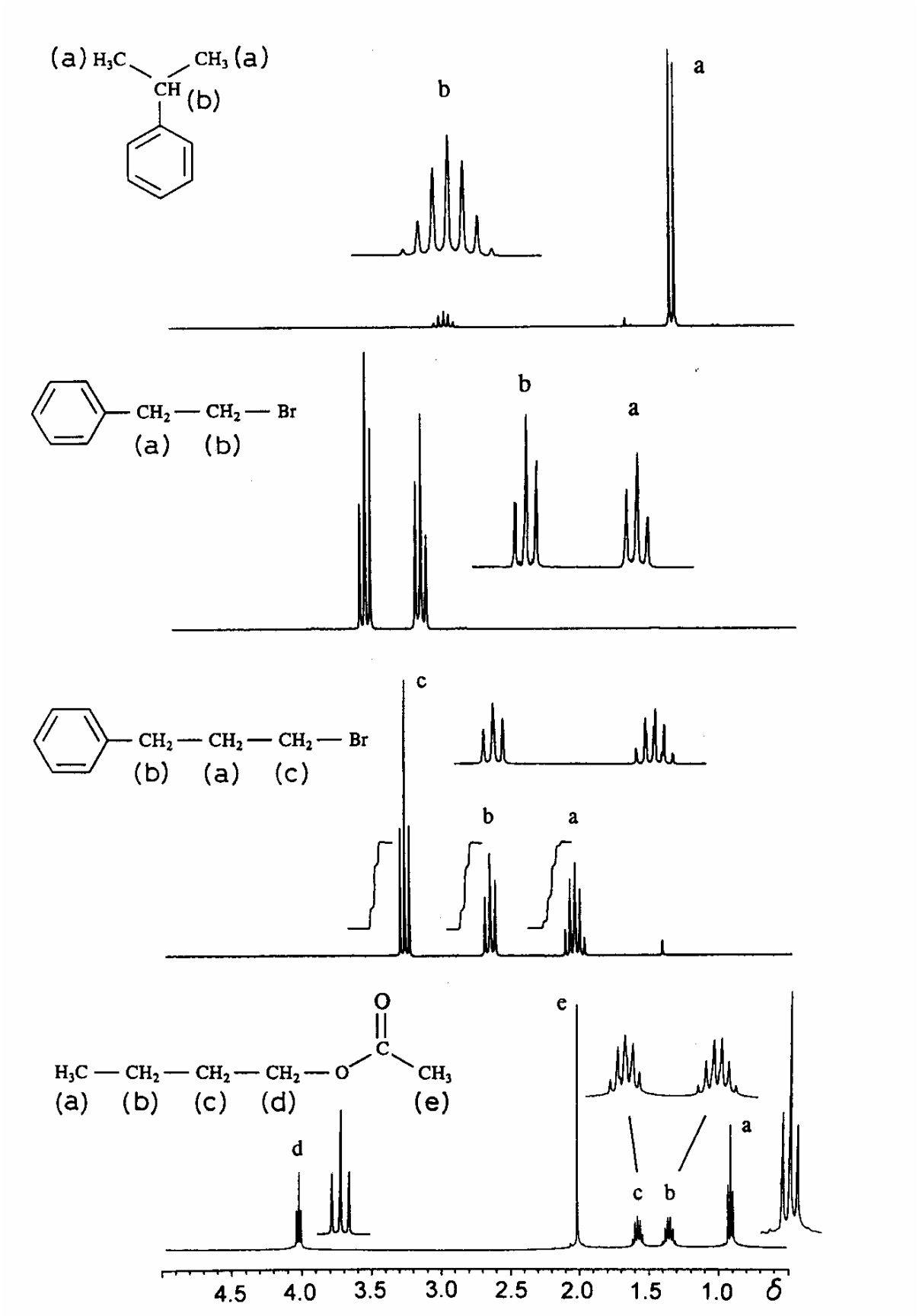


FIGURE 3.32 Pascal's triangle. Relative intensities of first-order multiplets; n = number of equivalent coupling nuclei of spin 1/2 (e.g., protons).

Characteristic splitting patterns in the ^{1}H NMR spectra of some alkyl groups.



3-1. Vicinal H-H Couplings ($^3J_{HH}$)

(1) The couplings in both saturated and unsaturated systems are largely transmitted via the σ-electrons, and these are always positive.

In general, $^3J(sp^2\text{-}sp^2) > {}^3J(sp\text{-}sp) > {}^3J(sp^3\text{-}sp^3)$

25 ~ 7 Hz 9.1 Hz 12 ~ 2 Hz

(2) Dihedral angle dependency

Karplus (1963): $\mathbf{J = 4.22 - 0.5 \cdot \cos\phi + 4.5 \cdot \cos^2\phi}$

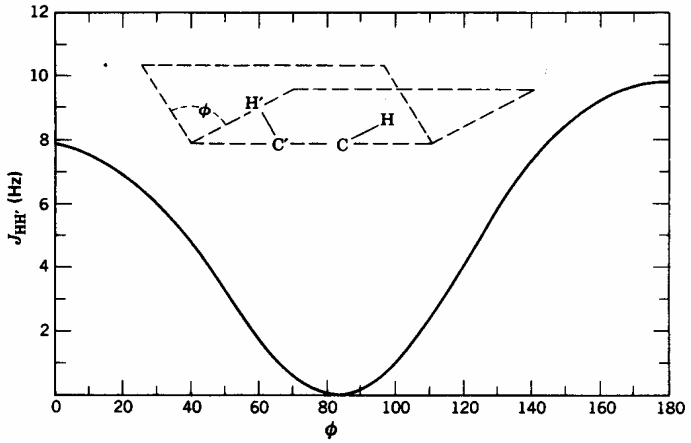


FIGURE 3.57 The vicinal Karplus correlation. Relationship between dihedral angle (ϕ) and coupling constant for vicinal protons.

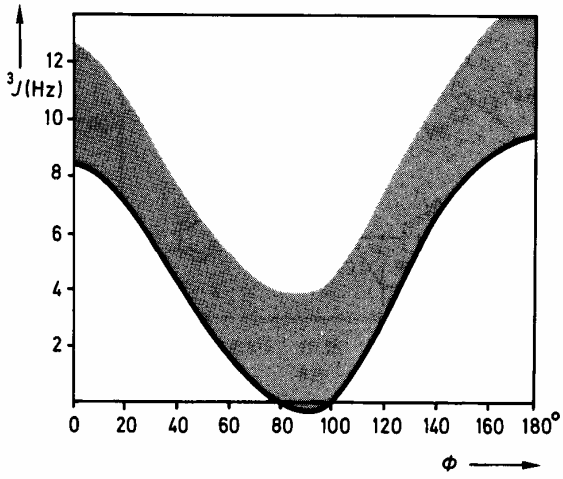


Figure 4.22 The Karplus curve for the dependence of vicinal H – H coupling on the dihedral angle ϕ: line, theoretical curve; shaded area, range of empirical results

A. Six-membered Ring Systems (all sp^3 carbons)

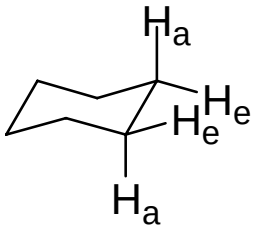
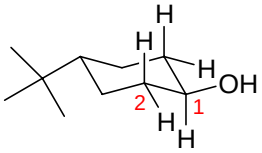


TABLE 3.6. Calculated and observed coupling constants, J, in cyclohexanes based on bond angle.

	Dihedral Angle	Calculated J(Hz)	Observed J(Hz)
Axial-axial	180°	9	8–14 (usually 8–10)
Axial-equatorial	60°	1.8	1–7 (usually 2–3)
Equatorial-equatorial	60°	1.8	1–7 (usually 2–3)

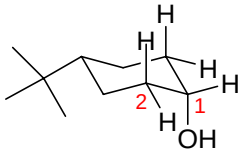
Examples

①



$J_{H1,H2eq}$ = + 4.31

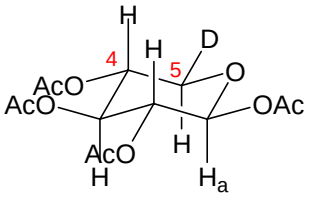
$J_{H1,H2ax}$ = + 11.07



$J_{H1,H2eq}$ = + 2.72

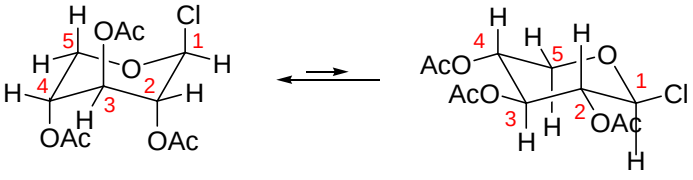
$J_{H1,H2ax}$ = + 3.00

② The value of J is reduced by an electron withdrawing group



$J_{4,5}$ = +8.1 Hz

③ Anomeric effect

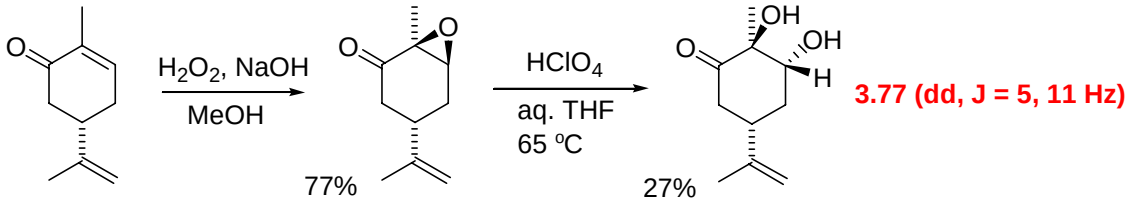


$J_{1,2}$ = 2.0 Hz , $J_{1,3}$ = 1.5 Hz

$J_{3,5e}$ = 0.6 Hz , $J_{4,5a}$ = 3.0 Hz

$J_{4,5e}$ = 3.7 Hz, $J_{5a,5e}$ = 12.9 Hz

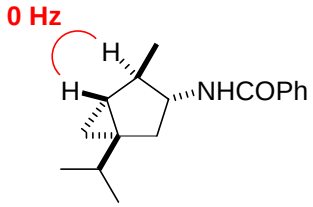
④

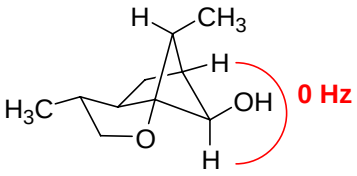


3.77 (dd, J = 5, 11 Hz)

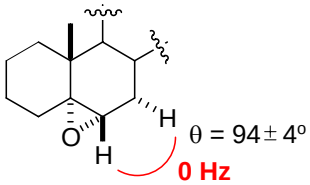
⑤ Small ^3J

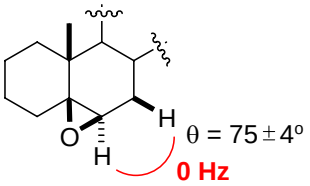
a. dihedral angle ~90°

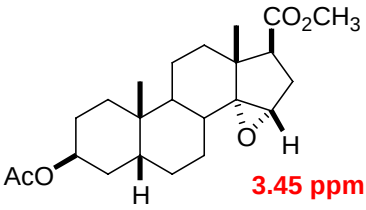




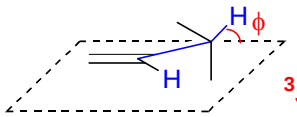
b. epoxide H's

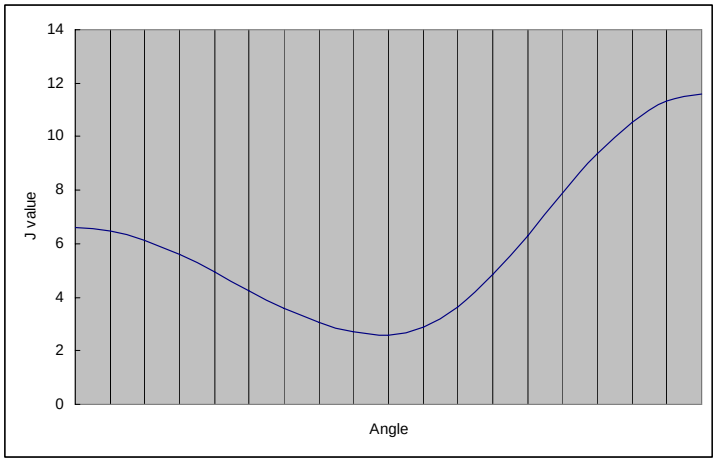






B. ^3J (sp^2-sp^3)





$0^o \leq \theta \leq 90^o$

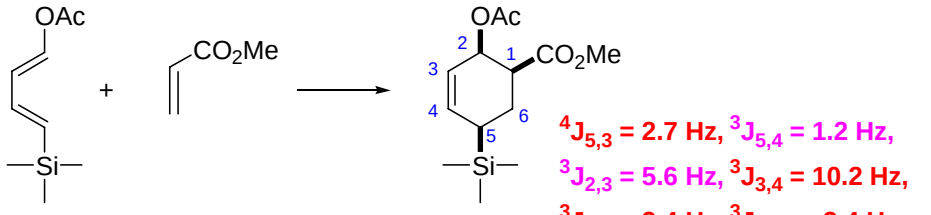
$J = 6.6 \cdot \cos^2\theta + 2.6 \cdot \sin^2\theta$

$90^o \leq \theta \leq 180^o$

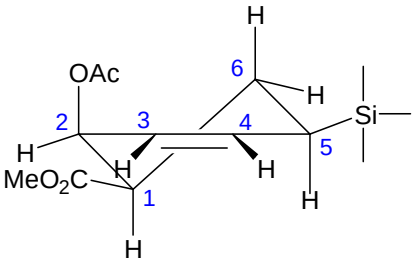
$J = 11.6 \cdot \cos^2\theta + 2.6 \cdot \sin^2\theta$

6.6 (0°), 2.7 (90°), 11.7 (180°)

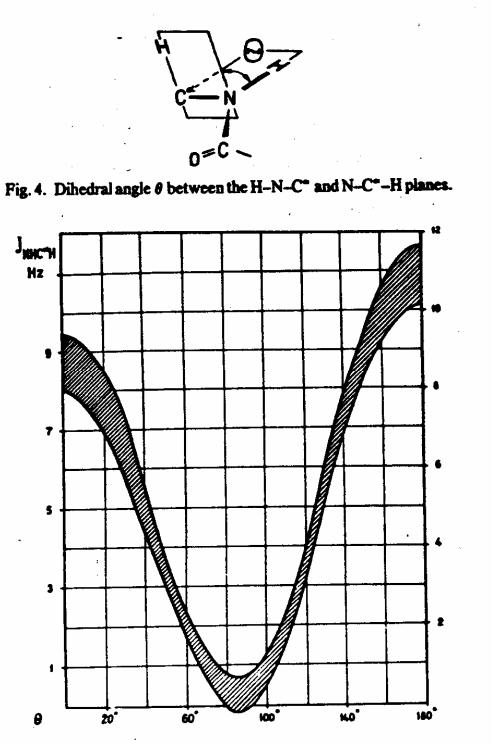
Examples

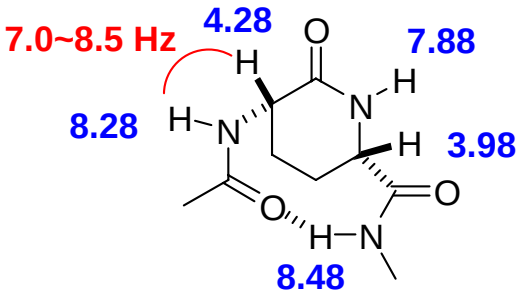


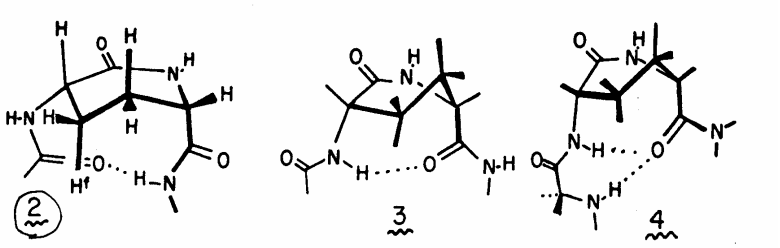
$^4J_{5,3}$ = 2.7 Hz, $^3J_{5,4}$ = 1.2 Hz,
$^3J_{2,3}$ = 5.6 Hz, $^3J_{3,4}$ = 10.2 Hz,
$^3J_{1,2}$ = 3.4 Hz, $^3J_{1,6e}$ = 3.4 Hz,
$^3J_{1,6a}$ = 13.1 Hz



C. Amino Acid Derivatives

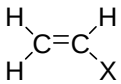
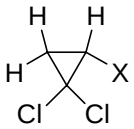
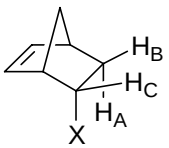






(3) CH–CH–X: Increasing electro-negativity of X gives smaller ^3J

$^3J = J_0 - \alpha \cdot Ex$ Ex: electronegativity of X; J_0, α: constants

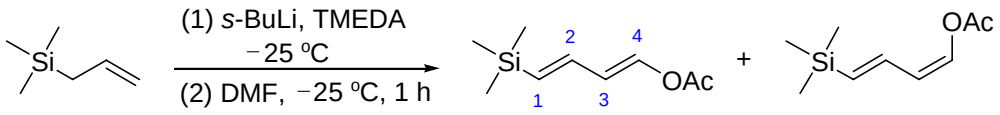
	J	J_0 (Hz)	α (Hz)
$CH_3–CH_2X$	^3J	9.4	0.7
	$^3J_{cis}$	24.5	4.2
	$^3J_{trans}$	27.3	3.5
	$^3J_{cis}$	17.7	2.4
	$^3J_{trans}$	13.6	2.8
	$^3J_{cis}$ or J_{BC}	12.6	1.4
	$^3J_{trans}$ or J_{AC}	8.8	1.7

(4) ^3J (sp^2-sp^2)

12~18 Hz $^3J_{trans} > {}^3J_{cis}$ **6~12 Hz**

Examples

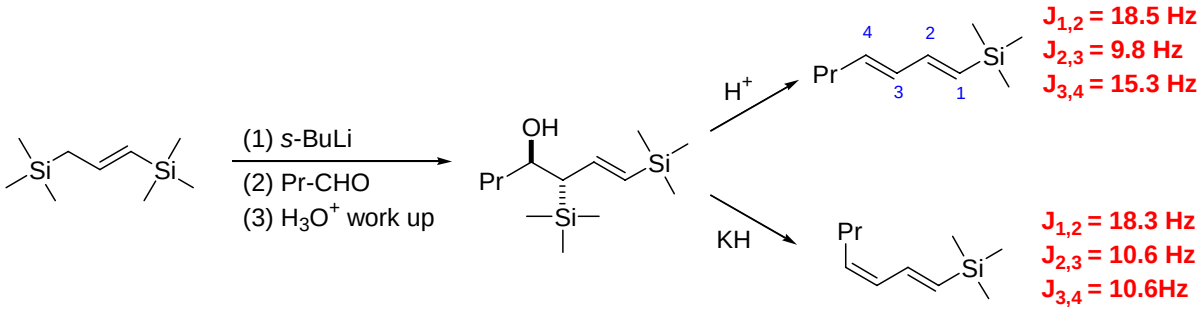
①



$J_{1,2}$ = 18.3 Hz
$J_{2,3}$ = 10.5 Hz
$J_{3,4}$ = 12.5 Hz

$J_{1,2}$ = 18.0 Hz
$J_{2,3}$ = 10.5 Hz
$J_{3,4}$ = 6.4 Hz

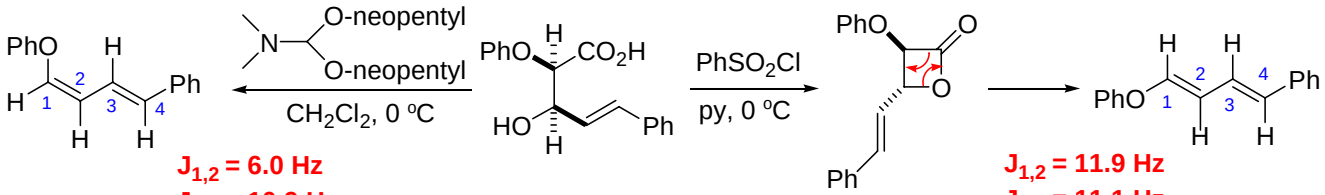
②



$J_{1,2}$ = 18.5 Hz
$J_{2,3}$ = 9.8 Hz
$J_{3,4}$ = 15.3 Hz

$J_{1,2}$ = 18.3 Hz
$J_{2,3}$ = 10.6 Hz
$J_{3,4}$ = 10.6Hz

③

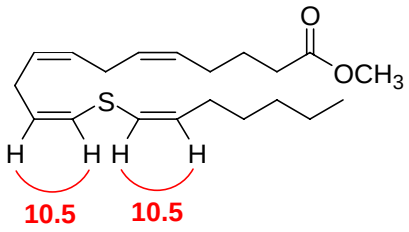


$J_{1,2}$ = 6.0 Hz
$J_{2,3}$ = 10.9 Hz
$J_{3,4}$ = 15.9Hz

Tetrahedron Lett. **1984**, *25*, 4881

$J_{1,2}$ = 11.9 Hz
$J_{2,3}$ = 11.1 Hz
$J_{3,4}$ = 15.6 Hz

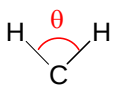
④



3-2. Geminal H-H Couplings ($^2J_{HH}$): –20 ~ +40 Hz

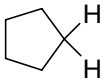
(1) Factors that influence the value of ^2J

a. S-P Hybridization



As θ increases, more s-character in C–H that gives higher value of ^2J

Methane (CH_4) sp^3 **^2J = –12.4 Hz** Ethylene (CH_2=CH_2) sp^2 **^2J = +2.5 Hz**



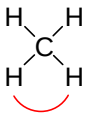
^2J = –13.0

^2J = –4.0

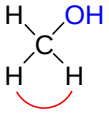
b. Electronegative atom in α-position leads to a positive shift in $^2J_{HH}$ (Inductive effect)

Examples

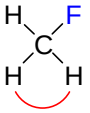
①



– 12.4



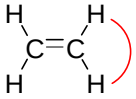
– 10.8



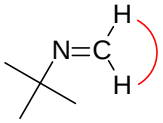
– 9.6

Electronegative atoms withdraw electrons of p-character leaving more s-character in C–H bond.

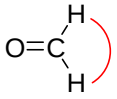
②



+ 2.5



+ 16.5

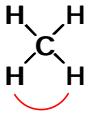


+ 41

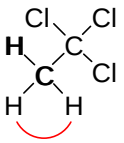
c. Eletronegative atom in β-position leads to a negative shift in $^2J_{HH}$

Example

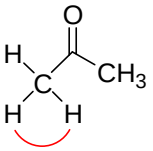
①



– 12.4

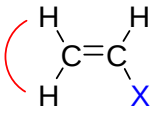


– 13.0



– 14.9

② sp^2 H's

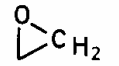
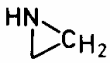
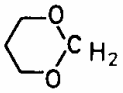
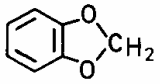
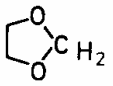


$^2J = 8.5 - 3E_x$ E_X: Electronegativity

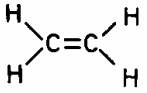
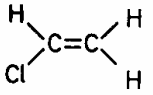
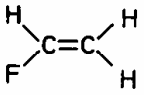
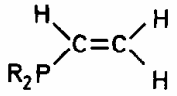
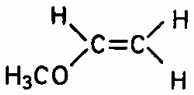
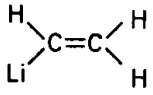
X = $)_4$Sn	**+ 2.8 Hz**	X = Cl	**- 1.4 Hz**
X = H	**+ 2.5 Hz**	X = OCH_3	**- 2.0 Hz**
X = $)_3$P	**+ 2.02Hz**	X = F	**- 3.2 Hz**
X = CH_3	**+ 2.08Hz**	X = MgBr	**+ 7.4 Hz**
X = SCH_3	**- 0.3 Hz**	X = Li	**+ 7.1 Hz**

Table 4.10 The influence of substituents on geminal-coupling constants

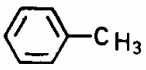
1. α-Substitution

CH_4	-12.4		+ 5.5
CH_3Cl	-10.8	$RN{=}CH_2$	+16.5
CH_3Cl_2	- 7.5	$O{=}CH_2$	+42.2
	+2.0		- 6
	± 1.5		0

2. β-Substitution

	+ 2.5		- 1.4
	- 3.2		+ 2.0
	- 2.0		+ 7.1

3. Adjacent π bonds

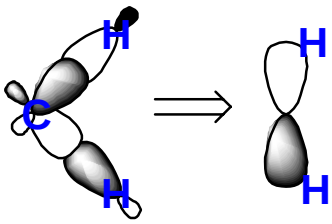
CH_3CN	- 16.9		- 14.5
$CN{-}CH_2{-}CN$	- 20.4		

d. Hyper-conjugation effects

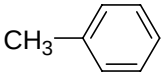
Electron withdrawing substituents which take electrons from antisymmetric orbitals of CH_2 give **negative contribution**.

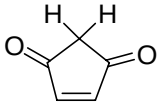
Examples

①

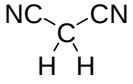


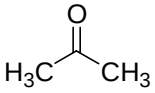
CH_4 $^2J = -12.4$ Hz

 – 14.5 Hz

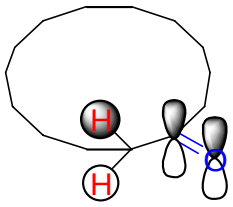
 – 21.5 Hz

$CH_3{-}CN$ – 19.2 Hz

 – 20.3 Hz

 – 14.9 Hz

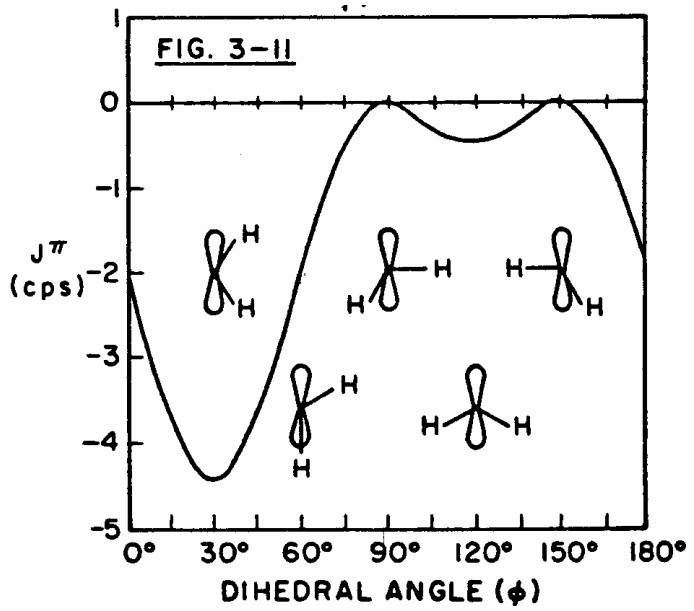
②

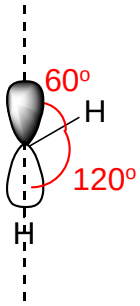


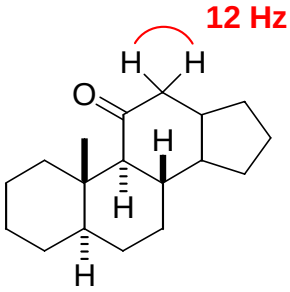
$^2J_{HH} = {}^2J_{HH}(\sigma) + {}^2J_{HH}(\pi)$

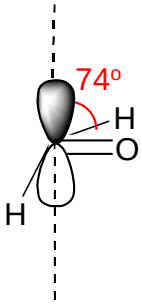
–12.4 Hz **Hyperconjugation**

Barfield, M. *J. Am. Chem. Soc.* **1963**, *85*, 1899.

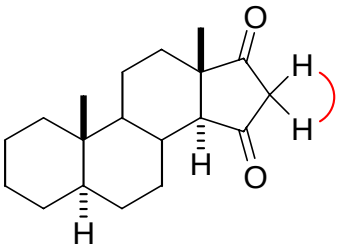


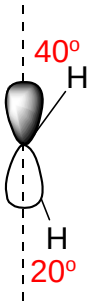






$^2J(\pi)$ = ~ 0-1 Hz





$^2J(\pi)$ = 4 Hz

total $^2J(\pi)$ = 2 x 4 Hz = 8 Hz

two carbonyl groups

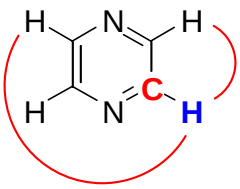
◈ **Determination of J_{HH}** when two protons are **chemically equivalent**

① Use JHD

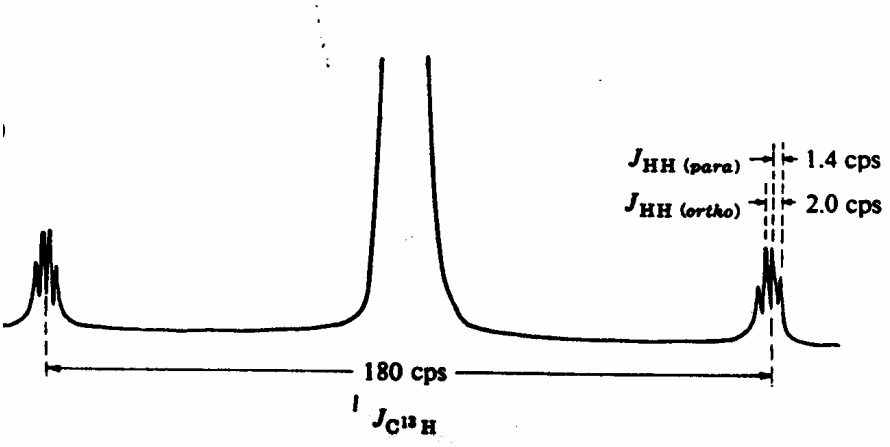
$J_{HH} = 6.514 \times J_{HD}$

$CHDCl_2$ $J_{HD} = -1.15$ Hz ∴ $J_{HH} = (-1.15) \times 6.514 = -7.5$ Hz

② Use ^{13}C-satellites



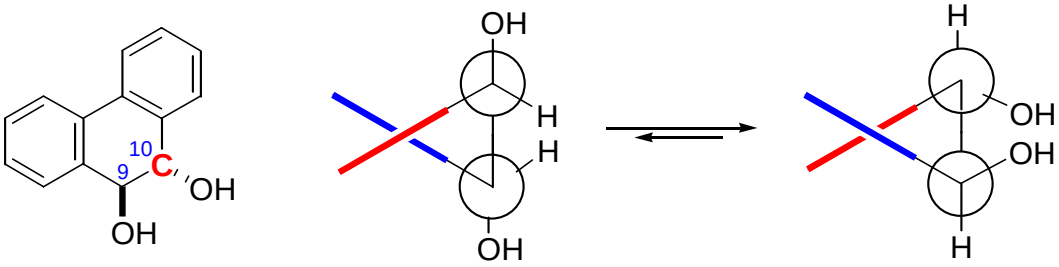
Pyrazine



Carbon 13 satellite spectrum of pyrazine.

^{3}J from ^{13}C-satellite proton resonance

J. Org. Chem. **1983**, *48*, 4139



	H_9,H_{10} δ (ppm)	$^3J_{9,10}$ (Hz)	$^1J_{H\text{-}C}$ (Hz)
Diol	4.61	10.4	142.2
Diacetate	6.07	5.6	152.5

3-3 Long-range couplings

Review:

Chem. Rev. **1969**, *69*, 757.

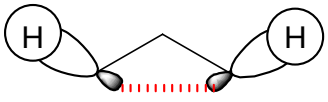
Pure & Appl. Chem. **1964**, *14*, 15.

(1) Sigma (σ) – bond couplings

$^2J \geq {}^3J \gg {}^4J$

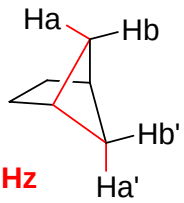
4~12 Hz usually 0 Hz

a. W-letter Rule or **W-coupling** (or M-coupling)



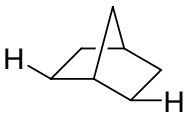
J. Am. Chem. Soc. **1961**, *83*, 2769.

Examples

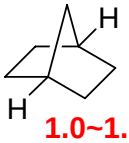


$J_{aa'}$ = 7~8 Hz

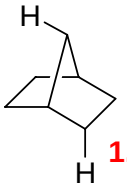
$J_{ab'}$ and $J_{ba'}$ = 0 Hz



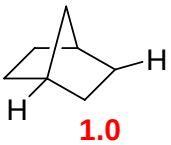
1.0~1.8



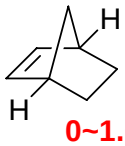
1.0~1.6



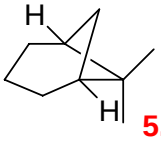
1.7~2.6



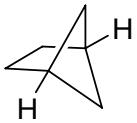
1.0



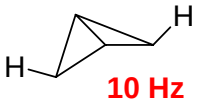
0~1.0



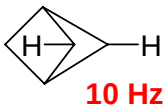
5.8~6.4



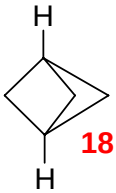
8 Hz



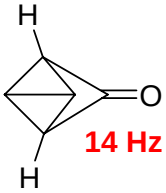
10 Hz



10 Hz



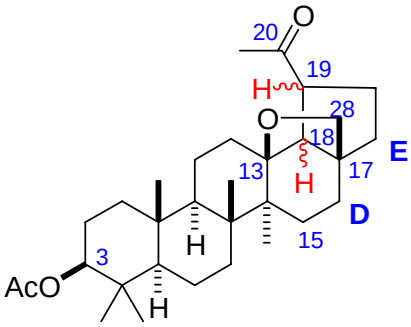
18 Hz



14 Hz

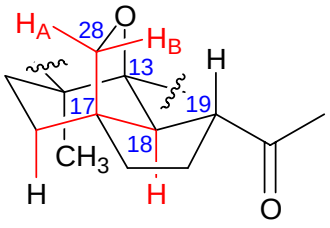
Stereochemical applications

① 3β-acetoxy-20-oxo-13β,28-epoxy-30-lupane (Ring D/E junction: cis or trans?)

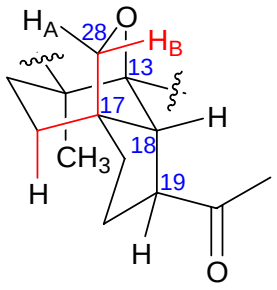


4.02 (dd, J = 7.3, 2.0 Hz, 1H)

3.09 (d, J = 7.3 Hz, 1H)



H_A and H_B should have ^4J coupling in this structure



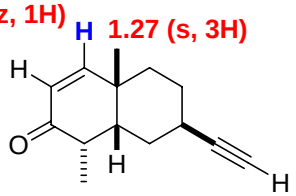
18β-H, 19α-H

This is the righ structure

② Structure of chamaecynone (*Tetrahedron Lett.* **1966**, 3663)

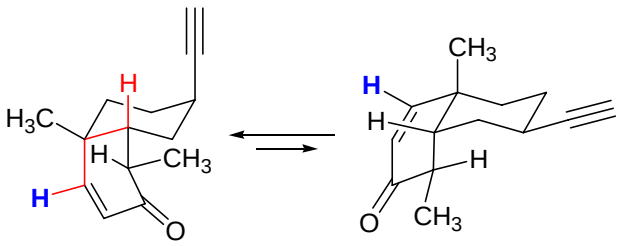
6.32 (dd, J = 9.8, 2.2 Hz, 1H)

5.76 (d, J = 9.8 Hz, 1H)



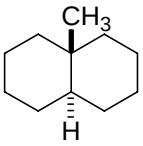
1.01 (d, J = 7.0 Hz, 3H)

1.94 (d, J = 2.3 Hz, 1H)

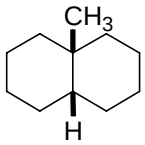


b. $\Delta W_{1/2} = W_{1/2}(Me) - W_{1/2}(TMS)$

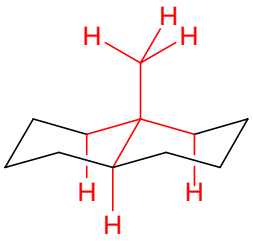
①



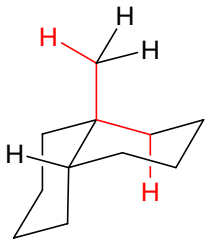
trans - $\Delta W_{1/2}$ = 0.65 Hz



cis - $\Delta W_{1/2}$ = 0.15 ~ 0.30 Hz

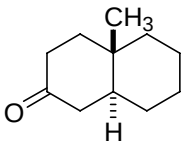


3 x W_{H-H}



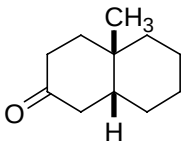
1 x W_{H-H}

②

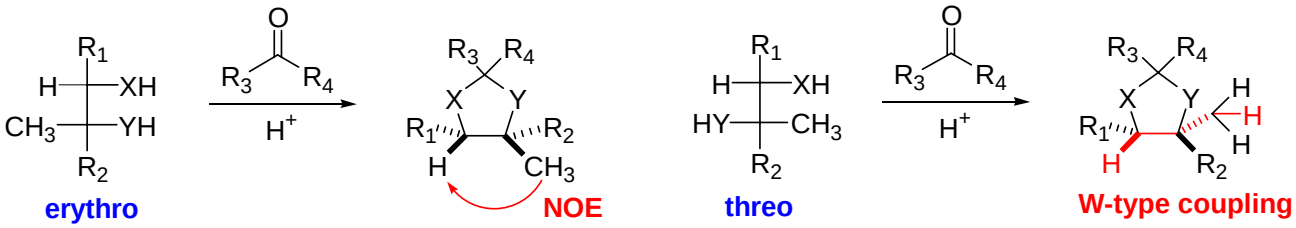


trans - $\Delta W_{1/2}$ = 1.05 Hz

cis - $\Delta W_{1/2}$ = 0.35 Hz

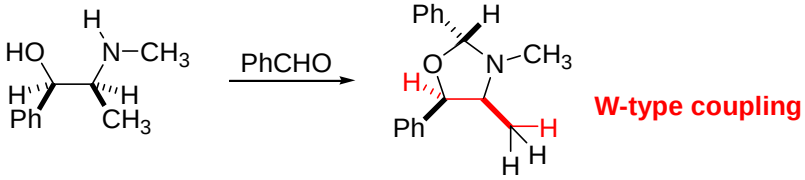


c. To distinguish **threo** and **erythro** isomers of certain α-glycols and related compounds

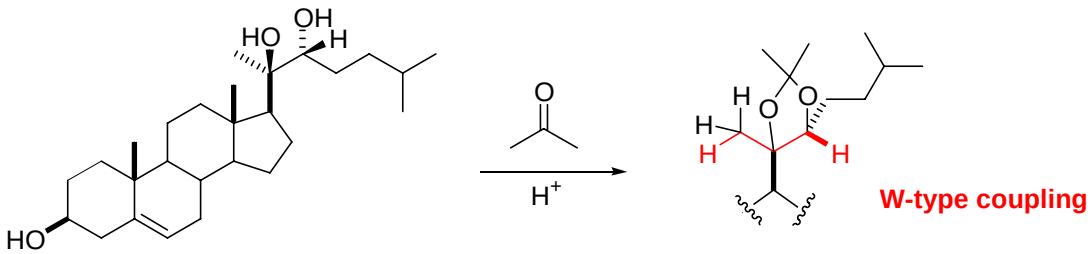


Examples

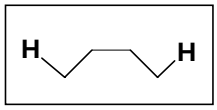
① (–)-ephedrine



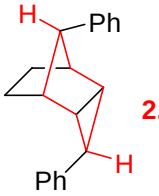
②



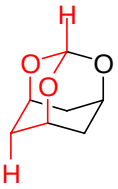
(2) ^5J σ-bond couplings



0.5 ~ 1.0 Hz



2.3 Hz



1.25 Hz

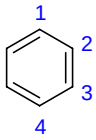
1.7 Hz

(3) Coupling in unsaturated systems

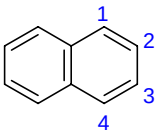
a. Aromatic compounds

$J_{AB} = J_{AB}(\pi) + J_{AB}(\sigma)$

$J_{AB}(\pi)$: generally small (~ 2Hz); not much change in bond order of π orbital (P_{AB}).



$P_{A,B}$		$J_{AB}(\pi)$ calculated	J_{AB} (total) observed
$P_{1,2}$	0.67	0.80	8~9
$P_{1,3}$	0.00	0	2~5
$P_{1,4}$	–0.17	0.05	0.5



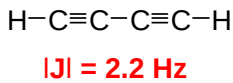
$P_{A,B}$		$J_{AB}(\pi)$ calculated	J_{AB} (total) observed
$P_{1,2}$	0.72	0.95	8.6
$P_{2,3}$	0.60	0.66	6.0
$P_{1,3}$	0.00	0	1.4
$P_{1,4}$	–0.36	0.23	0.6

b. Unsaturated non-aromatic compounds

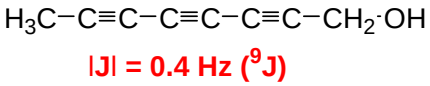
Karplus, M. *J. Am. Chem. Soc.* **1960**, *82*, 4432.

	$J_{AB}(\pi)$	J_{AB} ($J_{AB}^{\pi} + J_{AB}^{\sigma}$)
H−C=C−H	+1.5	+7 ~ +18
H−C≡C−H	+4.6	+9.1
H−C=C−C−H	–1.7	–1.4 ~ –1.8
H−C≡C−C−H	–3.7	–2.3
H−C=C=C−H	–6.7	–7.0 ~ –6.1
H−C−C=C−C−H	+2.0	+2.0
H−C−C≡C−C−H	+2.9	+2.7
H−C=C=C=C−H	+7.8	+8.95

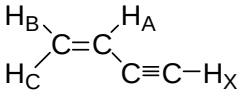
Examples



|J| = 2.2 Hz



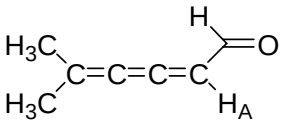
|J| = 0.4 Hz (^{9}J)



$J(H_A,H_X) = -2.1$ Hz

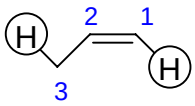
$J(H_B,H_X) = 0.8 \sim 0.9$ Hz

$J(H_C,H_X) = 0.7$ Hz

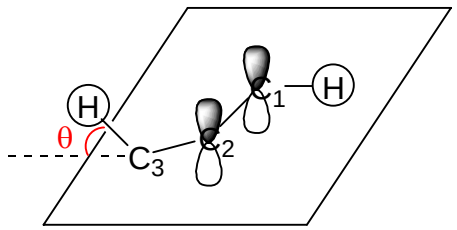


$|J(CH_3, HA)| = 1.2$ Hz

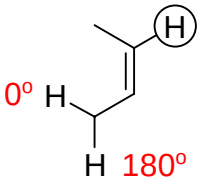
c. Allylic coupling



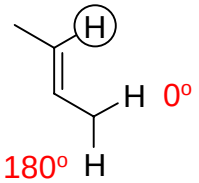
Angle dependency



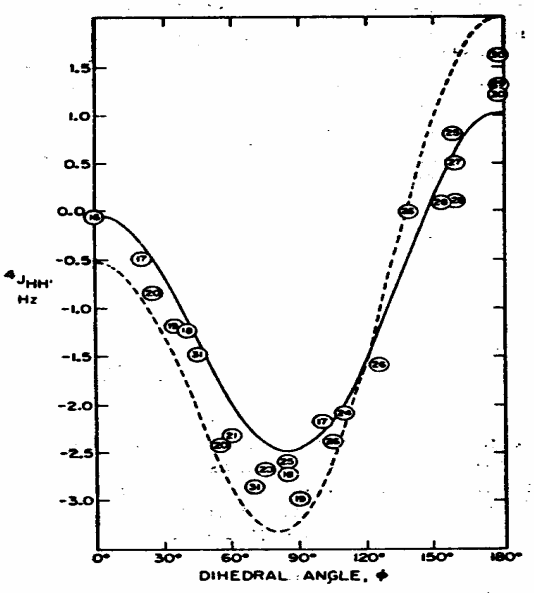
|J|: **maxium when θ = 90°**

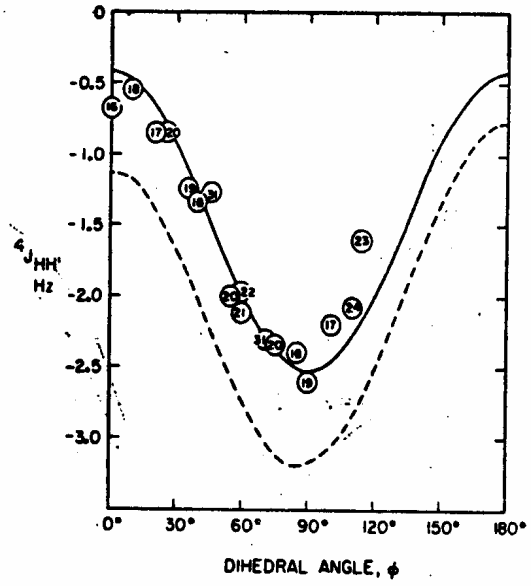


transoid (left)

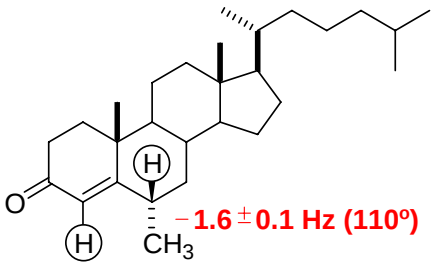


cisoid (right)

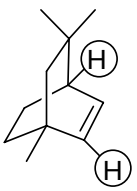




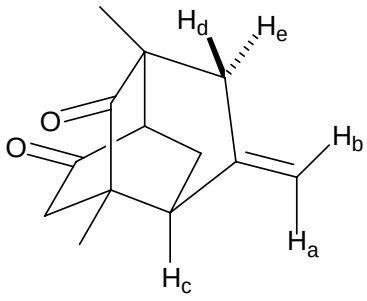
Examples



-1.6 ± 0.1 Hz (110°)



+ 1.30 Hz (180°)



$J_{a,c} = -0.55$ Hz (10°) **c**

$J_{b,c} = -0.2$ Hz (10°) **t**

$J_{a,d} = -1.18$ Hz (35°) **t**

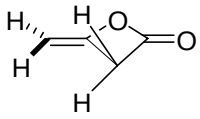
$J_{b,d} = -1.24$ Hz (35°) **c**

$J_{a,e} = -2.97$ Hz (90°) **t**

$J_{b,e} = -2.60$ Hz (90°) **c**

Generally, transoid coupling > cisoid coupling

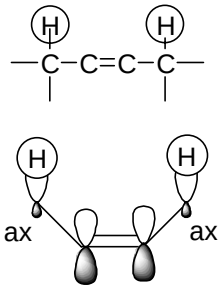
<exceptions>

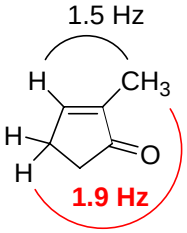


J_{cisoid} = 1.82 Hz

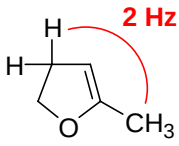
$J_{transoid}$ = 1.34 Hz

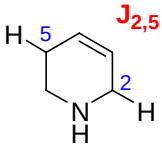
d. Homoallylic coupling: ^5J = 0.6 ~ 3.0 Hz





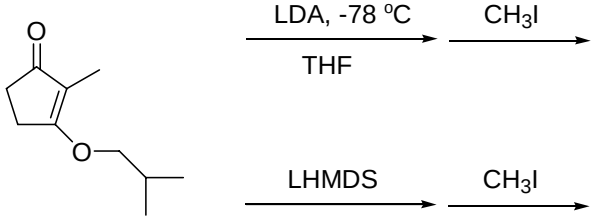
$^5J_{aa} > J_{ae} > J_{ee}$





$J_{2,5}$ = 3 Hz

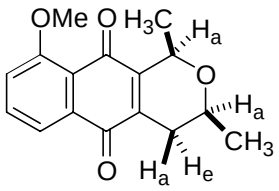
①

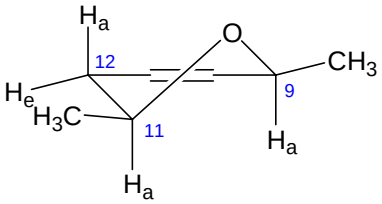


1.63 ppm (t, *J* = 1.4 Hz, 3H)

1.76 ppm (d, *J* = 1.3 Hz, 3H)

②

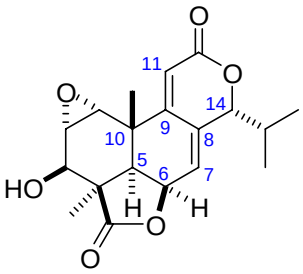


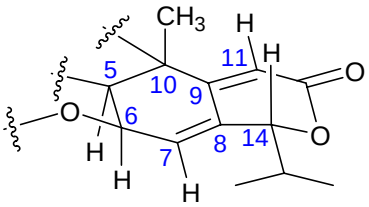


$J_{9a,12a}$ = 3.5 Hz

$J_{9a,12e}$ = 2.9 Hz

③





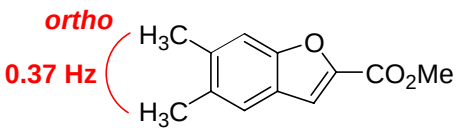
$J_{6,7}$ = 5 Hz

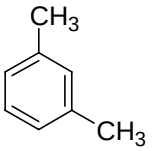
$J_{6,14}$ = 1.7 Hz

$J_{7,11}$ = 2.0 Hz

$J_{7,14}$ = 2.0 Hz

④ Interbenzylic couplings

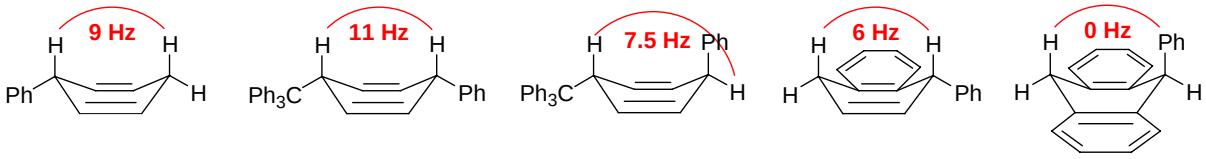


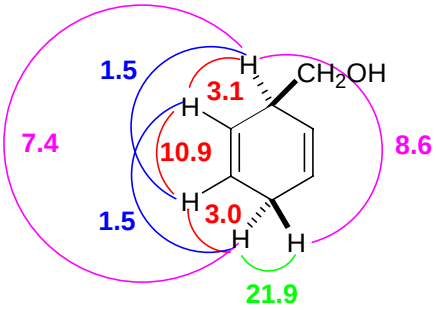


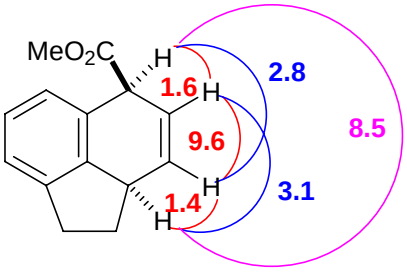
< 0.35 Hz

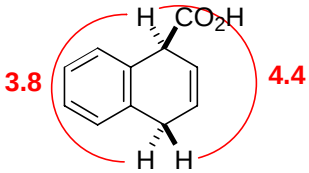
1/3 of typical homoallylic couplings

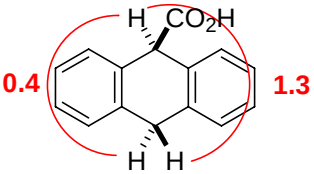
⑤ 1,4-Dihydrobenzene systems – |**J**|: usually large



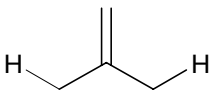


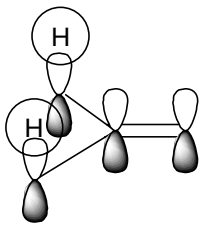




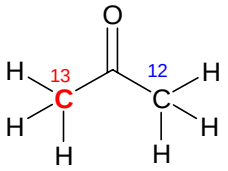


e. "Pseudoallylic" coupling



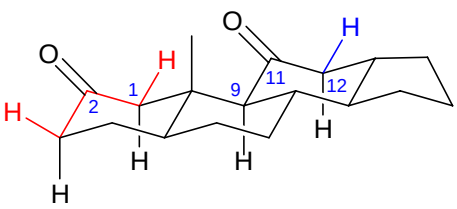


①



$^4J_{HH}$ = 0.54 Hz

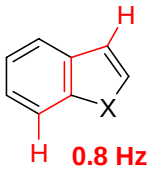
②



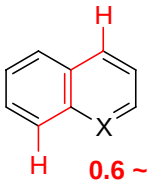
3.52 ppm (dd, *J* = 13.5, 2.0 Hz, 1H)
2.26 ppm (d, *J* = 12 Hz, 1H, 12β-H)
1.90 ppm (d, *J* = 12 Hz, 1H, 12α-H)

f. Long-range couplings in polycyclic aromatic systems

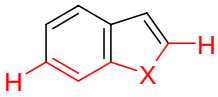
① polynuclear heterocyclic system: **zig-zag path**



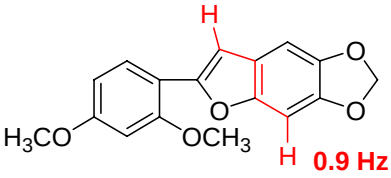
0.8 Hz



0.6 ~ 0.8 Hz

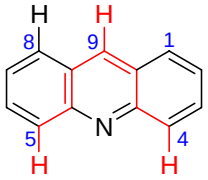


0.4 Hz

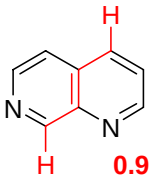


0.9 Hz

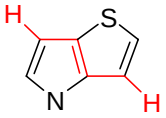
X = O, N, S



$J_{4,9}$ = $J_{5,9}$ = 0.9 Hz
$J_{8,9}$ = 0.4 Hz

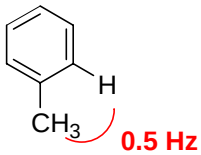


0.9 Hz

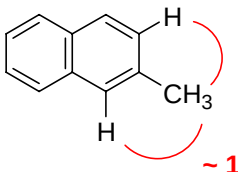


1.3 Hz

② **$J_{Ar\text{-}CH,Ar\text{-}H}$**: Stronger J if coupled via a "**localized**" double bond.

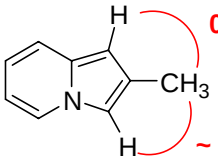


0.5 Hz



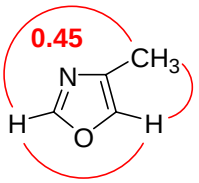
0 Hz

~ 1.0 Hz



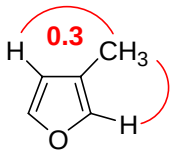
0 Hz

~ 1.0 Hz



1.28

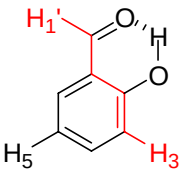
1.01



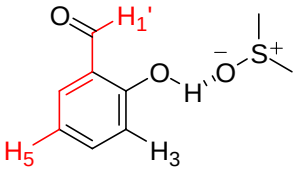
1.8

g. Zigzag couplings in simple aromatic phenols

①

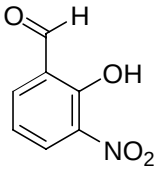


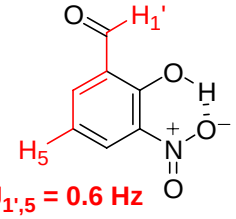
$J_{1',3}$ = 0.6 Hz
in CH_2Cl_2

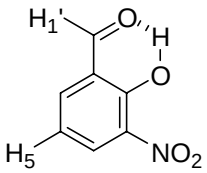


$J_{1',3}$ = 0 Hz
$J_{1',5}$ = 0.7 Hz
in DMSO

②





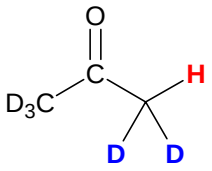


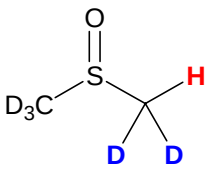
$J_{1',5}$ = 0.6 Hz
in CCl_4, C_6H_6 or acetone

3-4. $^{2}J_{HD}$: small and broad

D: 0.015% Natural abundance; H: 99.985 %

D: I (spin quantum number) = 1, possible spin states = -1, 0, +1 → triplet





$^{2}J_{HD}$ = 2.3 Hz, quintet (5)

$^{2}J_{HD}$ = 1.9 Hz, quintet

Possible spin state = -2, -1, 0, +1, +2

Only $^{2}J_{HD}$ can be detected.

※ Isotope Chemical Shift

① CH_4

CH_3D 0.019±0.001 ppm up-field shift

CH_2D_2 0.027±0.003

CHD_3 0.045±0.004

② CH_3COCH_3

CD_3COCH_2D 0.034±0.001 ppm up-field shift

③ $^{12}CF_3H$

$^{13}CF_3H$ 0.126 ppm up-field shift

3-5. ^{14}N–H Coupling

^{14}N: Natural abundance 99.63%; I (spin quantum number) = 1

$^{1}J_{14N-H}$

a. Fast exchanging H: sharp and singlet without N–H coupling

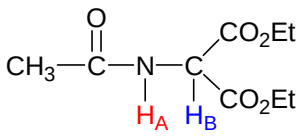
b. Slow exchanging H: broad peak around 2.0~2.4 ppm (quadrupole relaxation)

cf. amide–H: 6–9 ppm

c. R_3N^{+}–H: $^{1}J_{+N-H}$ = ~ 50–60 Hz, triplet (broad)

Examples

①



H_A: broad doublet

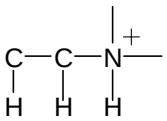
H_B: d, J_{AB} = 7.3 Hz at 5.21 ppm.

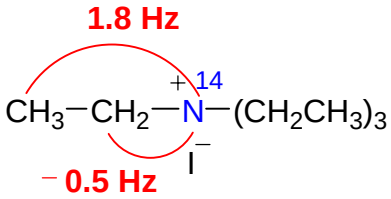
② $CH_3CH_2CH_2NH_3^{+}$

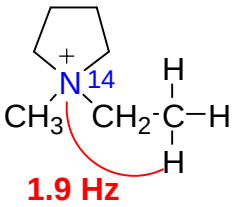
$^{1}J_{14NH}$ = ~ 50 Hz at 6.7 ppm

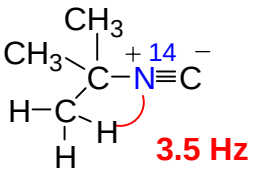
$^{2}J_{14N-H}$ and $^{3}J_{14N-H}$: Only with $R_4{}^{14}N^{+}$

$^{1}J_{14N-H} > 0$; $^{2}J_{14N-H} < 0$; $^{3}J_{14N-H} > 0$;

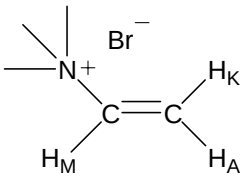








- NMR spectrum of



$^{3}J_{14NHA}$ = 5.5 Hz $^{3}J_{14NHK}$ = 2.6 Hz $|^{2}J_{14NHM}|$ = 3.5 Hz

$|^{2}J_{14NCH3}|$ = 0.5 Hz $^{3}J_{HKHM}$ = 14.8 Hz $^{3}J_{HAHM}$ = 8.3 Hz $^{2}J_{HAHK}$ = – 4.1 Hz

3-6. ^{15}N–H Coupling

^{15}N: Natural abundance = 0.36%; I (spin quantum number) = 1/2

^{15}N-enriched compounds should be prepared!

%S = 0.43 x $^{1}J(^{15}N–H) – 6$

%S = 100cosϕ(cosϕ-1) ϕ: bond angles between N and its substituents

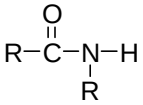
$^{+}NH_4$: ϕ = 107.3° → 22.9% S-character

$^{+}NH_4$: $^{1}J_{15NH}$ = 73.2 Hz → 25.47% S-character

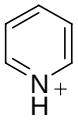
$^{1}J_{15NH}$

62 Hz (20.7)

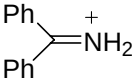
73~76 Hz (26.7)



88~92 Hz (33.6)



90 Hz (32.7)



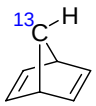
92.6 Hz (33.3)

3-7. ^{13}C–H Coupling

^{13}C: Natural abundance 1.11%; I (spin quantum number) = 1/2

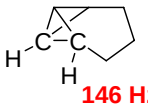
S-character of C–H bond

%S = 0.20·$^{1}J_{13C–H}$

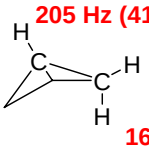


135 Hz (27%)

200 Hz (40%)



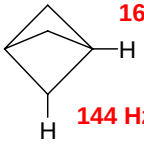
146 Hz (29.2%)



205 Hz (41%)

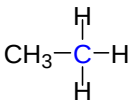
153 Hz (30.6%)

169 Hz (33.8%)



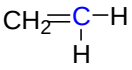
164 Hz (33%)

144 Hz (29%)



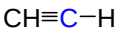
125 Hz (25%)

sp^3



156.2 Hz (31%)

sp^2



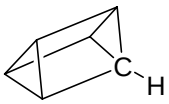
249 Hz (50%)

sp

Based on INDO–MO calculation,

Improved equation

$\%S = ({}^1J_{13CH} + 18.4)/5.7$



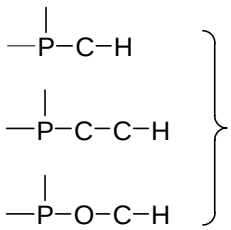
Calculated $^1J_{13CH}$ = 189 Hz

Observed $^1J_{13CH}$ = 180 Hz

3-8. ^{31}P–H Coupling

^{31}P: Natural abundance 100%; I (spin quantum number) = 1/2

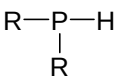
$^2J \sim {}^3J$



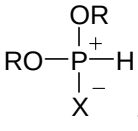
$^2J \sim {}^3J$

J_{31PH} = 3 ~ 25 Hz

^1J

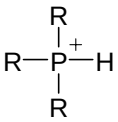


$^1J_{31PH}$ = 179 ~ 210 Hz



$^1J_{31PH}$ = 515 ~ 695 Hz

X = O, S



$^1J_{31PH}$ = ~ 525 Hz

Examples

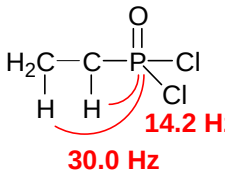
①

PH_3: $^1J_{31PH}$ = 179 Hz

②

CH_3–PH_2: $^1J_{31PH}$ = 207 Hz

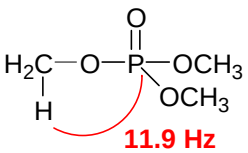
③



14.2 Hz

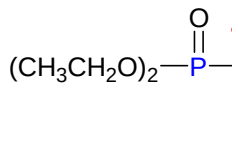
30.0 Hz

④



11.9 Hz

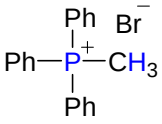
⑤



4.11 ppm; $^{3}J_{31PH}$ = 8.38 Hz

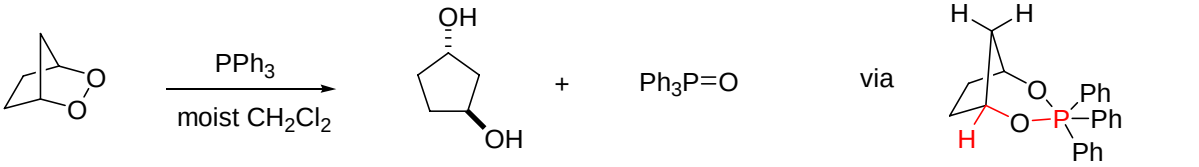
1.35 ppm

⑥



3.27 ppm; $^{2}J_{31PH}$ = 13.6 Hz

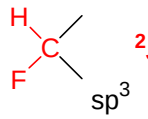
J. Org. Chem. **1981**, *46*, 4105.



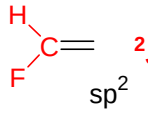
4.56 ppm; $^{3}J_{31PH}$ = 21.1 Hz

3-9. ^{19}F–H Coupling

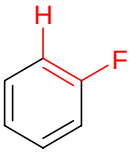
^{19}F: Natural abundance 100%; I (spin quantum number) = 1/2



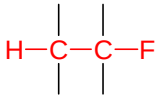
$^{2}J_{19FH}$ = 45 ~ 80 Hz



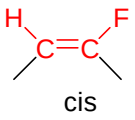
$^{2}J_{19FH}$ = 72 ~ 90 Hz



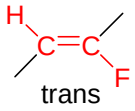
$^{3}J_{19FH}$ = ***ortho***: 6 ~ 10 Hz
meta: 6 ~ 8 Hz
para: -2 ~ 2 Hz



$^{3}J_{19FH}$ = 5 ~ 30 Hz



$^{3}J_{19FH}$ = -3 ~ 20 Hz



$^{3}J_{19FH}$ = 12 ~ 52 Hz

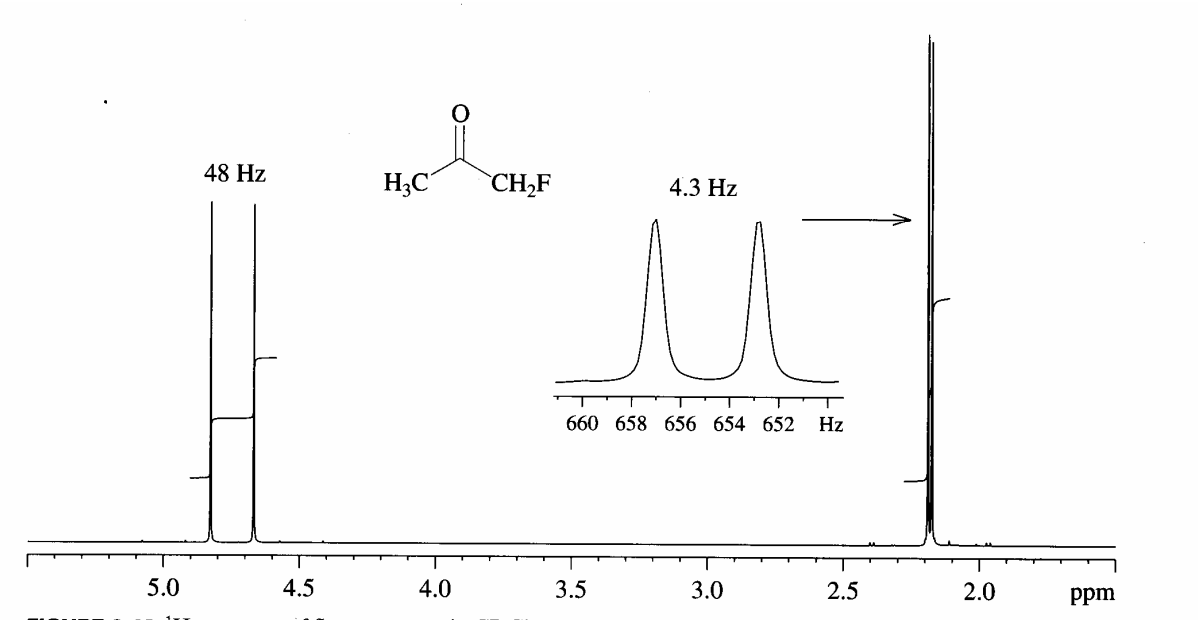
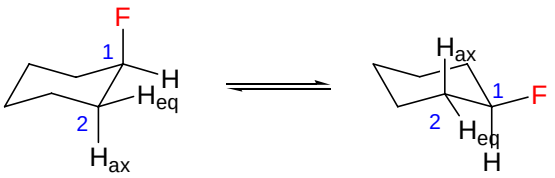


FIGURE 3.42 ^{1}H spectrum of fluoroacetone in $CDCl_3$ at 300 MHz.

Examples

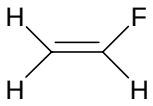
①



$^2J_{H1F}$ = 49 Hz
$^3J_{H2axF}$ = 43.5 Hz
$^3J_{H2eqF}$ < 3 Hz

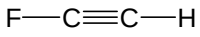
$^2J_{H1F}$ = 49 Hz
$^3J_{H2axF}$ < 3 Hz
$^3J_{H2eqF}$ < 3 Hz

②



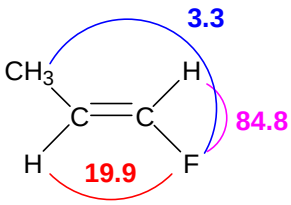
$^3J_{HFcis}$ = 20.1 Hz
$^3J_{HFtrans}$ = 52.4 Hz
$^3J_{HFgem}$ = 84.7 Hz

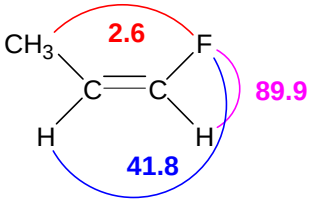
③



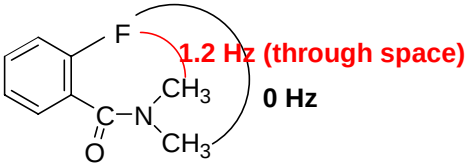
$^3J_{FH}$ = 21 Hz

④

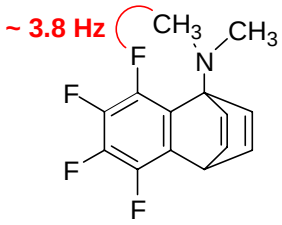




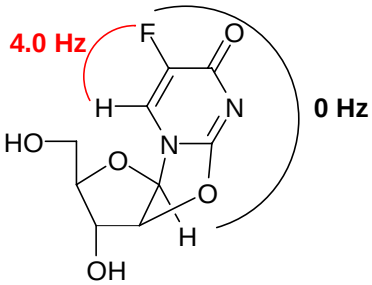
⑤



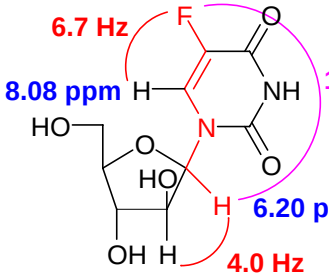
⑥



⑦

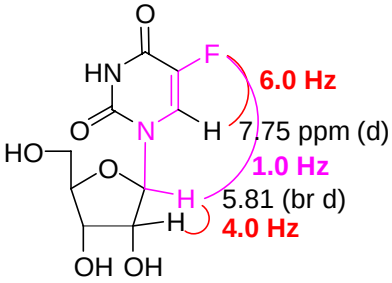


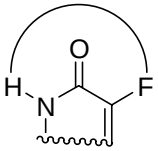
⑧



measured in D_2O

⑨





not observed

4. Environmental Effect

4.1 Sample

Sensitivity ∝ $N\cdot\{(I+1)/I^3\}\mu^3\cdot B_0^2$

Relative sensitivity:		
	^{1}H	1.00
	^{19}F	0.834
	^{13}C	0.0159
	^{2}H	0.0096

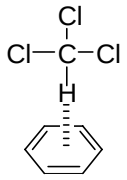
4.2 Solvent Effect

- Solvent effect on the **external standard** – Sample peaks move on the solvent used, but no effect on the external standard (reference).
- Solvent effect on the **internal standard** – Both sample and the reference peaks are subjected to the solvent effect.

▶ **Chemical interaction with a solvent**

(a) Solvation

(i) H-bonding with a solvent (including π-complex formation)

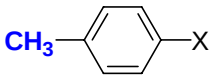


2 kcal/mole

–OH, –NH, $–CO_2H$, PhOH have a large temperature-dependent solvent shift.

► **Solvation with benzene**

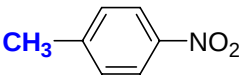
①



CH_3 peak

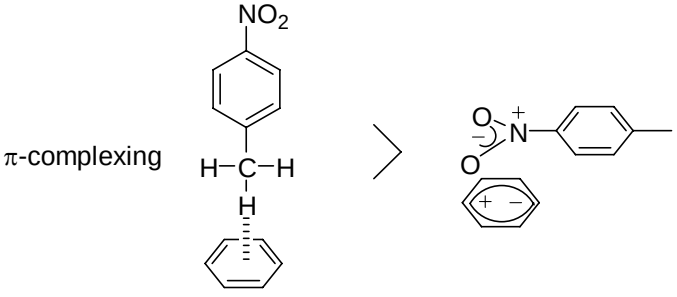
Δ = δ(in CCl_4) – δ(in benzene)

Δ is largest when X = NO_2

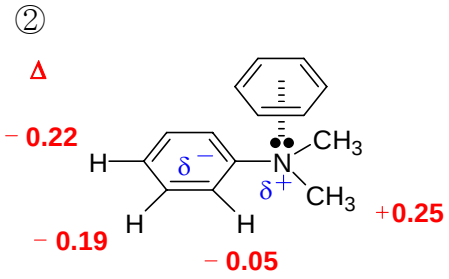


Most deshielded in CCl_4; most shielded in benzene

← →

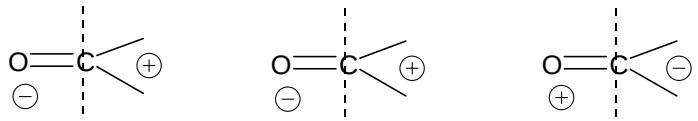


②

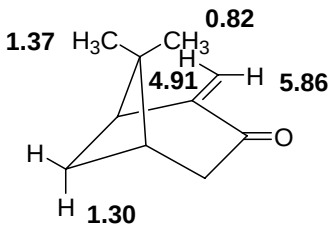


③ Carbonyl reference plane rules

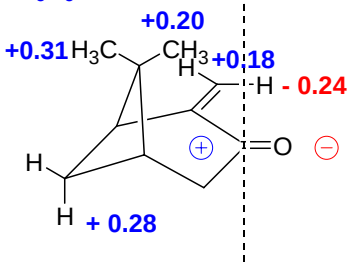
a. C_6D_6/CCl_4 **b. C_5D_5N/CCl_4** **c. C_6F_6/CCl_4**



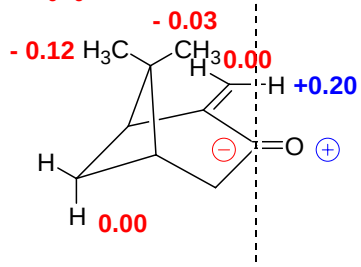
In CCl_4



In C_6D_6

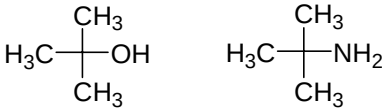


In C_6F_6



(ii) Indirect solvent effect caused by solvation on the near-by functional groups

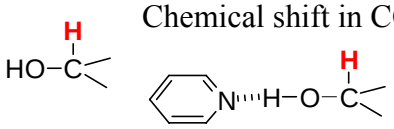
①



Solvation to –OH and $–NH_2$ → chemical shift of *t*-Bu will be perturbed.

CH_3's are non-equivalent

②



Chemical shift in CCl_4 and in pyridine are different.

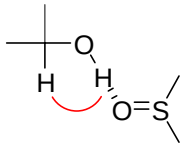
(b) Proton exchange (–OH, $–NH_2$, ------)

—OH + XH* ⇌ —OH* + XH

$\tau^* = \sqrt{2}/(\pi \cdot \Delta\nu)$

τ*: life time; Δν: chemical shift difference between –OH and –XH* in Hz

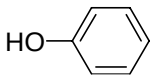
Solvent effect: fixation of exchangeable H's by forming strong H-bond with DMSO or acetone.



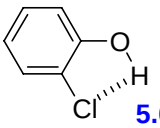
$^3J_{HH}$ can be seen

※ Add D_2O to make sure of the presence of alcoholic proton.

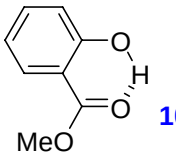
Intramolecular H-bonding (δ in cyclohexane)



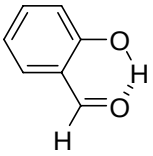
4.24



5.60



10.58



10.95

5. Chemical Shift – semi-quantitative considerations

5.1. Factors responsible for chemical shifts

$H_{effect} = H_0 \cdot (1 - \sigma)$

σ = shielding constant: $4\pi e^2/(3mc^2)\int rp(r)dr$ = 17.8 ppm for H

If a hydrogen atom is placed in an electric field E (in esu unit),

$\Delta\sigma = -(881/226)\cdot(a^3E^2/mc^2) = -\mathbf{0.74 \times 10^{-18}E^2}$ (downfield shift)

a: Bohr radius, 0.529×10^{-8} cm for H

m: weight of electron

Examples

(a) a unit charge located at 1Å, 1.5Å, 2Å

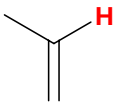
E = 4.8×10^6, 2.14×10^6, 1.2×10^6 esu

Δσ = 17 ppm, 3.4 ppm, 1.1 ppm downfield shift

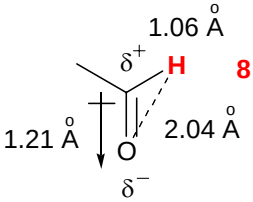
(b) a dipole

$E = \mu(1 + 3\cos^2\theta)^{1/2}/R^3$

μ: dipole moment, R: distance



4 ~ 6 ppm



8 ~ 9.5 ppm

4 ~5 ppm electric field effect of the dipole

Dipole moment of C=O is ca. 2×10^{-10} esu

$\sigma_E = -4.6 \times 10^{-6}$ (**4.6 ppm downfield shift by the C=O dipole**)

① Local diamagnetic effects

Dailey, Shoolery rule

CH_3–CH_2–X system

Electronegativity of X = $0.684\cdot(\delta_{CH2} - \delta_{CH3}) + 1.78$ in ppm

$= 0.02315\cdot(\Delta CH_3 - \Delta CH_2) + 1.71$ in Hz

Assumption

1) paramagnetic contribution ≈ 0
2) neighboring atom's contribution ≈ constant

② Paramagnetic effects – **induced dipole by polarizable atom** (directional)

"Due to non-spherical electron distribution of the particular atom" → downfield shift

※ Temperature-independent paramagnetizm

※ Paramagnetic effects can be neglected in ^{1}H NMR, but important for ^{13}C, ^{19}F NMR.

③ **The magnetic anisotropy effect** of neighboring groups

Magnetic susceptibility (χ)

$\mu = \chi H_0$

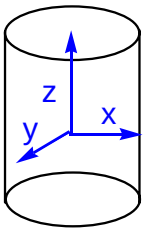
μ: Induced magnetic dipole moment in H_0.

χ directional

► If $\chi_{xx} = \chi_{yy} \neq \chi_{zz}$

$\Delta\chi_z = \chi_{zz} - \chi_{yy} = \chi_{zz} - \chi_{xx}$

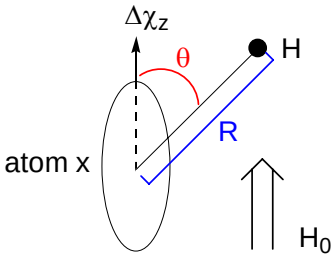
$\Delta\chi_z$: Anisotropy of χ



In a magnetic field H_0,

H atom experiences secondary magnetic field H'

$\mathbf{H' = -H_0\cdot\Delta\chi_z(1 - 3\cos^2\theta)/3R^3}$ **McConnell's equation**



"Anisotropy shift"

$\Delta\sigma = -H'/H_0 = \mathbf{\Delta\chi_z(1 - 3\cos^2\theta)/3R^3}$

If $\Delta\chi_z < 0$; $3R^3 > 0$;

The sign of $\Delta\sigma$ depends on the value of $(1 - 3\cos^2\theta)$

When $\theta = 55^o44'$ $\Delta\sigma = 0$

$\Delta\sigma > 0$ → + up-field shift (shielding)

$\Delta\sigma < 0$ → – down-field shift (deshielding)

► If $\chi_{xx} \neq \chi_{yy} \neq \chi_{zz}$

$\Delta\chi_z = \chi_{zz} - \chi_{yy}$

$\Delta\chi_x = \chi_{xx} - \chi_{yy}$ $\Delta\sigma = \Delta\sigma_z + \Delta\sigma_x$

$\Delta\chi < 0$ when $\chi_{zz} > \chi_{xx}$ or χ_{yy}

(a) C≡X The shielding zone (cone)

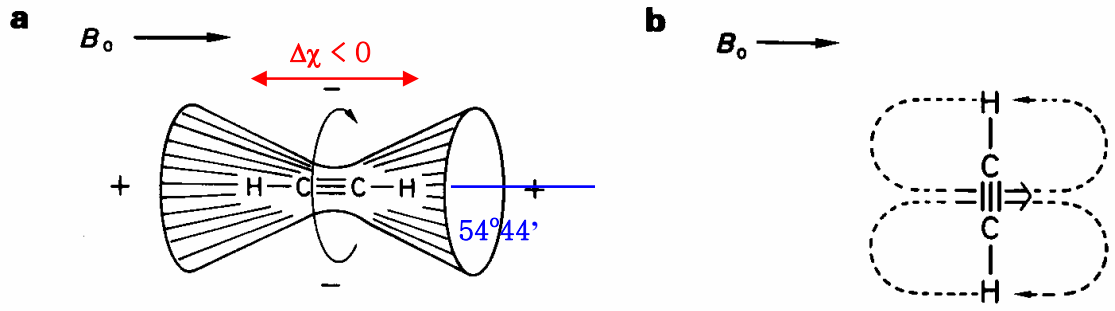
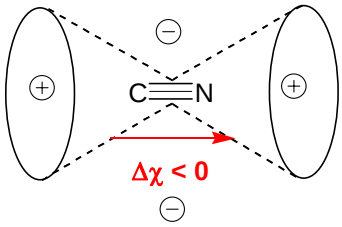
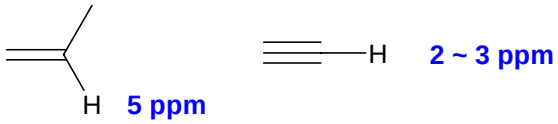


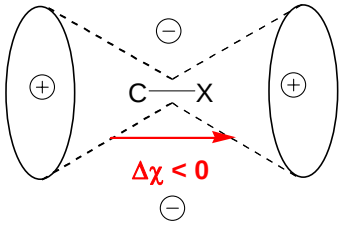
Figure 4.8 Schematic representation of the magnetic anisotropic effect of the triple bond



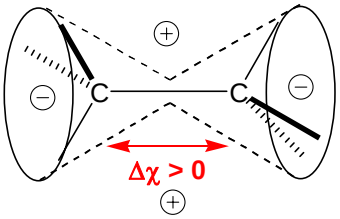
e.g.



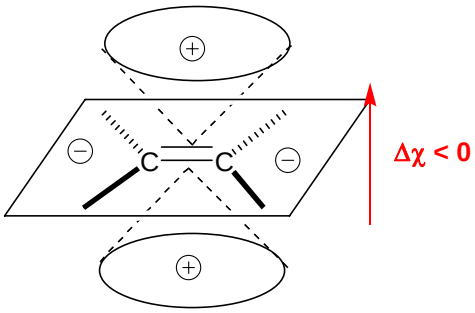
(b) C–X



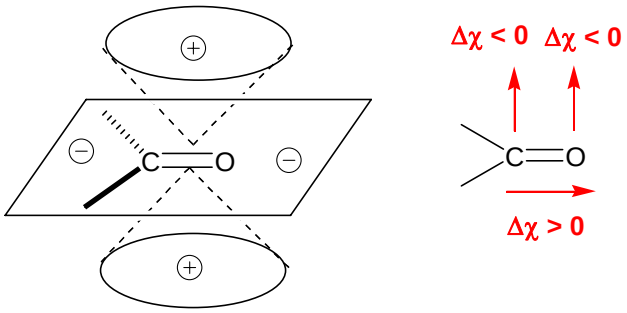
(c) C–C



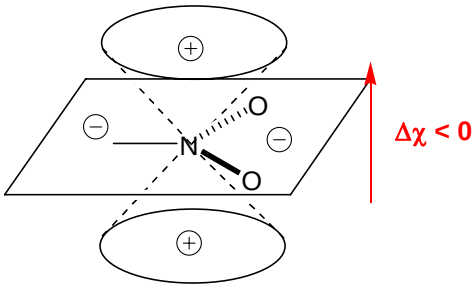
(d) C=C



(e) C=O



(f) NO_2

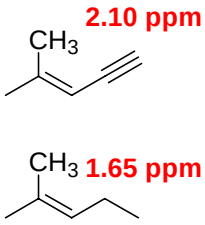


Examples

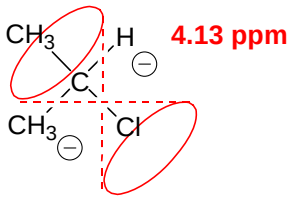
(a) C≡X

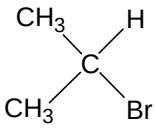
① CH_3–C≡C–H 1.80 ppm (quintet)

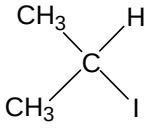
②



(b) C–X







|Δχ| for C–X Cl < Br < I

c.f.

①	CH_3Cl	CH_3Br	CH_3I
	3.05	2.68	2.16 ppm
②	CH_3CH_2Cl	CH_3CH_2Br	CH_3CH_2I
	3.57	3.36	3.20 ppm

(c) C–C

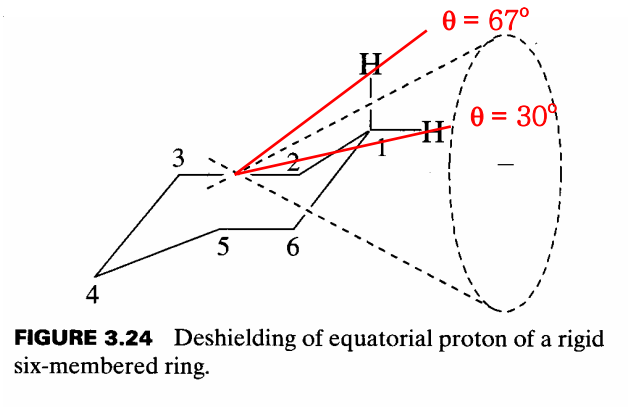


FIGURE 3.24 Deshielding of equatorial proton of a rigid six-membered ring.

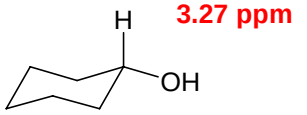
$\theta_{ax} = 67°$

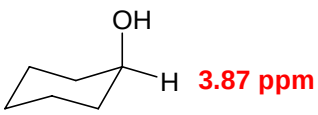
$r_{ax} = 2.35$ Å

$\theta_{eq} = 30°$

$r_{eq} = 2.80$ Å

$\delta_{Heq} - \delta_{Hax} \approx 0.4 \sim 0.6$ ppm

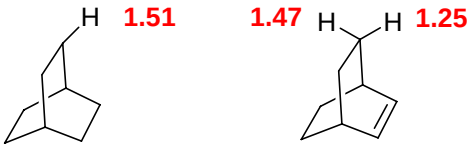




$\Delta\delta = 0.60$ ppm

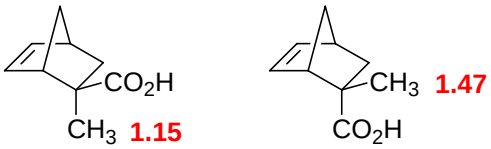
(d) C=C

①

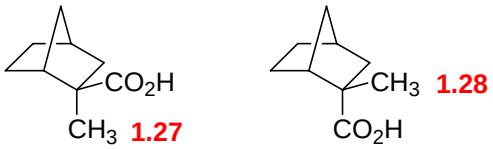


②

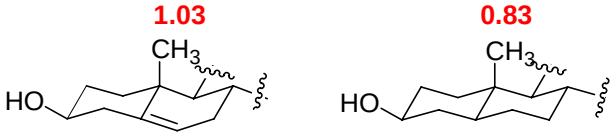
③



cf.

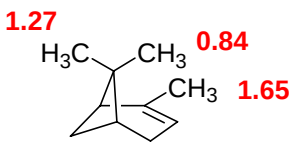


④



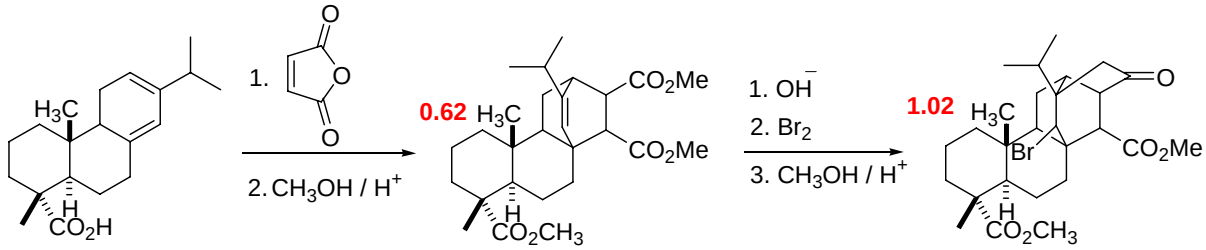
cholesterol　　5α-cholestanol

⑤



α-pinene

⑥



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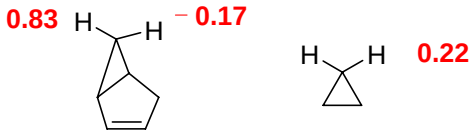
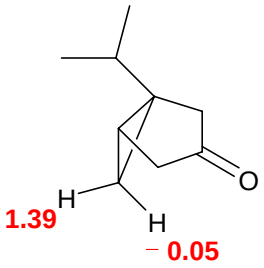
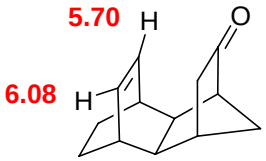


(e) C=O

①



②



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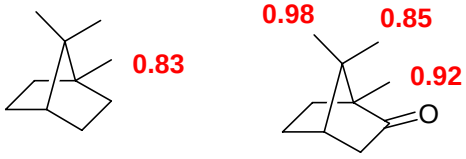

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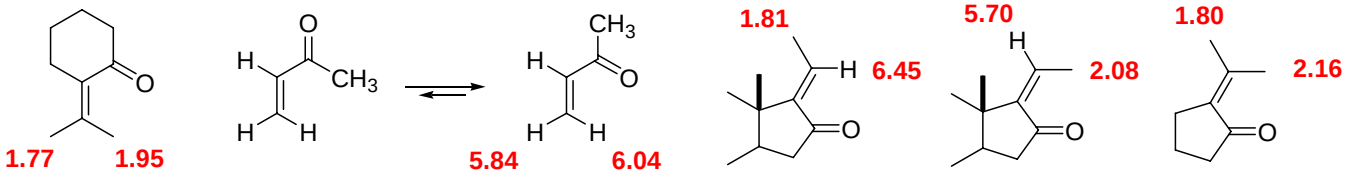
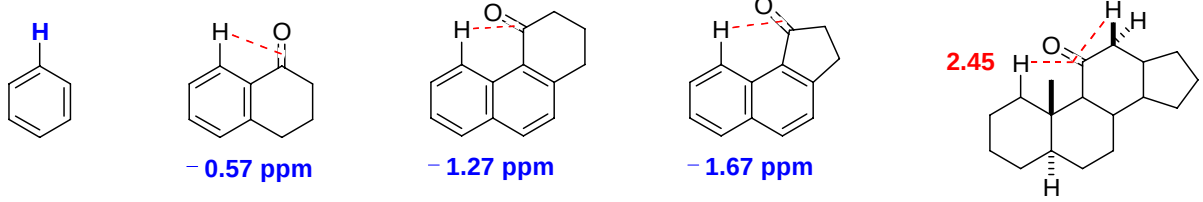
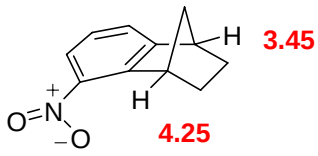


⑤ Deshielding

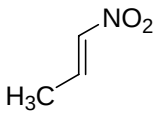


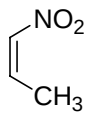
(f) $-NO_2$

①



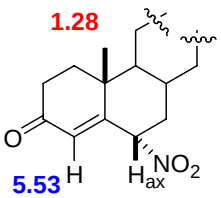
②

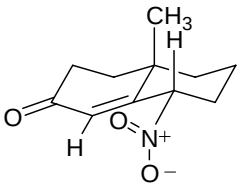




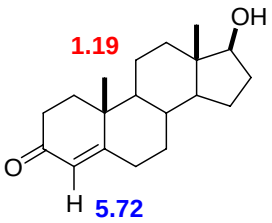
0.27 ppm deshielded
relative to the trans isomer

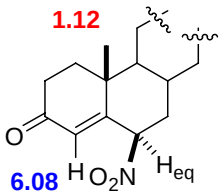
③

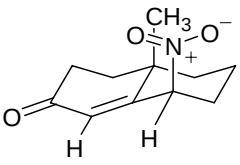




5.33 (ddd, J = 12.3, 4.7, 2.0 Hz, 1H)

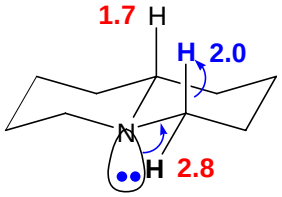






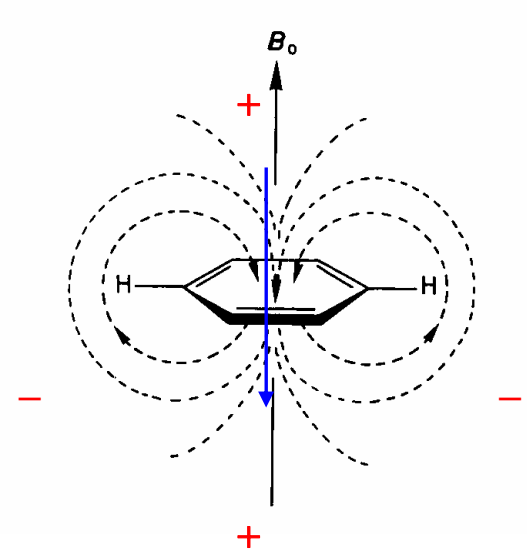
4.84 (dd, J = 4.6, 2.0 Hz, 1H)

(g) "Quinolizidine" type



Axial hydrogens α to N are shielded by ~ 1 ppm relative to the equatorial hydrogens

(h) Interatomic currents: Ring currents

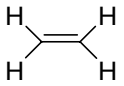


$\Delta\chi$ (benzene) = – 96 x 10^{-30} cm^3·esu

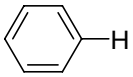
$\Delta\sigma = -H'/H_0 = \Delta\chi_z(1 - 3\cos^2\theta)/3R^3$

Magnetic field induced by ring currents in the benzene rings

Note



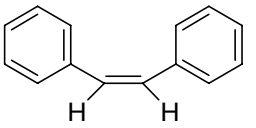
5.84 ppm



7.25 ppm

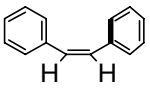
Examples

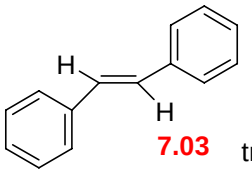
①



6.21

cis-stilbene 6.53

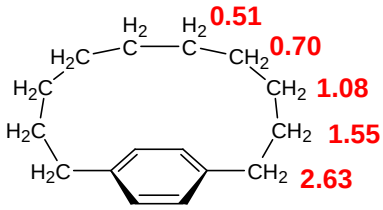




6.38

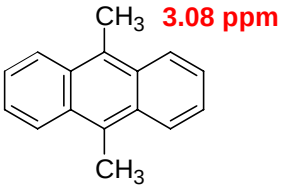
7.03 trans-stilbene

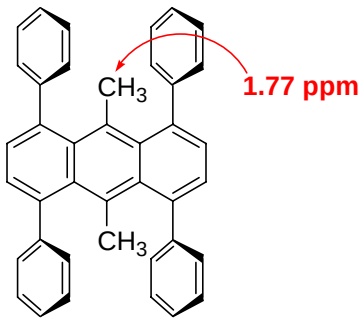
②



[10]-paracyclophane

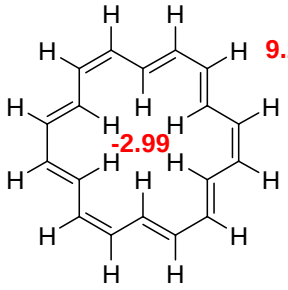
③ *J. Am. Chem. Soc.* **1967**, *89*, 5458.



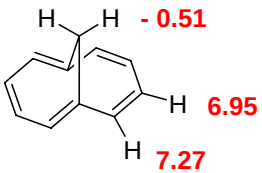


④ Aromatic (4n+2)π system

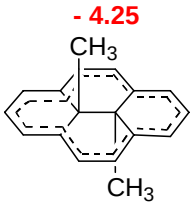
The shielding effect of the ring current is proportional to the area of the ring.



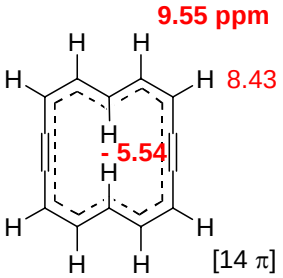
[18] annulene



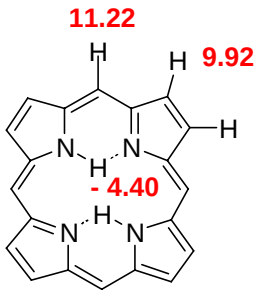
[10 π]



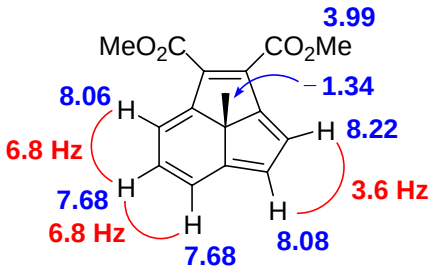
[14 π]



[14 π]



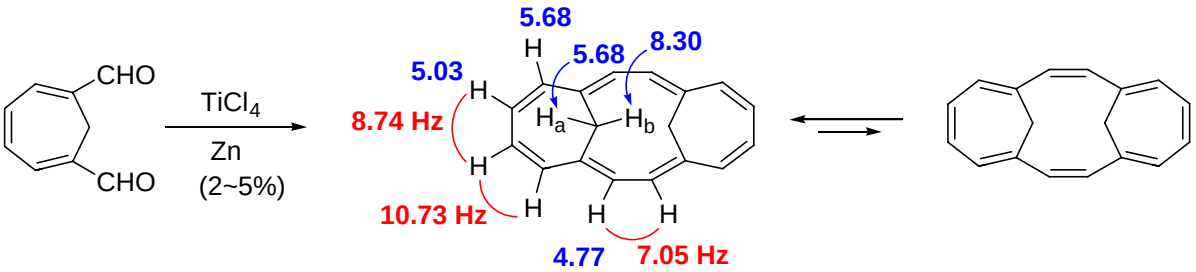
[22 π]



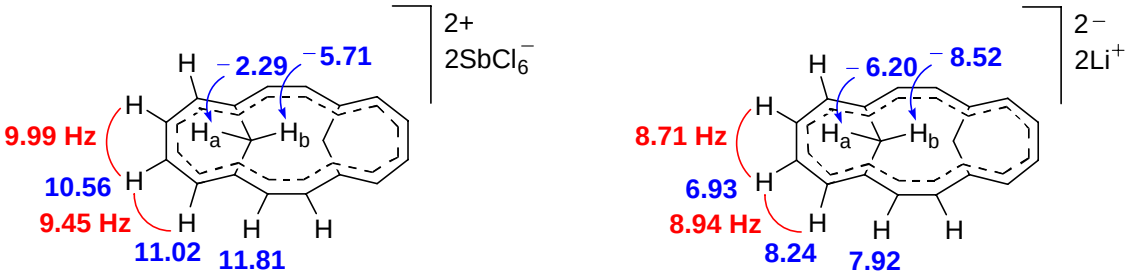
[10 π]

⑤ Doubly-bridged [16] annulene

Tetrahedron Lett. **1982**, *23*, 1221; **1985**, *26*, 3087; **1985**, *26*, 3091.



localized π-bond paramagnetic ring current effect



[14]-annulene [18]-annulene

diamagnetic ring current effect

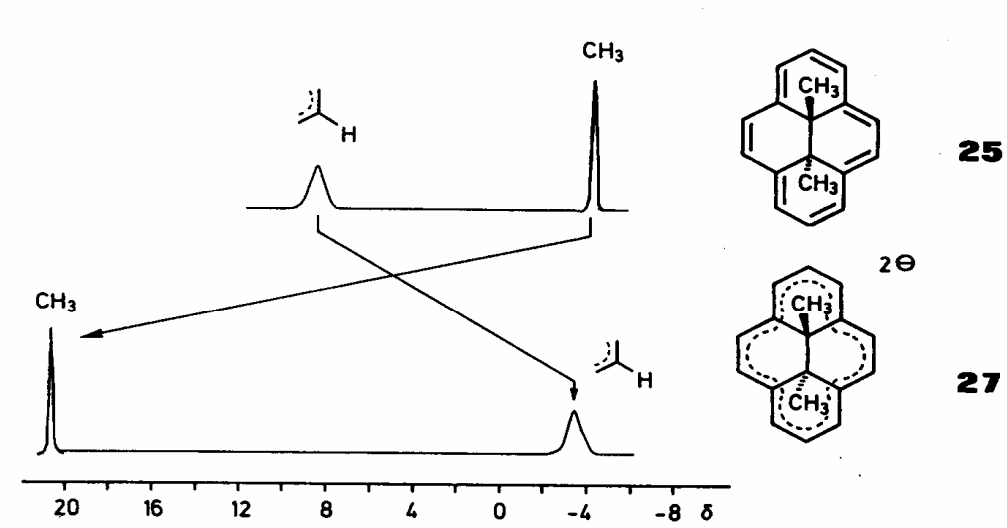
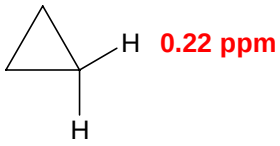
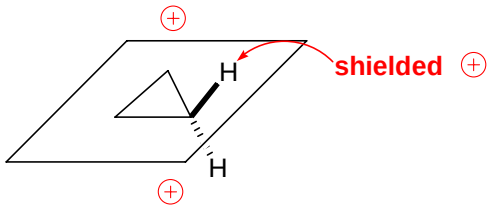


Figure 4.13 Schematic comparison of n.m.r. spectra of the annulenes **25** and **27** with 14 and 16 π-electrons, respectively

(i) Shielding effect by three-membered rings

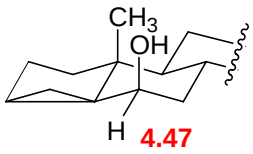
(1) Cyclopropane ring

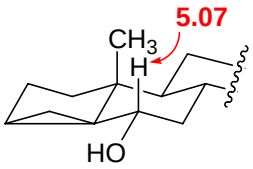




Examples

①



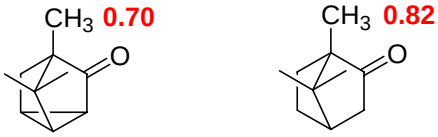


②

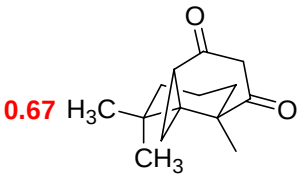
0.30 ppm up-field shifted

③

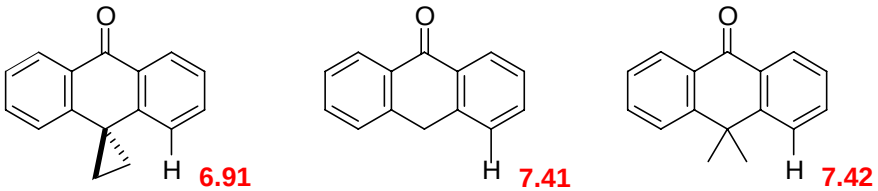
④



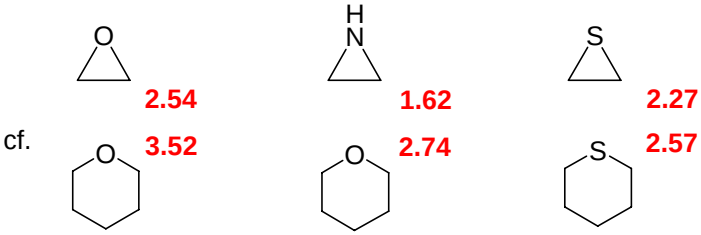
⑤

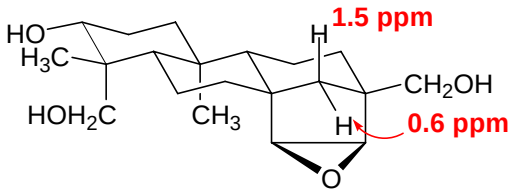


⑥



(2) Other three-membered rings





5.2 Proton Chemical Shifts in Aromatic Molecules Substituted Benzenes

Spectroscopy for Organic Molecules

Myong Ji Univ., Dept. of Chem.

Proton chemical shifts in aromatic molecules

Substituted benzenes

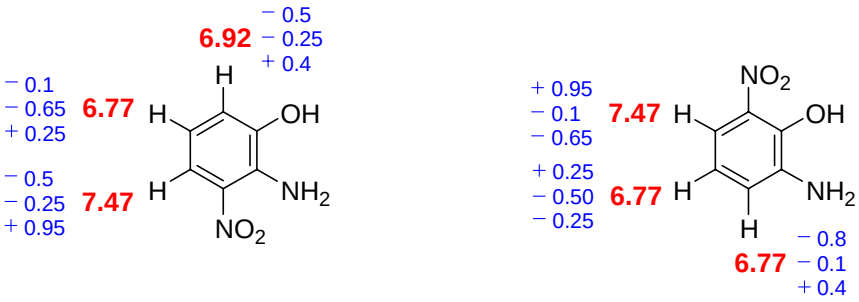
$\delta_{Ar\text{-}H} = 7.27 + \Sigma P_i$

Table for the Pi values

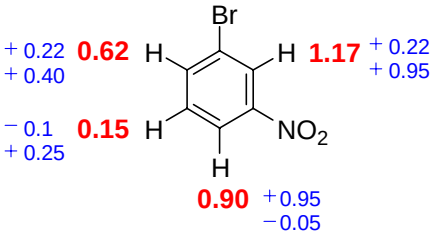
subst.	P_i^o	P_i^m	P_i^p	subst.	P_i^o	P_i^m	P_i^p
NHMe	-0.9	-0.2	-0.7	Br	0.22	-0.1	-0.05
NH_2	-0.8	-0.25	-0.65	C (sp)	0.2	-0.05	-0.05
NMe_2	-0.65	-0.2	-0.65	Ph	0.2	0.05	-0.05
OH	-0.5	-0.1	-0.5	CN	0.25	0.2	0.3
OMe	-0.5	-0.1	-0.45	I	0.4	-0.25	0
OR	-0.35	-0.05	-0.3	NHCOR	0.4	-0.2	-0.3
F	-0.3	0	-0.25	N^+H_3	0.4	0.2	0.2
Me	-0.15	-0.1	-0.15	COAr	0.45	0.1	0.2
CMe_3	-0.1	0	-0.25	CHO	0.55	0.2	0.3
OCOPh	-0.1	0.05	-0.1	COR	0.6	0.1	0.2
SH	-0.05	-0.1	-0.2	COOR	0.7	0.1	0.2
Cl	0	-0.05	-0.1	$CONH_2$	0.7	0.2	0.25
SR	0.1	-0.1	-0.2	COCl	0.8	0.2	0.35
C (sp^2)	0.15	0	-0.15	COOAr	0.9	0.15	0.25
OCOR	0.2	-0.1	-0.2	NO_2	0.95	0.25	0.4

Examples

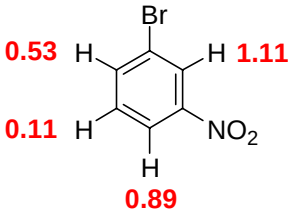
①



② Δδ



Calcd values based on the equation

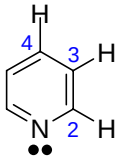


Oserved values

Heteroaromatics

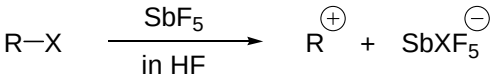
1. α-Protons are strongly up-field shifted by the heteroatom.

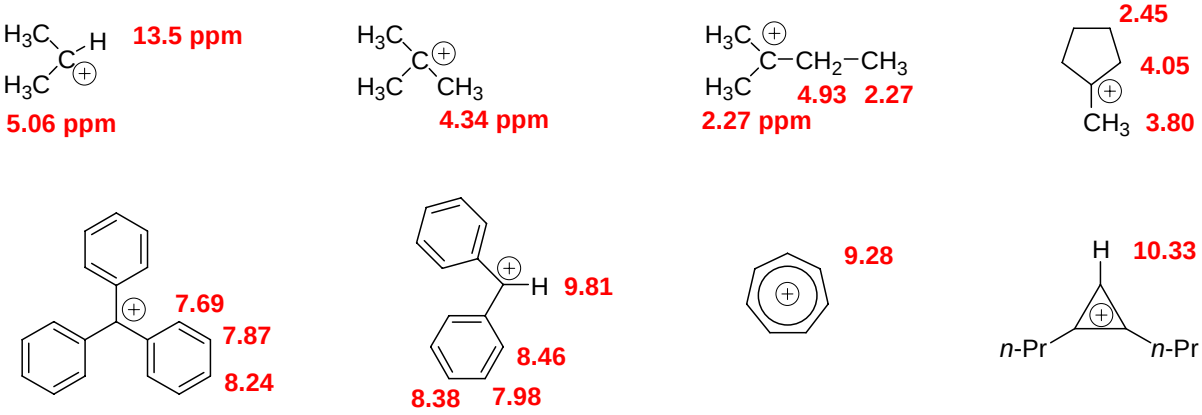
2. Asymmetric electron distribution: electron density is higher near the heteroatom, which lower the aromaticity

		δ ppm (relative to benzene)	ρ_{exp}
	H-2	–1.31	0.91
	H-3	+ 0.16	1.01
	H-4	– 0.26	0.98

5.3 Carbonium Ions, Carbanions and Related Systems

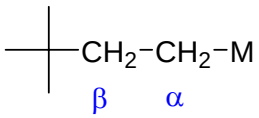
Carbonium ions





Carbanions

①



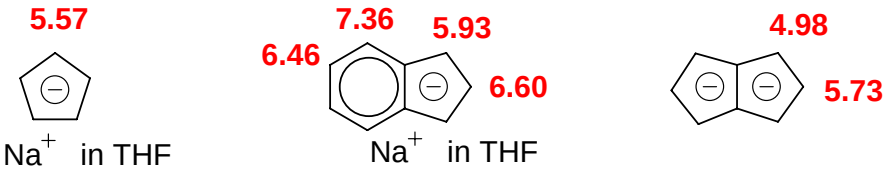
in ether

Chemical shift (δppm)

M	Li	Mg	Zn	Al	Hg
α	−1.08	−0.68	0.15	−0.20	1.01
β	1.35	1.39	1.47	1.25	1.58
e.n. of M	1.0	1.2	1.5	1.5	1.9
	Ionic				Covalency

e.n.: electronegativity

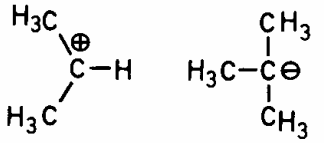
②



③

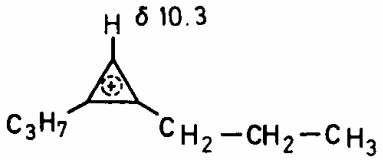
more covalent character

Table 4.1 Proton resonances in carbocations and carbanions



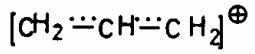
δ 5.06 13.50

δ 4.35

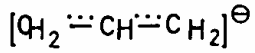


δ 10.3

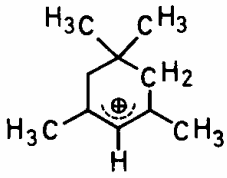
δ 3.15 1.88 1.01



δ 8.97 9.64 8.97



δ 2.46 6.28 2.46



δ 1.21

δ 3.07

δ 3.33

δ 8.02

CH_3Li CH_3-CH_2Li

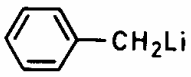
δ -1.3 1.33 -0.99

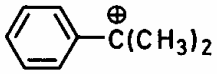
$(CH_3)_2Mg$ $(CH_3-CH_2)_2Mg$

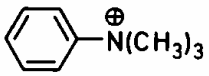
δ -1.3 1.26 -0.64

$(CH_3-CH_2-CH_2)_2Mg$

δ 0.90 1.50 -0.57





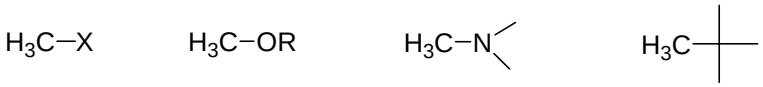


δ_o	6.09	8.80	7.98
δ_m	6.30	7.97	7.66
δ_p	5.50	8.45	7.60

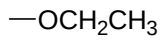
6. Non-first-order Spin Systems

6-1. Nomenclature of the spin system

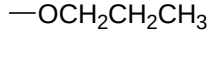
A_3 (singlet)



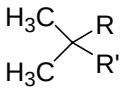
A_2X_3 (quartet)(triplet)



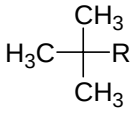
$A_2M_2X_3$ or **$A_2X_2Y_3$** (triplet)(sextet)(triplet)



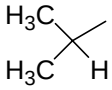
A_6 (singlet) or **A_3B_3** (2 singlet)



A_9 (singlet)



AX_6 or **AX_3Y_3** (doublet or 2 doublet for Me)



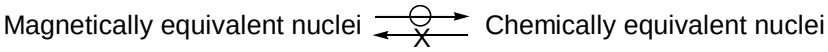
For first-order spectra

(i) Chemical shift separation >> the coupling constant

(ii) Magnetically equivalent nuclei

The Pascal Triangle for I = 1/2

Magnetically equivalent nuclei vs. **chemically equivalent** nuclei



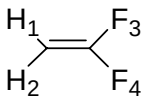
CH_2F_2

$J_{1,3} = J_{2,3}$

$J_{1,4} = J_{2,4}$

A_2X_2 (magnetically equivalent)

$CH_2=CF_2$



$J_{1,3} \neq J_{2,3}$

$J_{1,4} \neq J_{2,4}$

AA'XX' (magnetically nonequivalent)

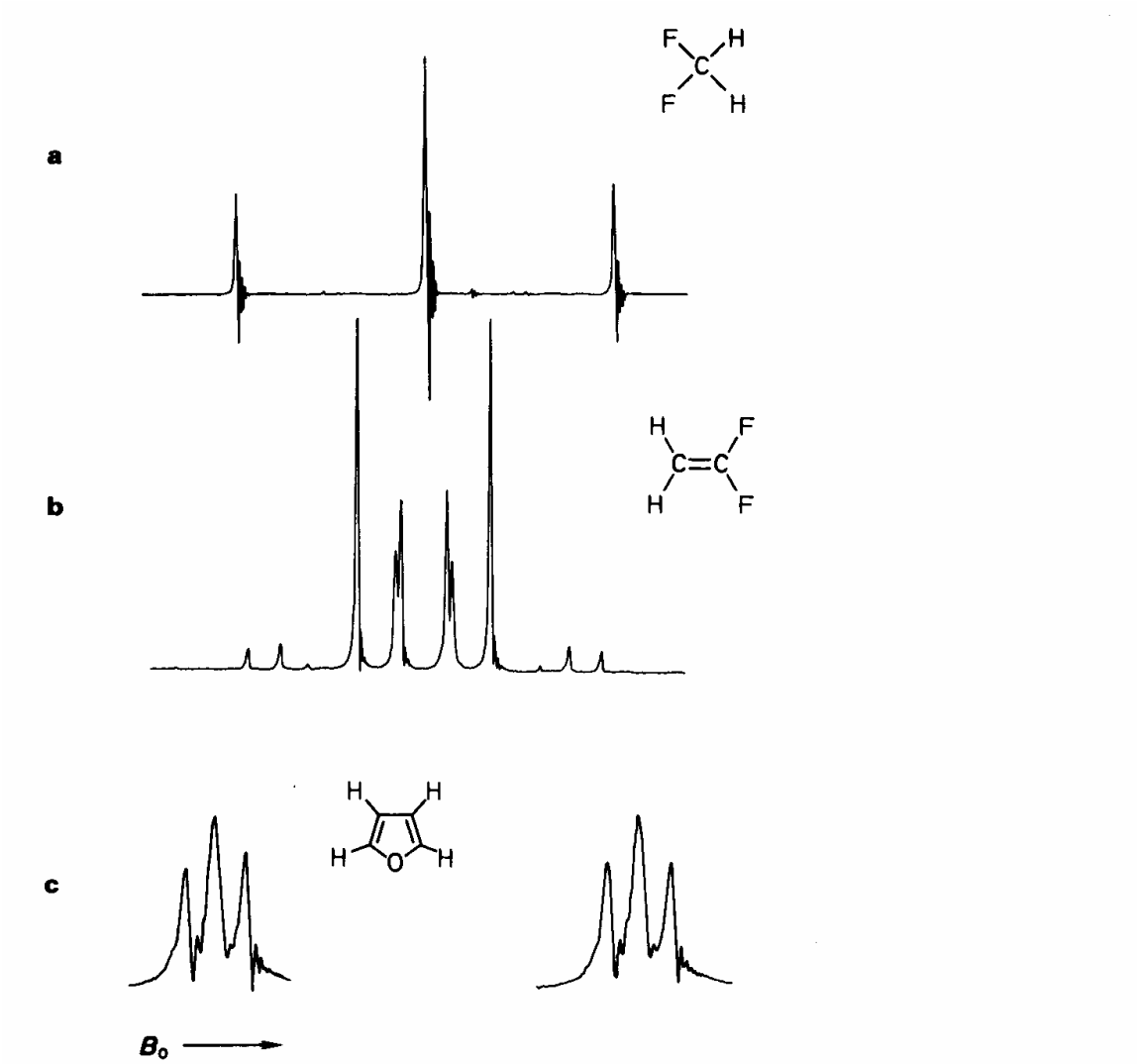
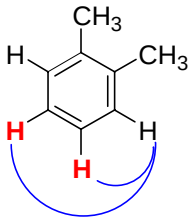
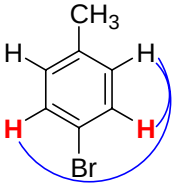


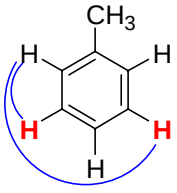
Figure 2.21 Proton magnetic resonance spectrum of (a) difluoromethane, (b) 1,1-difluoroethylene (after Ref. 2), and (c) furan



AA'BB'



AA'XX'



AA'BB'C

more than 100 lines

6.2 Two-Spin Systems

Δν (Ha,Hb) /J (Ha,Hb)

AX ⟶ AB ⟶ AA' ⟶ A_2

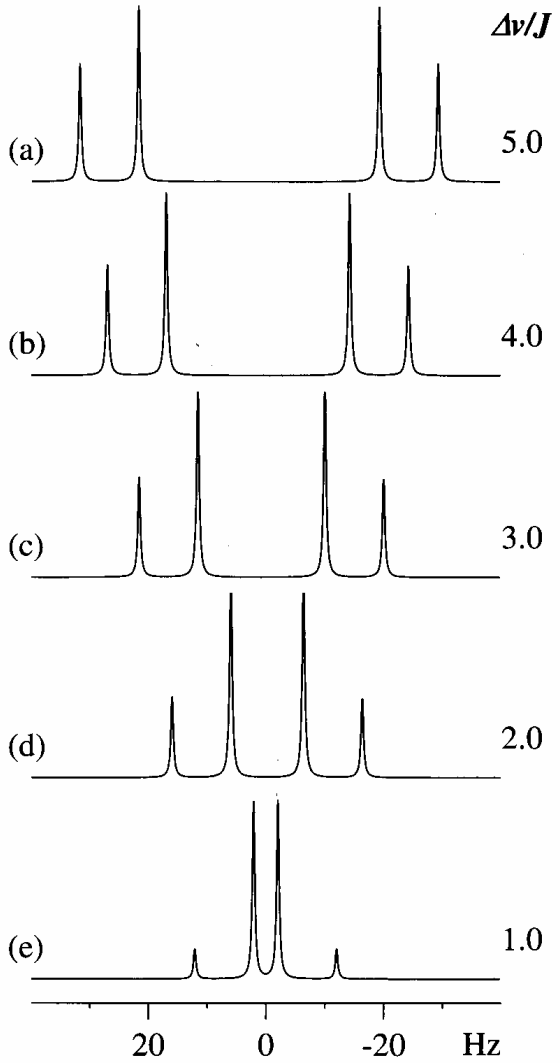


FIGURE 3.28 A two-proton system, spin coupling with a decreasing difference in chemical shifts and a large *J* value (10 Hz); the difference between AB and AX notation is explained in the text.

► The AB System

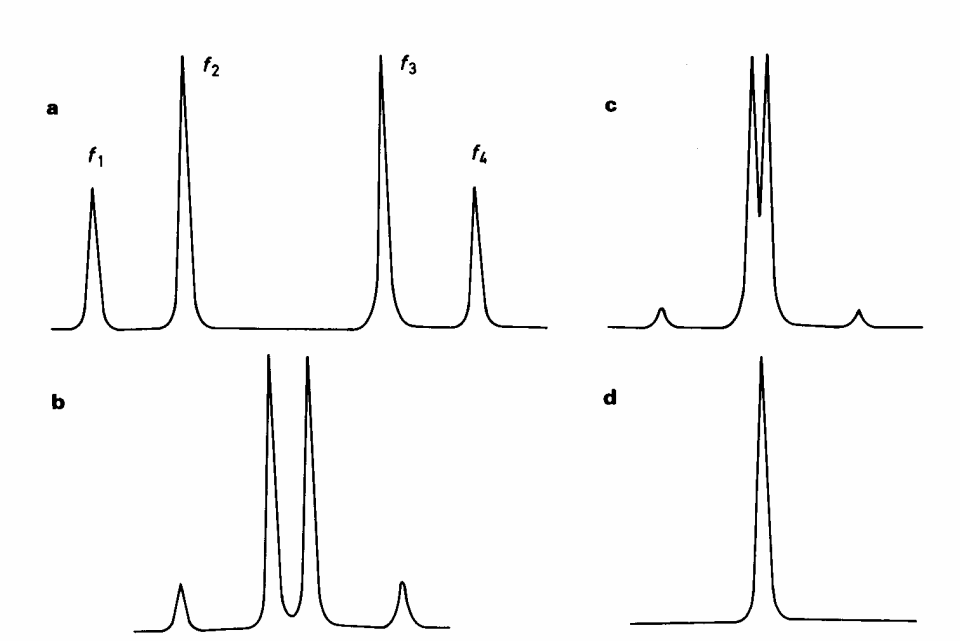
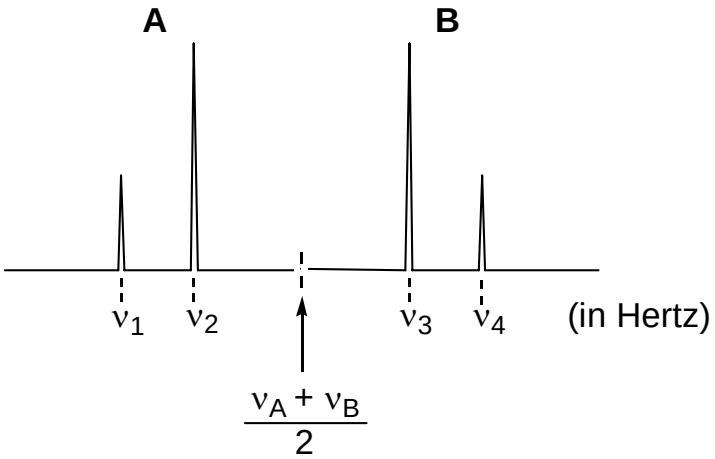


Figure 5.5 Dependence of the AB system on the ratio $J/\nu_0\delta$; spectra illustrated are for values of $J/\nu_0\delta$ of (a) 1:3, (b) 1:1, (c) 5:3, and (d) 5:1.



$\nu_1 - \nu_2 = \nu_3 - \nu_4 = J_{AB}$

a. Symmetrical around $(\nu_A + \nu_B)/2$

$\nu_1 - \nu_2 = \nu_3 - \nu_4$

$I_1 : I_2 = I_4 : I_3$

b. $J_{AB} = \nu_1 - \nu_2 = \nu_3 - \nu_4$

(or get average)

c. $\nu_A - \nu_B = \{(\nu_1 - \nu_4)(\nu_2 - \nu_3)\}^{1/2}$

d. $I_1 / I_2 = I_4 / I_3 = (\nu_2 - \nu_3) / (\nu_1 - \nu_4)$

<u>Calculation of the chemical shift in AB system</u>

Suppose $(\nu_A + \nu_B)/2 = X$, $\nu_A - \nu_B = \{(\nu_1 - \nu_4)(\nu_2 - \nu_3)\}^{1/2} = Y$

Then

$\nu_A + \nu_B = 2X$,

$\nu_A - \nu_B = Y$

Solve the two equations for ν_A and ν_B

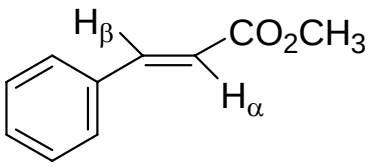
$\nu_A = (2X + Y)/2$ $\nu_B = (2X - Y)/2$

$\therefore$ **$\nu_A = (\nu_A + \nu_B)/2 + \{(\nu_1 - \nu_4)(\nu_2 - \nu_3)\}^{1/2}/2$**

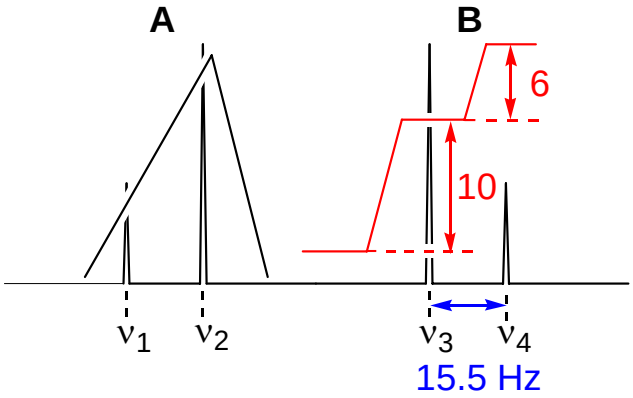
$\nu_B = (\nu_A + \nu_B)/2 - \{(\nu_1 - \nu_4)(\nu_2 - \nu_3)\}^{1/2}/2$

※ Even if one of the two protons is hidden, exact parameter can be determined.

e.g.



given $\begin{cases} \nu_3 - \nu_4 = 15.5\ \text{Hz} \\ I_3 / I_4 = 10 / 6 \end{cases}$



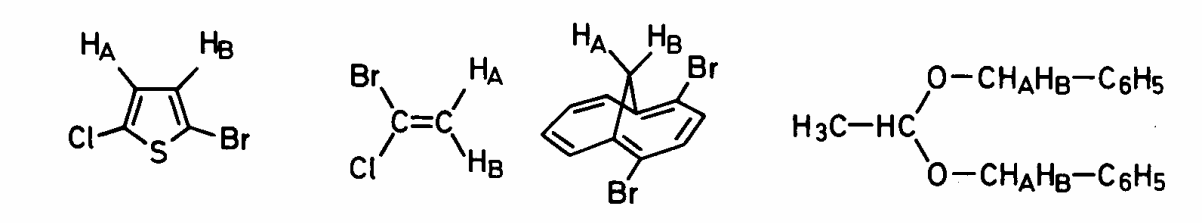
Suppose $(\nu_2 - \nu_3) = X$

Then $(\nu_2 - \nu_3) / (\nu_1 - \nu_4) = X / (X + 2J) = I_1 / I_2 = I_4 / I_3 = 6 / 10$

Since J = 15.5 Hz,

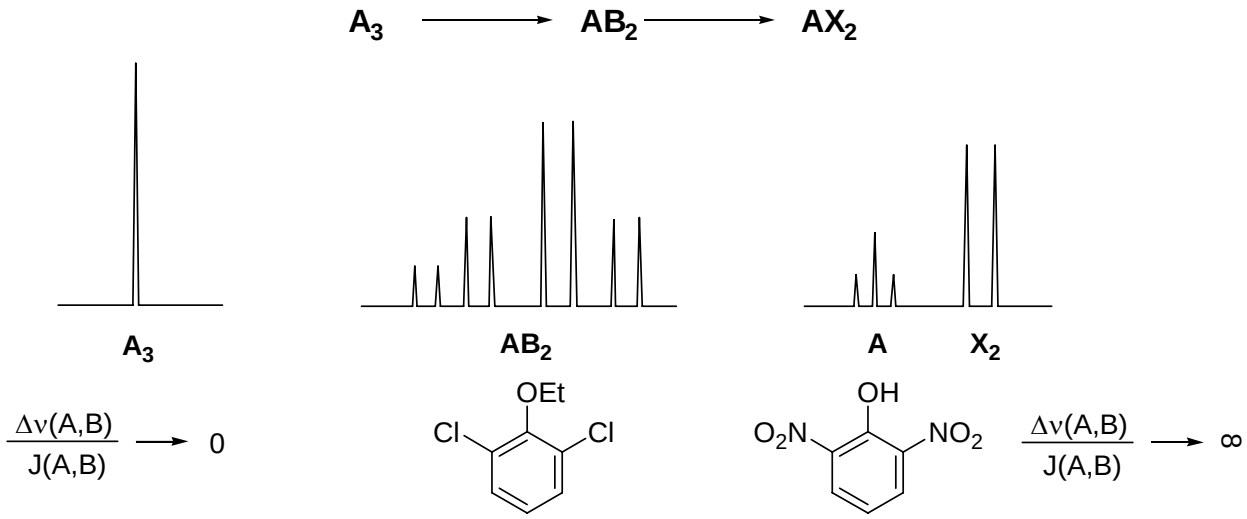
therefore X = 3J = 46.5 Hz

Some examples of the AB system

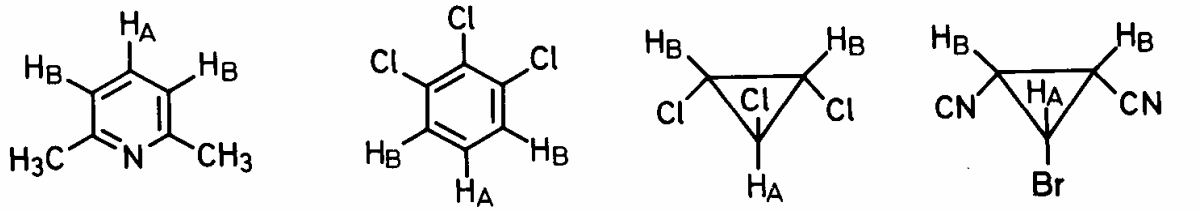


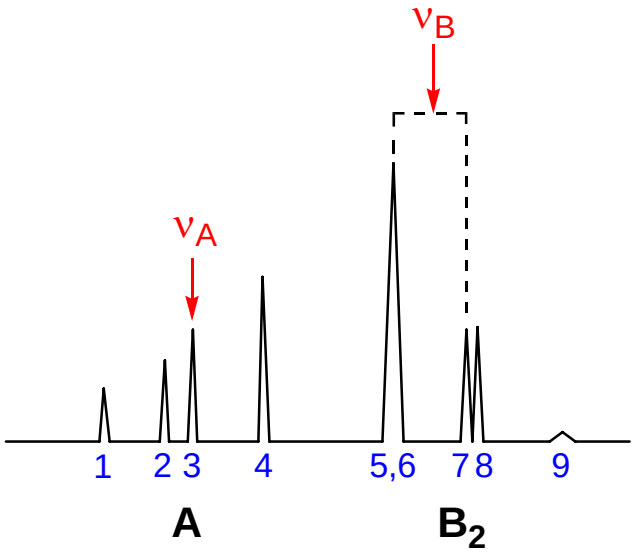
6.3 Three-Spin Systems

(1)



AB_2 System





1. $\nu_3 = \nu_A$

2. $(\nu_5 + \nu_7) / 2 = \nu_B$

3. ν_9: combination band

$2(\nu_B - \nu_A) = (\nu_9 - \nu_3) - (\nu_3 - \nu_2)$

4.

$(\nu_4 - \nu_3) + (\nu_8 - \nu_3) = (\nu_B - \nu_A) + 3\mathbf{J_{AB}}/2$

e.g.

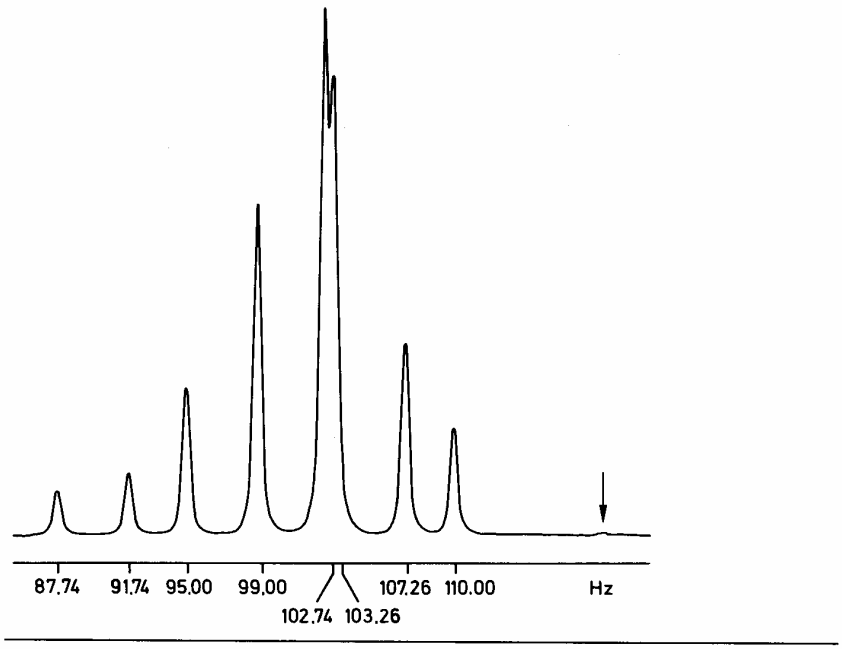
$\nu_3 = 0$, $\nu_4 = 6.6$ Hz, $\nu_5 = 19.3$ Hz, $\nu_7 = 25.6$ Hz, $\nu_8 = 27.7$ Hz

Using the equation 4, $6.6 + 27.7 = (\nu_B - \nu_A) + 3\mathbf{J_{AB}}/2$

According to the equations 1 and 2, $(\nu_B - \nu_A) = (19.3 + 25.6) / 2 = 22.5$

Therefore **$J_{AB} = 7.86$ Hz**

Exercise 5.10 Analyse the AB_2 spectrum below and determine the parameters ν_A, ν_B, and J_{AB}.



(2) ABX System: normally 12 peaks and maximum 15 peaks

$|\nu_X - \nu_A| >> J_{AX}$; $|\nu_X - \nu_B| >> J_{BX}$

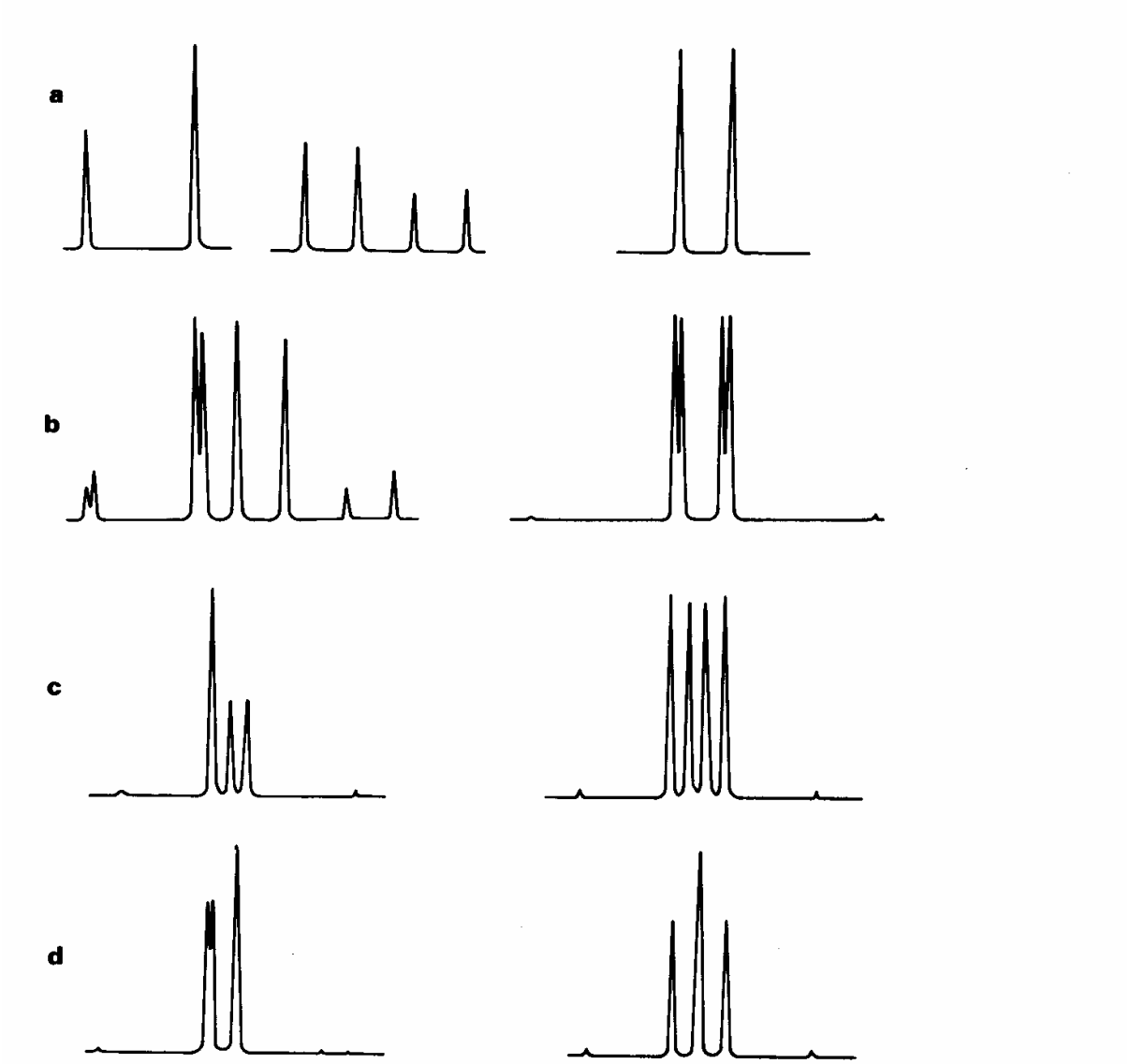
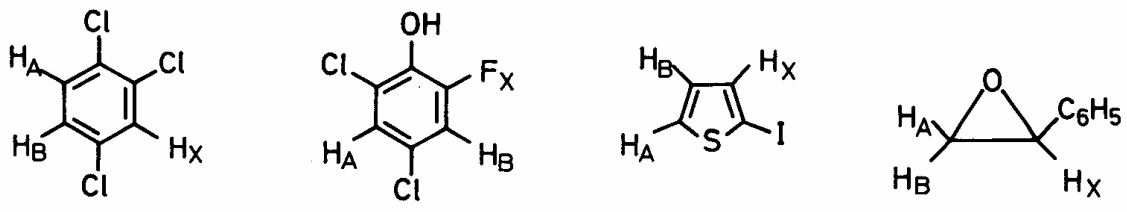
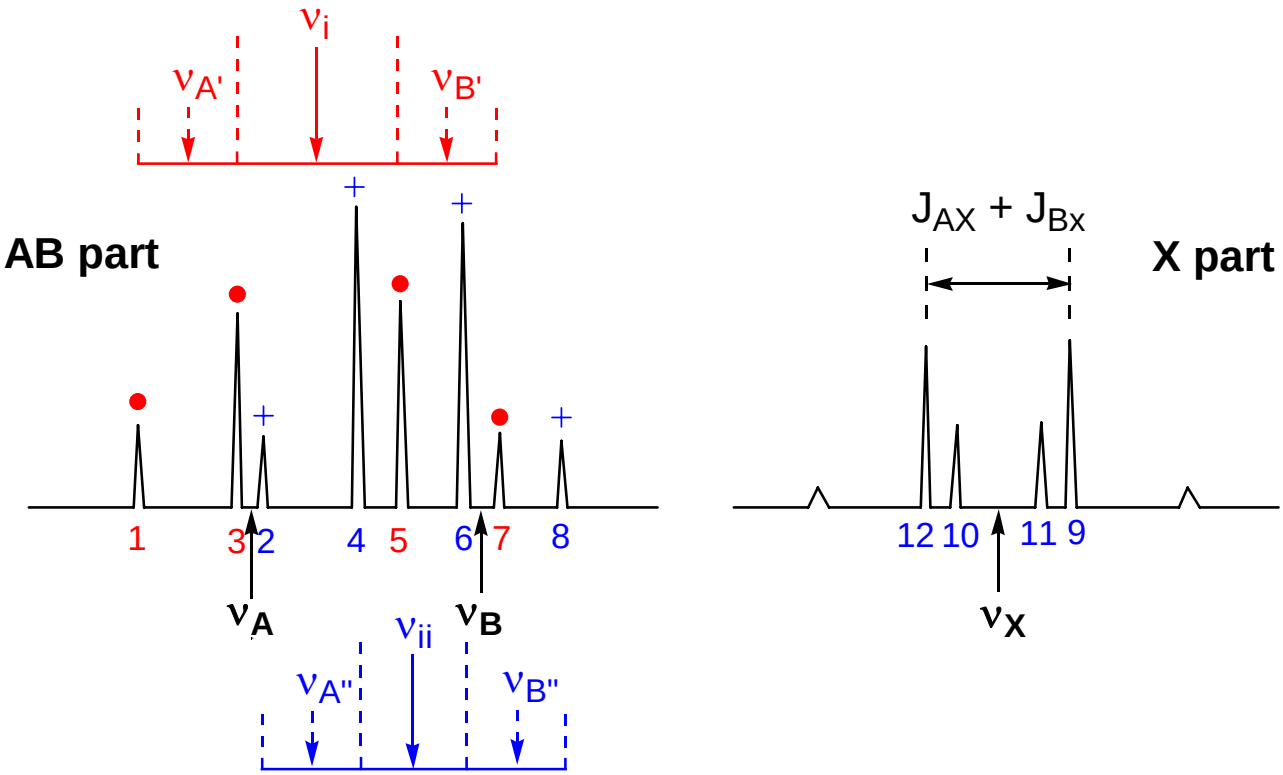


Figure 5.17 Dependence of the ABX system on the parameter $\nu_A - \nu_B$: left, the AB portion; right, the X portion. The following parameters apply in all examples: J_{AB} = 15.7 Hz; J_{AX} = 0 Hz; and J_{BX} = 7.7 Hz. The relative chemical shifts $\nu_0\delta$ (AB) amount to (a) 56.7 Hz, (b) 18.7 Hz, (c) 5.0 Hz, and (d) −0.6 Hz. Experimental data from 2-furfuryl-(2)-acrolein form the basis for the calculated spectra (after Ref. 3)

Examples of ABX system



Peaks Analysis



1. $\mathbf{J_{AB}} = \nu_3 - \nu_1 = \nu_4 - \nu_2 = \nu_7 - \nu_5 = \nu_8 - \nu_6$
2. $\nu_{12} - \nu_9 = \mathbf{J_{AX}} + \mathbf{J_{BX}}$
3. $\nu_i - \nu_{ii} = (\mathbf{J_{AX}} + \mathbf{J_{BX}}) / 2$

   ν_i, ν_{ii}: center of the two AB's
4. $\boldsymbol{\nu_A} = (\nu_{A'} + \nu_{A''}) / 2$, $\boldsymbol{\nu_B} = (\nu_{B'} + \nu_{B''}) / 2$

Analysis of **ABX** assuming **two AB sub-spectra**

ν_i, ν_{ii}: center of the two AB's

$\Delta_i = \nu_{A'} - \nu_{B'}$, $\Delta_{ii} = \nu_{A''} - \nu_{B''}$

$J_{AX} \cdot J_{BX} > 0$

$\nu_A = (\nu_i + \nu_{ii})/2 + (\Delta_i + \Delta_{ii})/4$

$\nu_B = (\nu_i + \nu_{ii})/2 - (\Delta_i + \Delta_{ii})/4$

$J_{AB} = (\nu_i - \nu_{ii}) + (\Delta_i - \Delta_{ii})/2$

$J_{BX} = (\nu_i - \nu_{ii}) - (\Delta_i - \Delta_{ii})/2$

$J_{AX} \cdot J_{BX} < 0$

$\nu_A = (\nu_i + \nu_{ii})/2 + (\Delta_i - \Delta_{ii})/4$

$\nu_B = (\nu_i + \nu_{ii})/2 - (\Delta_i - \Delta_{ii})/4$

$J_{AB} = (\nu_i - \nu_{ii}) + (\Delta_i + \Delta_{ii})/2$

$J_{BX} = (\nu_i - \nu_{ii}) - (\Delta_i + \Delta_{ii})/2$

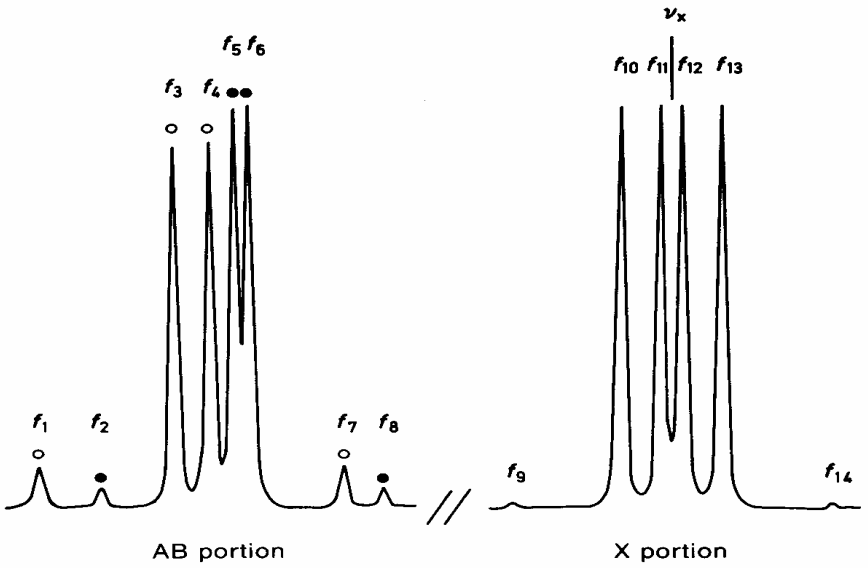


Figure 5.10 The ABX system with the parameters $\nu_0\delta$ (AB) = 5.0 Hz, J_{AB} = 8 Hz, J_{AX} = 4.2 Hz and J_{BX} = 1.8 Hz. The ab subspectra in the AB portion are identified by the open and closed circles. The parameters used are those of 2-chloro-3-aminopyridine (after Ref. 1)

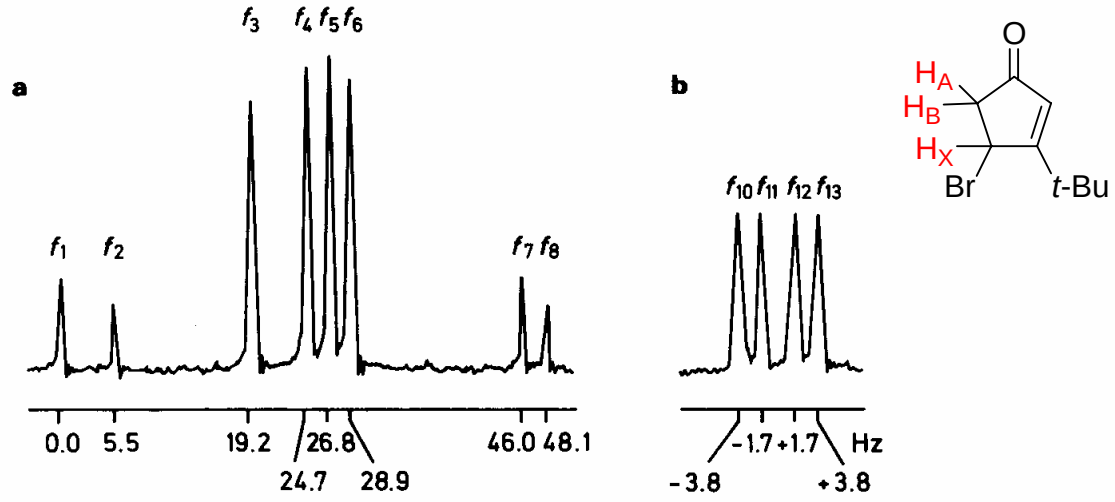


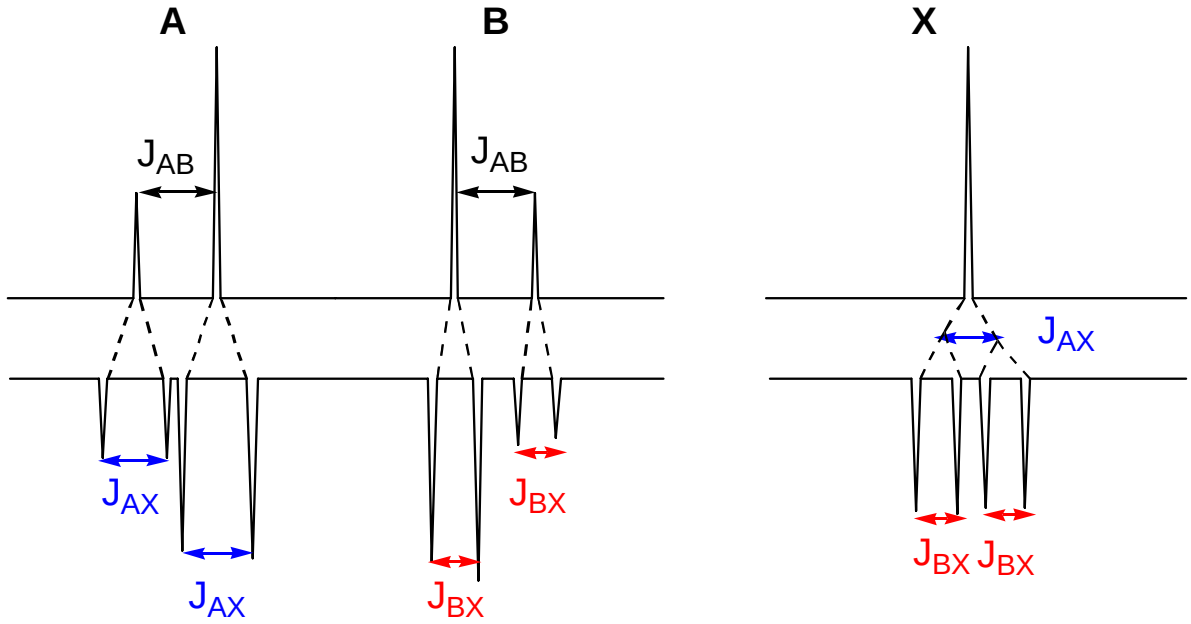
Figure 5.11 The ABX spectrum of 4-bromo-3-t-butylcyclopentene-2-one (**91**) (after Ref. 2): (a) AB portion, relative line frequencies in Hz; (b) X portion (in this case this lies at lower field); 60 MHz

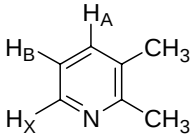
In ABX system

If ($\nu_A - \nu_B$) gets large then it becomes **AMX** system.

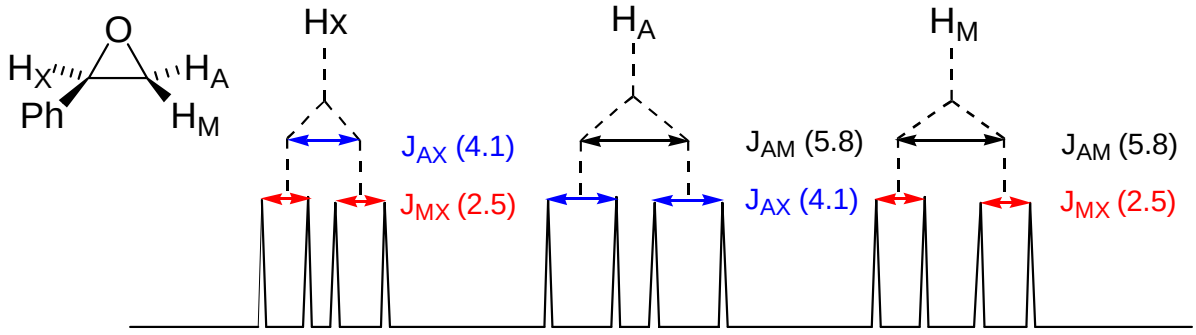
If ν_X comes close to ν_A, ν_B then it becomes **ABC** system.

One can analyze **ABX** system as **AMX** system (first-order system)

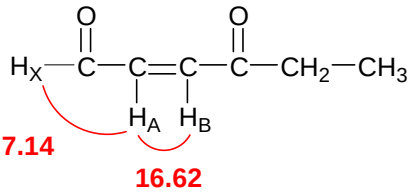


			First-order analysis J	Observed J
	(a) $J_{AX}\cdot J_{BX} > 0$	J_{AB}	7.35 Hz	7.35 Hz
		J_{AX}	4.68 Hz	5.0 Hz
		J_{BX}	1.62 Hz	1.3 Hz
	(b) $J_{AX}\cdot J_{BX} < 0$	J_{AB}	7.35 Hz	7.35 Hz
		J_{AX}	4.45 Hz	5.0 Hz
		J_{BX}	0.75 Hz	–1.3 Hz

AMX system

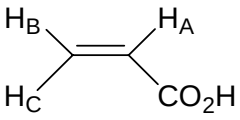


Virtual coupling



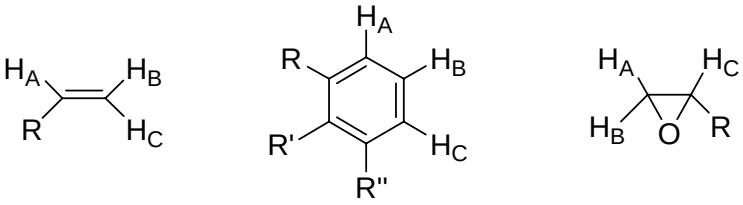
Even though H_X is coupled only to H_A, H_X consist of more than two lines (four lines)

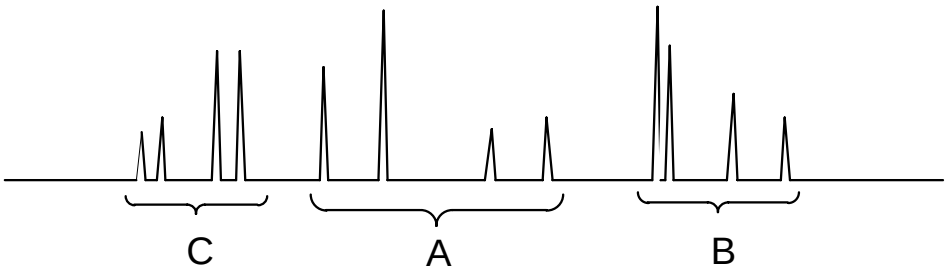
(3) ABC System: Maximum 15 lines



No simple algebraic expressions.

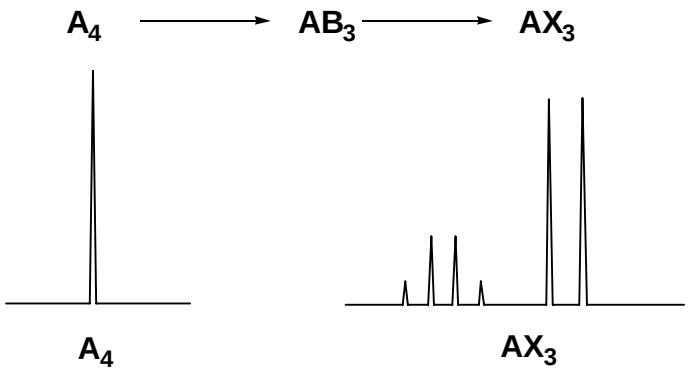
Examples



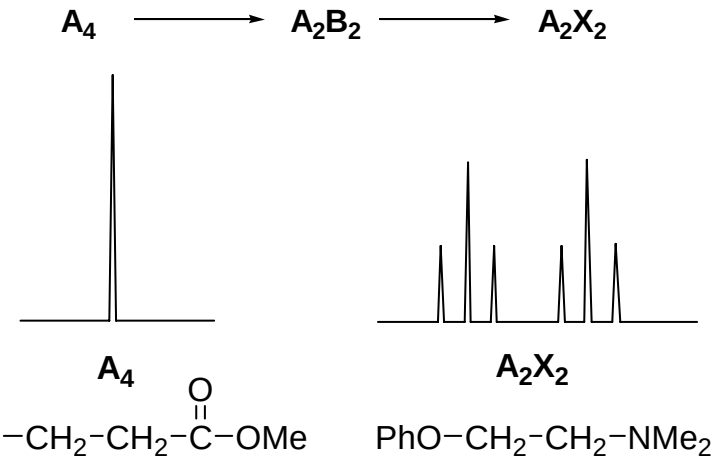


6.4 Four-Spin Systems

(1)



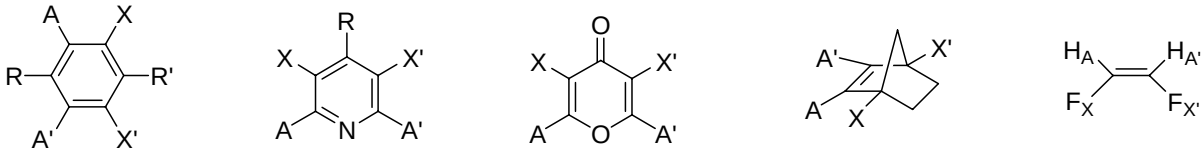
(2)



(3) **AA'XX': 24 lines**

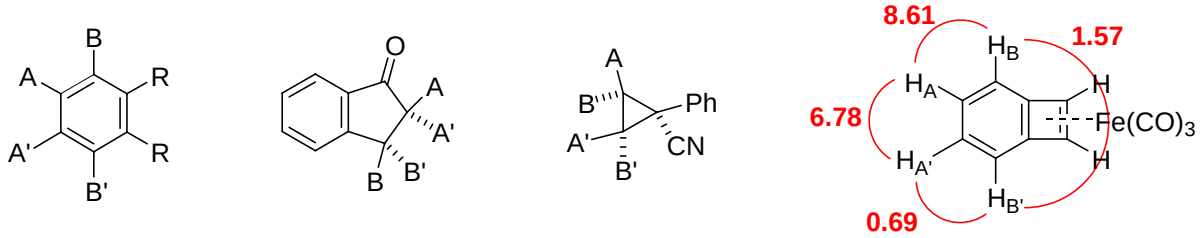
Normally 20 lines are observed

AA': Chemically equivalent but magnetically nonequivalent



(4) **AA'BB'**

If $\Delta\nu_{AX}$ becomes small, AA'XX' becomes AA'BB'. 24 lines are observed.

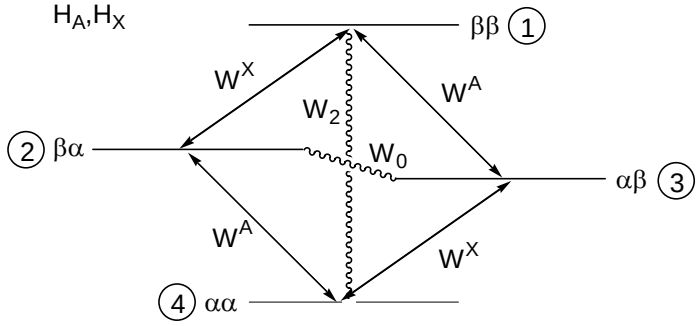


7. Nuclear Overhauser Effect (NOE)

Change in NMR intensity via change in Boltzmann distribution of a nuclear spin by a **dipolar mechanism upon saturation of a second interacting nuclear spin.**

Dipolar mechanism maintains the relaxation (T_1), thereby increasing ground state population → increased intensity.

Explanation



Energy levels of an AX spin system

W^A: transition probability of spin A
W^X: transition probability of spin X
W_2: transition probability between ① and ④ (double quantum jump) or relaxation – important when T_1^{DD} is important.
W_0: transition probability between ② and ③ (zero quantum jump) or relaxation.

Irradiation of X will saturate the transition ②→① and ④→③.
Therefore $P_1 = P_2$, $P_3 = P_4$ (P: population of each energy level).

Assuming that
Before irradiation, $P_2 \approx P_3 = C$, $P_2 - P_1 = P_4 - P_3 = \Delta$

Before irradiation	After irradiation
$P_1 = C - \Delta$	$P_1 = C - \Delta/2$
$P_2 = C$	$P_2 = C - \Delta/2$
$P_3 = C$	$P_3 = C + \Delta/2$
$P_4 = C + \Delta$	$P_4 = C + \Delta/2$
$\therefore$ **$P_4 - P_1 = 2\Delta$**	$\therefore$ **$P_4 - P_1 = \Delta$**

Now, **W_2** process increases P_4 and decrease P_1, thereby restoring the population difference to its equilibrium value, which enhances transition of A (increased intensity of nuclei A).
W_2 is very effective when T_1^{DD}(dipole-dipole) predominates.
There is a fractional enhancement of the A signal.

$$f = \frac{W_2 - W_0}{2W^A + W_2 + W_0}\left(\frac{\gamma_X}{\gamma_A}\right)$$

maximum limit: $\left(\frac{\gamma_X}{\gamma_A}\right)\Big/2$ saturated or irradiated nuclei / observed nuclei

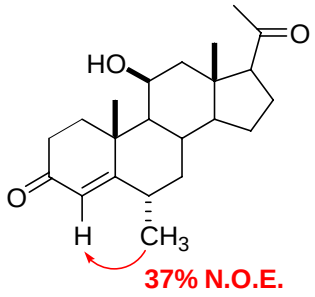
For proton, maximum N.O.E. = 50%; for carbon maximum N.O.E. = 200%

N.O.E. = $1/(A \cdot r_{AB}^{6})$

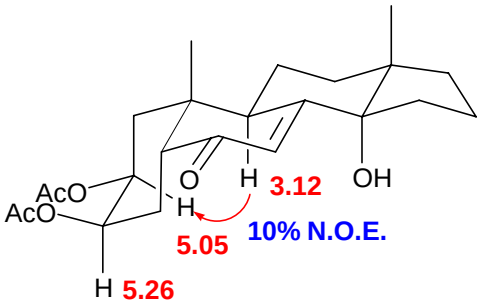
Effective N.O.E. can be obtained within the inter-atomic distance of **3Å**.

Examples

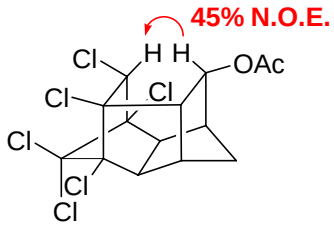
①



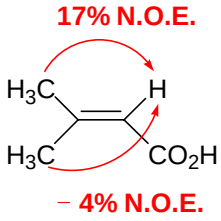
②



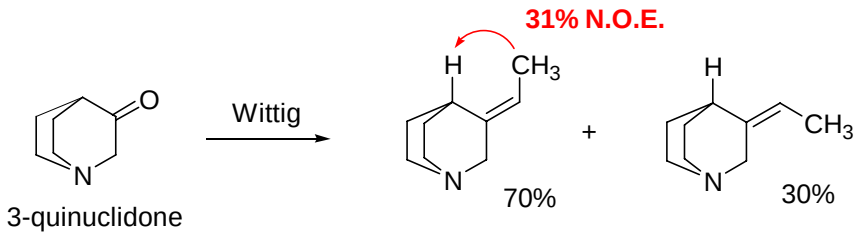
③



④

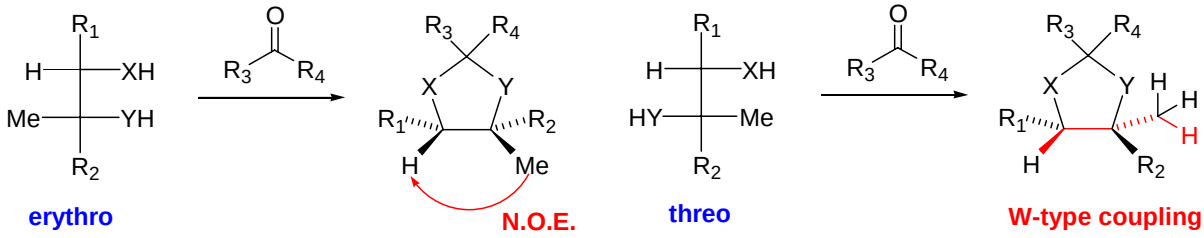


⑤

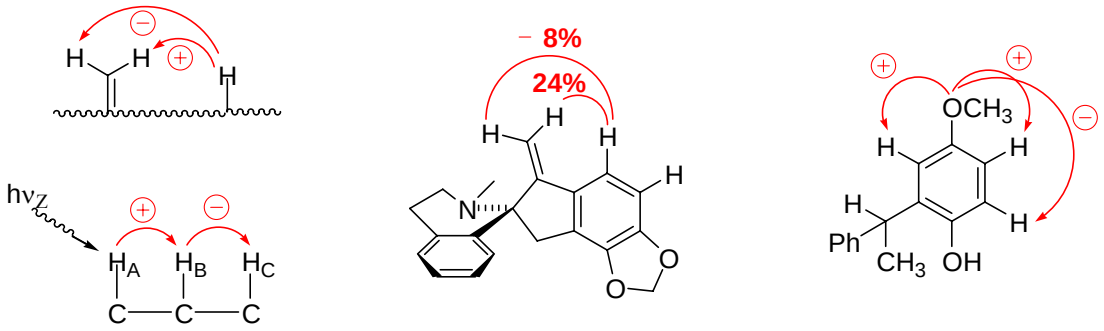


DMSO(d_6) is the best solvent for N.O.E. measurement. Solvent should be degassed, and preferably be sealed.

⑥ Threo & erythro isomers of α-glycols (*J. Am. Chem. Soc.* **1972**, *94*, 2865).



Negative N.O.E. in multi-spin system



Exercise 2.13. Figure 2.28 shows the 80 MHz ^{1}H n.m.r spectrum of 2,4-dinitrophenyl-2-pyridylsulphide. Assign the protons to the structural formula given and estimate the coupling constants.

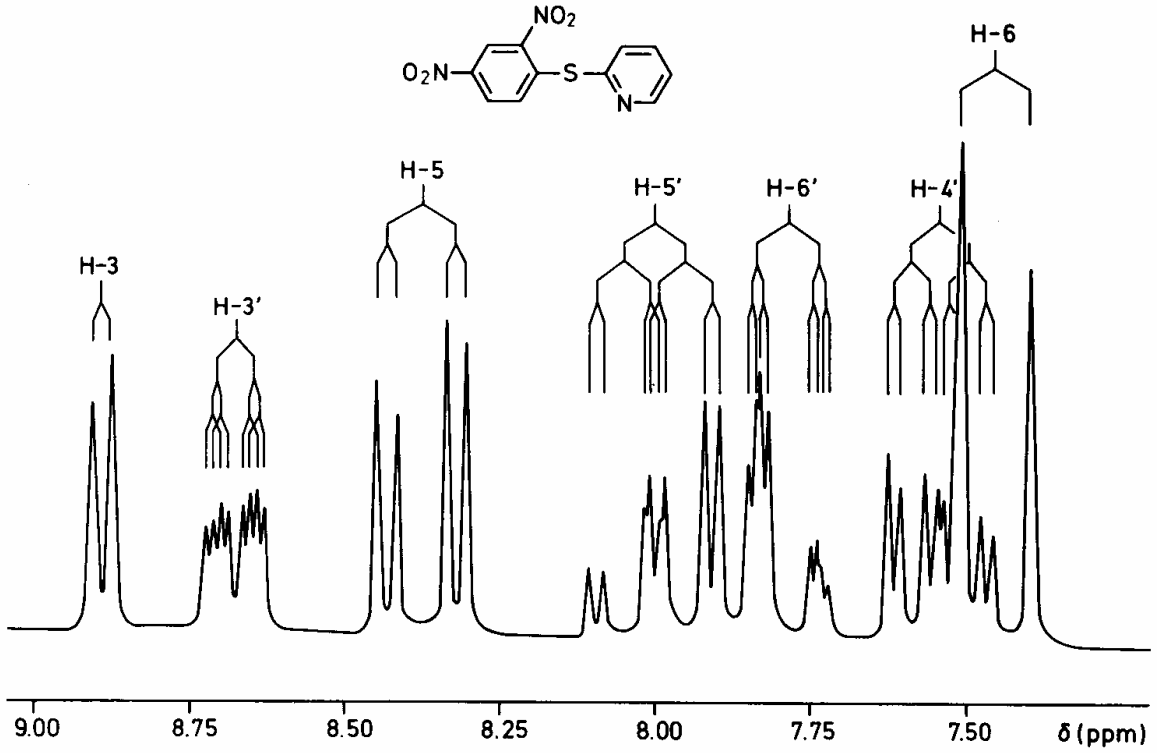


Figure 2.28 80 MHz ^{1}H n.m.r. spectrum of 2,4-dinitrophenyl-2-pyridylsulphide