2 NMR Spectrum

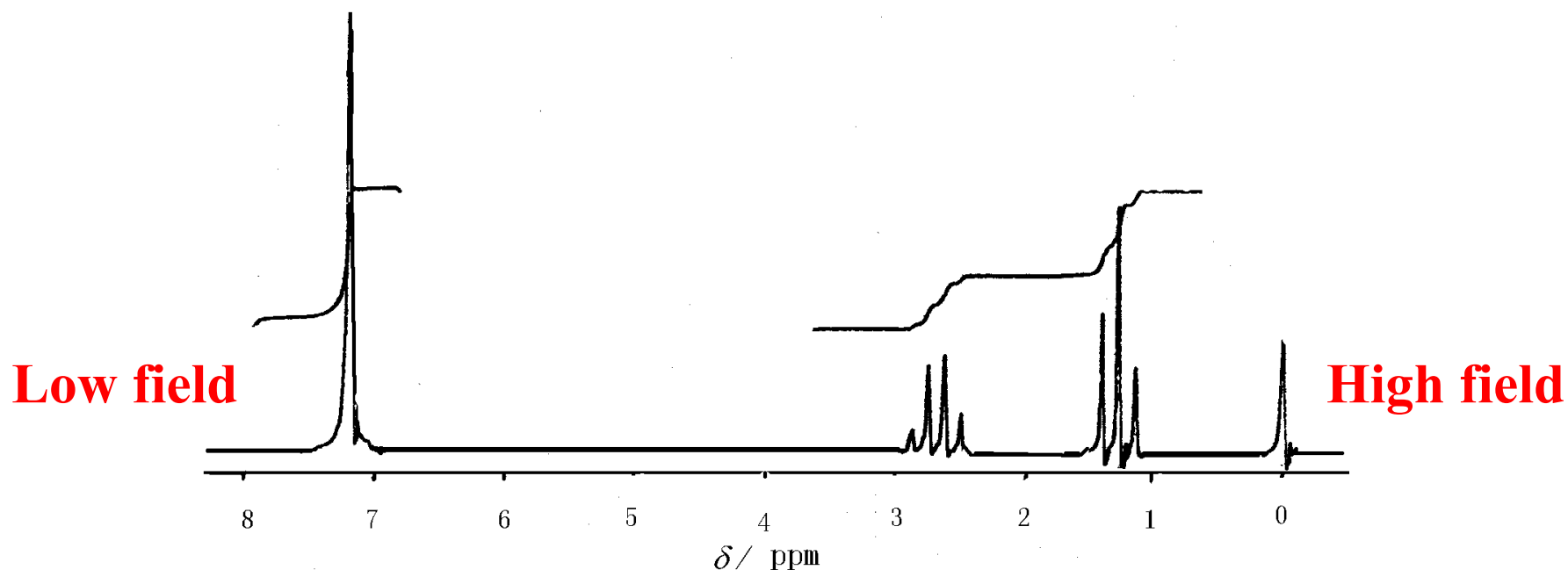**Low field**   **High field**

- Peak position: Chemical Shift (δ)
- Peak shape: peak splitting from spin-coupling
- Peak area: Integral curve height $\propto$ the number of protons

20:06

1

2.1 Chemical shift of ^{1}H

1．Factors that affects chemical shift

2. Chemical shifts of different ^{1}H

Carboxylic acid

aromatics

XCHn   **CCHn**

14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

aldehyde

alkene

**alkyne**

1. Factors that affect the chemical shift

(1) Induction effect

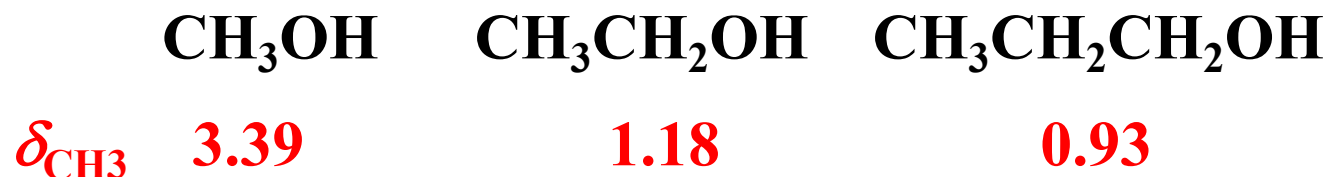Chemical shift is generated from the anti-magnetic shield effect of the electron cloud.

- **Electronegativity of adjacent atoms**

CH_3X	CH_3F	CH_3OCH_3	CH_3Cl	CH_3Br
δ	4.26	3.24	3.05	2.68
	4.0	3.5	3.1 2.8	

CH_3X	CH_3CH_3	CH_3H	CH_3Li
δ	0.88	0.2	- 1.95
	2.5	2.1	0.98

- **Numbers of adjacent electronegative atoms**

$$CH_3Cl \qquad CH_2Cl_2 \qquad CHCl_3$$

$$\delta \qquad 3.05 \qquad 5.30 \qquad 7.27$$
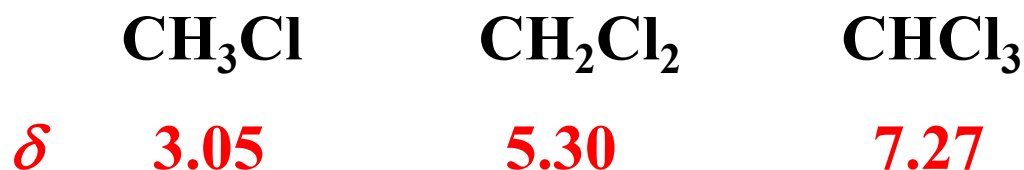
- **Numbers of chemical bonds from electronegative atoms**

$$CH_3OH \qquad CH_3CH_2OH \qquad CH_3CH_2CH_2OH$$

$$\delta_{CH3} \quad 3.39 \qquad 1.18 \qquad 0.93$$

(2) Hybridized state of adjacent C

S content ↑

sp^3

s + **p** hybridize → sp^2

sp
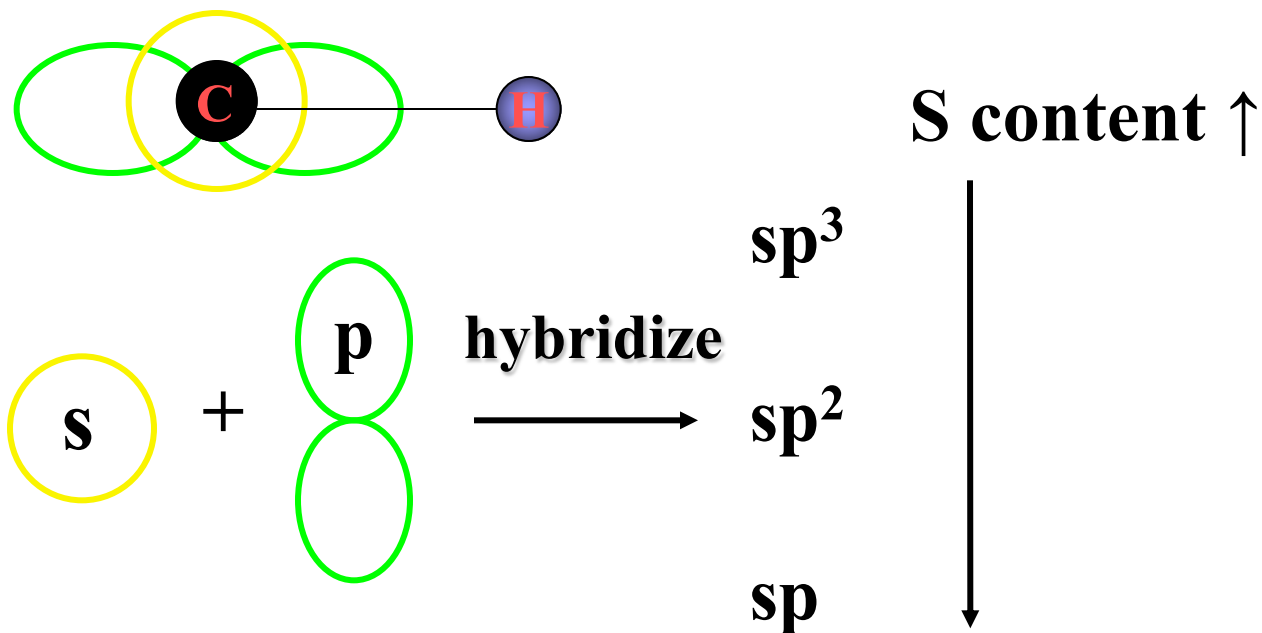
**ethane 0.88 ; ethene 5.23 ; ethyne 2.88**

(3) Anisotropy

For non-spherical symmetric electron clouds, e,g,

π electron，will induce an additional magnetic field that performs anisotropy:

If the induced magnetic field is in the opposite direction with the external magnetic field, the external magnetic field with be weakened, which is defined as **anti-magnetic shielding effect (+). High Field**

If the induced magnetic field is in the same direction with the external magnetic field, the external magnetic field with be enhanced, which is defined as **para-magnetic shielding effect (-). Low Field**

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- **Anisotropy of Aromatics**
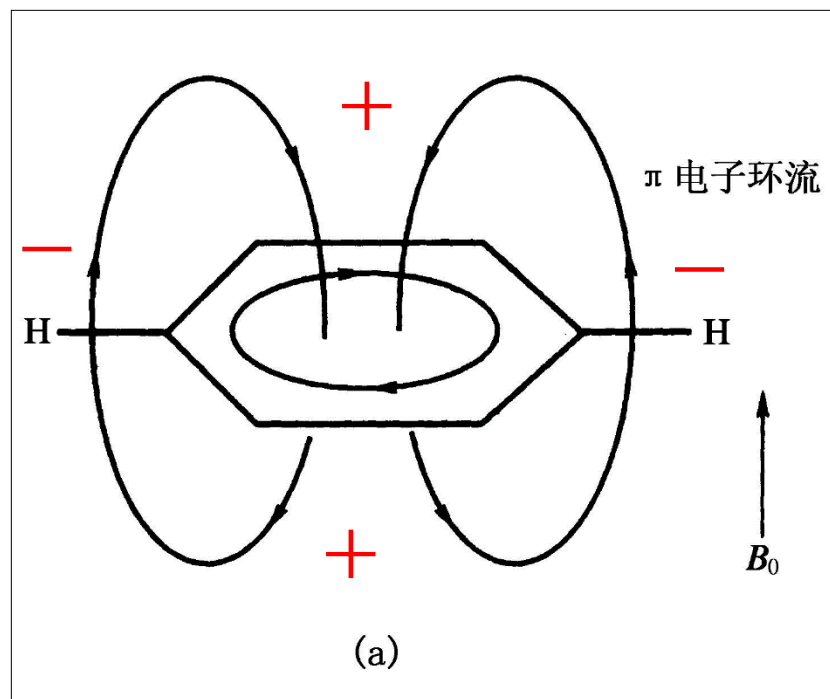
δ **= 7.27**
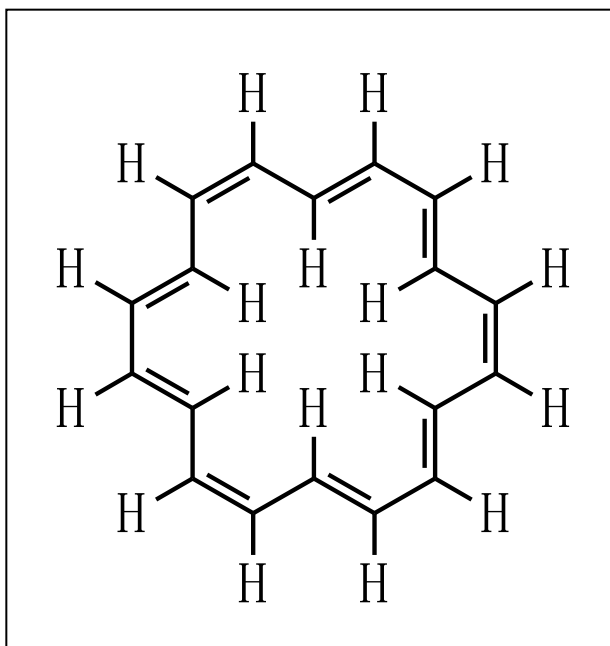
[18]Annulene

- **12 exo-cyclic H, para-magnetic shielding effect**
  $\delta_{环外氢} \approx$ **8.9**

- **6 endo-cyclic H, anti-magnetic shielding effect**
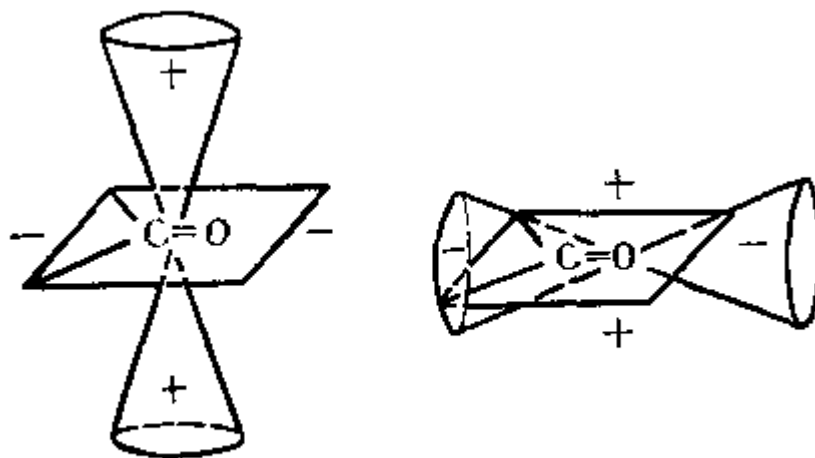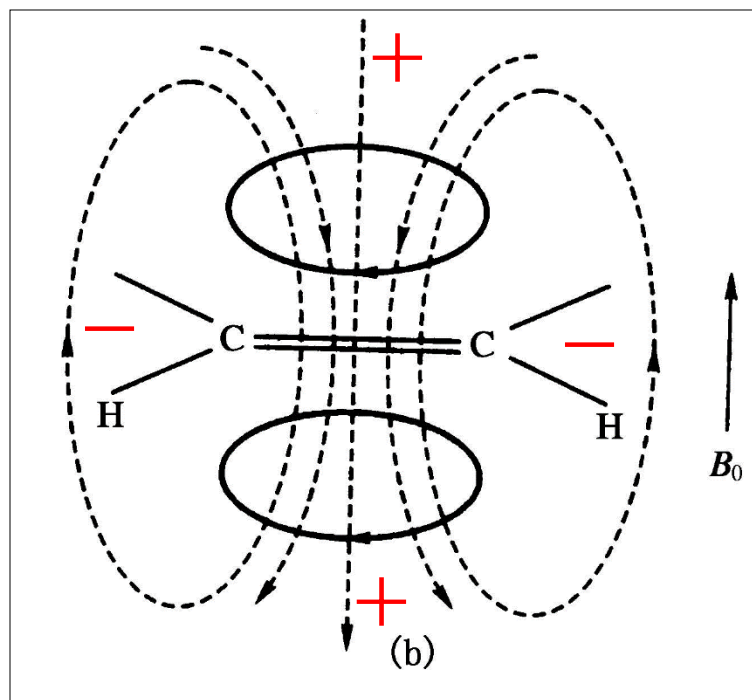 $\delta_{环内氢} \approx$ **-1.8**

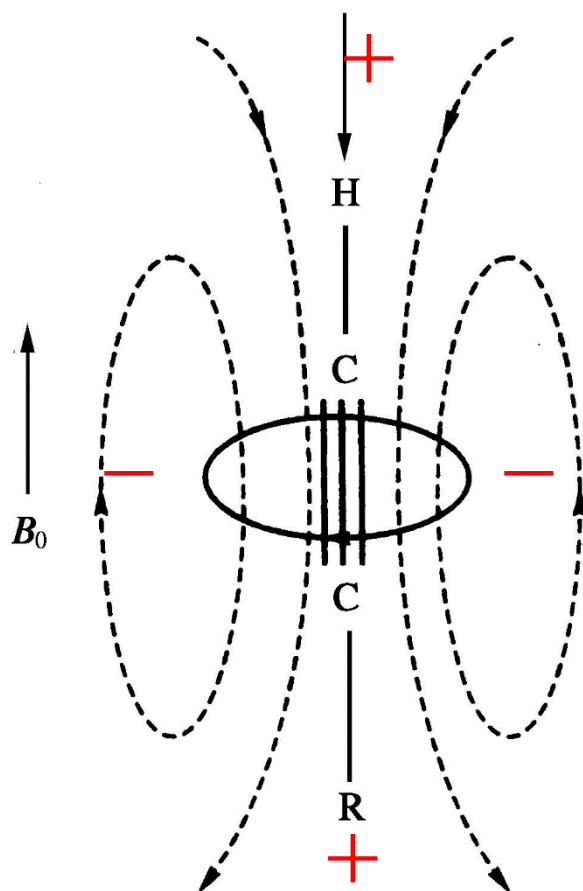# Anisotropy of Carbonyls

图2-5 羰基的屏蔽作用

H of aldehyde is in the para-magnetic shielding area together with the induction effect, thus δ = 9-10
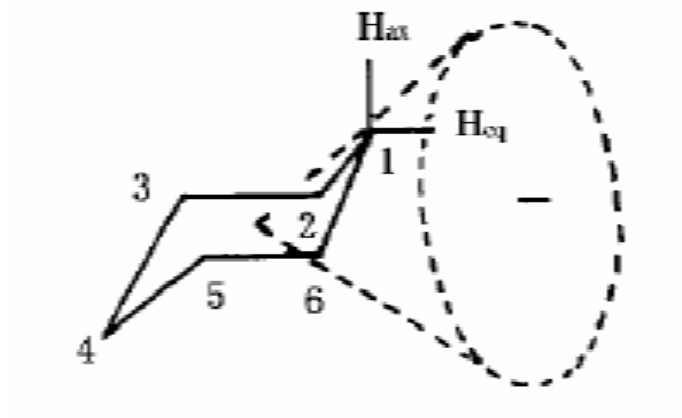
• **Anisotropy of C-C double bonds**

$$\delta = 5.23$$

• **Anisotropy of C-C triple bond**

anti-magnetic shielding + sp hybridization lead to δ **= 2-3** for H on the alkynes.

- **Anisotropy of C-C single bond**

Upright H（Hax）is in the anti-magnetic shielding area，high δ

Equatorial H（Heq）is in the para-magnetic shielding area，low δ

(4) Van der Waal Effect

The electron clouds will repel each other when two protons are very close. Magnetic shielding effect would be weakened due to the reduction of electron cloud density, **causing** δ **to shift to the low field.**

(5) Hydrogen Bonding
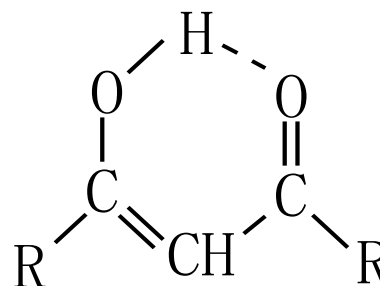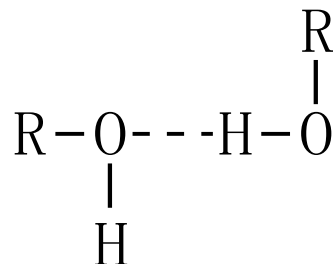
- δ moves to the low field

- δ is not constant , δ is between $0.5 \sim 5$ for alcohol OH , $4 \sim 7$ for phenol OH.

- Hydrogen bonding is an exothermic process; High temperature, low hydrogen bonding, δ shifts to the high field；

- In non-polar solvent, lower concentration, lower hydrogen bonding, δ shifts to the high field；

- Change temperature/concentration to determine the position for OH and NH；

- Intramolecular hydrogen bonding, δ always in the low field.

Ethanol

（a） 10%（wt/vol） （b） 5%（wt/vol） （c） 0.5%（wt/vol）

溶剂：CCl₄ 温度：40℃ 仪器：60兆赫
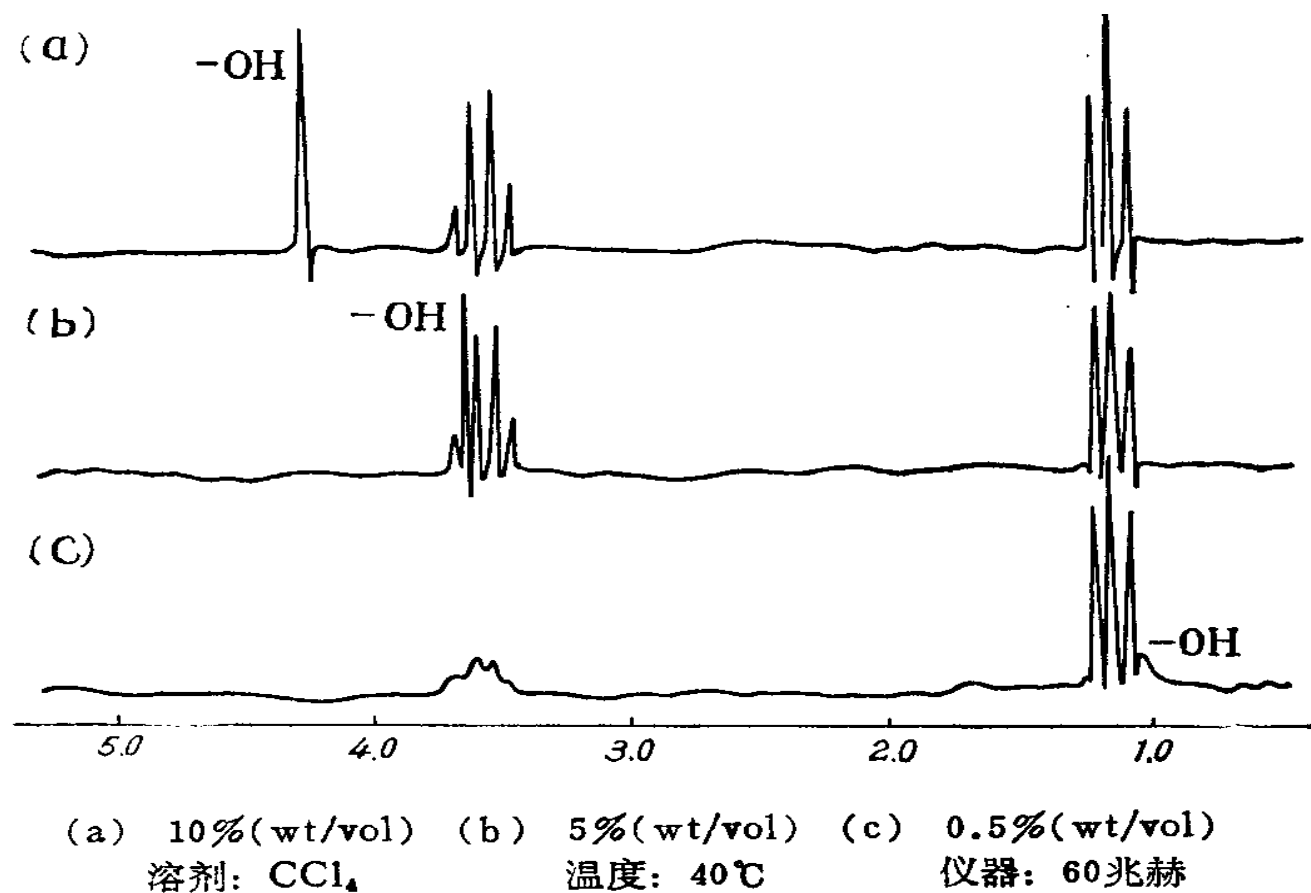
(6) Solvent Effect

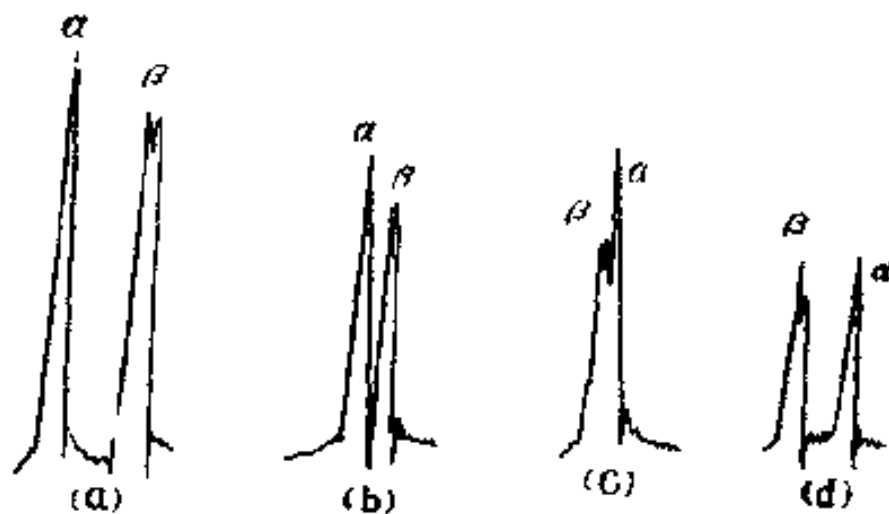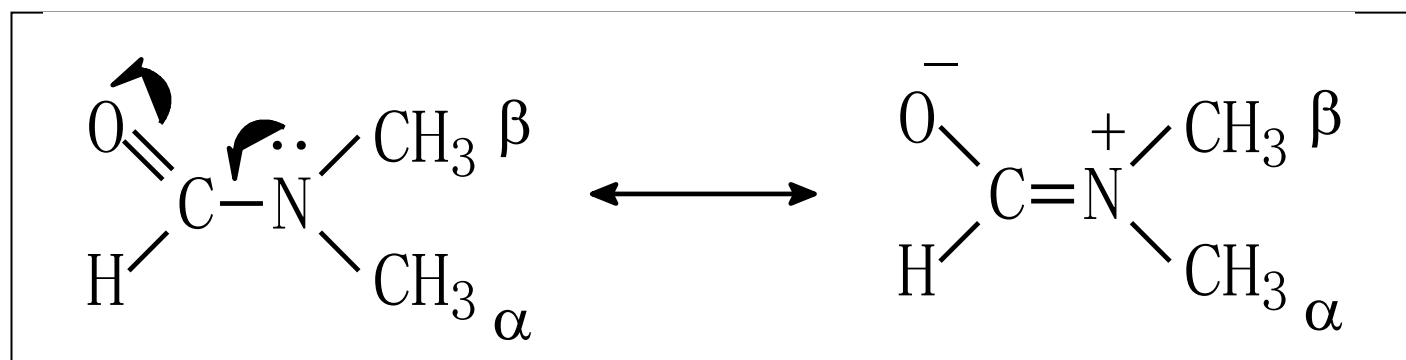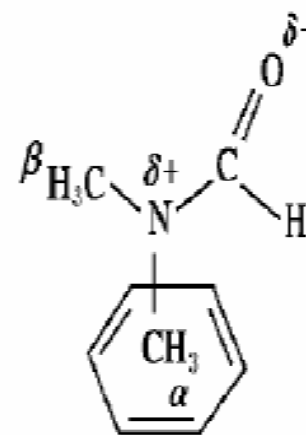图2-10 溶剂对二甲基甲酰胺甲基峰的影响
(a) 在纯 CDCl₃ 中   (b)～(d) 逐步加入苯
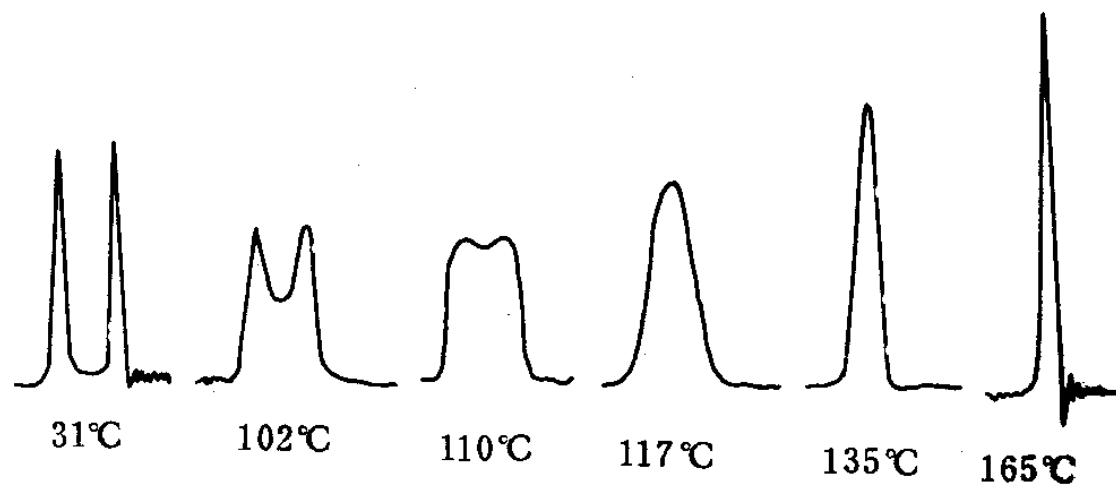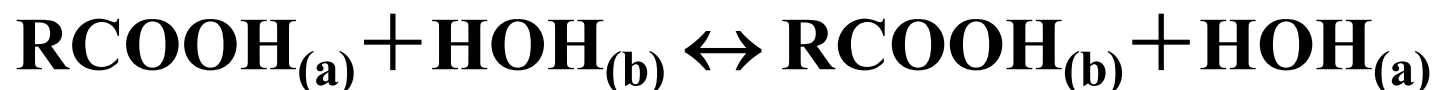
苯环与 N,N-二甲基甲酰胺形成的复合物

^{1}**H-NMR (500 MHz, CDCl$_3$):** δ (ppm) = 7.88 (br s, 2 H, CH_{ar}), 7.70 (br s, 1 H, CH_{ar}), 7.38 (d, ^{3}J$_{H,H}$ = 8.8 Hz, 2 H, CH_{ar}), 7.18 (s, 1 H, CH_{th}), 6.84 (s, 1 H, CH_{th}), 6.70 (d, ^{3}J$_{H,H}$ = 8.8 Hz, 2 H, CH_{ar}), 2.97 (s, 6 H, NCH_3), 2.86 (ps t, ^{3}J$_{H,H}$ = 7.4 Hz, 4 H, CH_2), 2.10 (ps p, ^{3}J$_{H,H}$ = 7.4 Hz, 2 H, CH_2), 2.03 (s, 3 H, CH_3), 2.00 (s, 3 H,

(7) Exchange reaction

N,N-dimethyl formamide

31℃   102℃   110℃   117℃   135℃   165℃

Intermolecular exchange

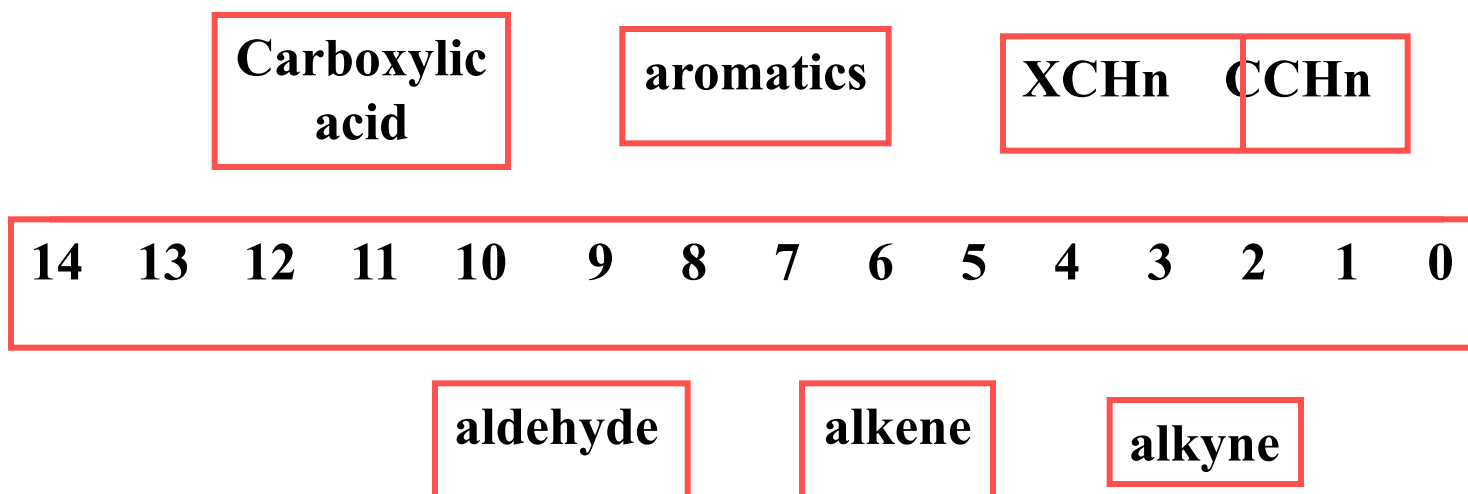$$\textbf{RCOOH}_{(a)} + \textbf{HOH}_{(b)} \leftrightarrow \textbf{RCOOH}_{(b)} + \textbf{HOH}_{(a)}$$

Only one average H signal can be detected on the NMR spectrum, the position of which is depend on the molar ratio of carboxylic acid and water.

$\delta_{obs} = N_a \cdot \delta_a + N_b \cdot \delta_b$

2.2 ¹H Chemical Shift for different compounds

Carboxylic acid	aromatics	XCHn	CCHn

14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

aldehyde	alkene	alkyne

Alkanes

Methyl, Methylene, Methylidyne

Shoolery equation :

$$\delta = 0.23 + \sum \sigma$$

Alkene/Alkyne

Alkynes

$\delta = 1.6 - 3.4$

化合物	δ （ppm）	化合物	δ （ppm）
H–C≡C–H	1.80	C≡C–C≡C–H	1.75～2.42
R–C≡C–H	1.73～1.88	H_3C–C≡C–C≡C–C≡C–H	1.87
Ar–C≡C–H	2.71～3.34	R–C(R)(R)–C≡C–H	2.20～2.27
C=C–C≡C–H	2.60～3.10	RO–C≡C–H	～1.30
–C(=O)–C≡C–H	2.13～3.28	CH_3–NH–C(=O)–CH_2–C≡C–H	2.55

Alkene

Tobey-Simon equation：

$$\delta = 5.25 + Z_{same} + Z_{trans} + Z_{cis}$$

Aromatics

$$\delta = 7.27 - \sum Z_i$$

6.30 6.22 7.04 7.75 6.47 8.04
7.40 6.68 7.29 7.38 7.29 7.51
            8.29   9.10

ß»à« ßÁ¿© àç·Ô ßÁà¤ ßÅßá à-ßø
£¨CDCl$_3$) £¨CDCl$_3$) £¨CDCl$_3$) (DMSO) (DMSO) (DMSO)
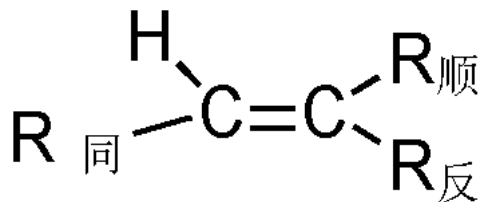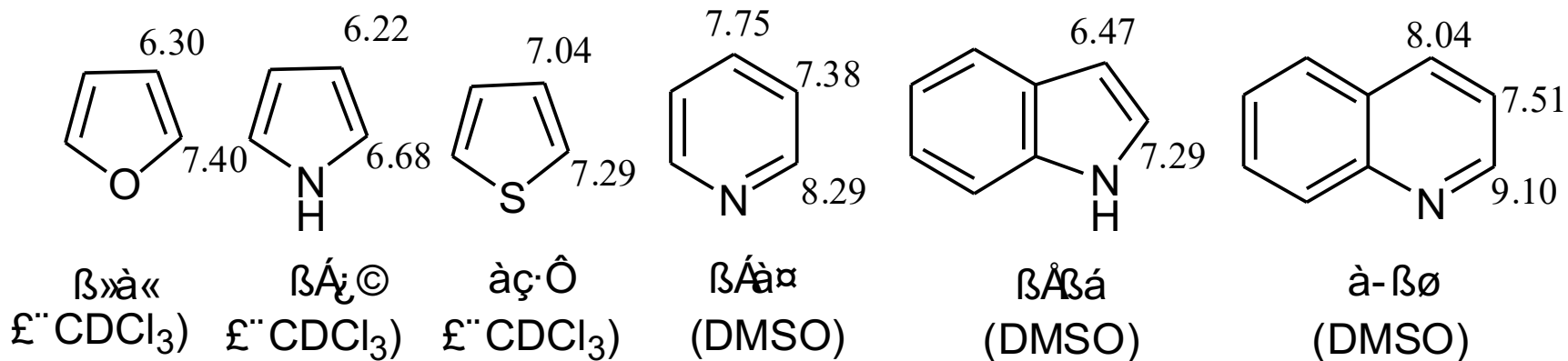
Active Hydrogen

- -OH, -NH, -COOH, -SH

- Form hydrogen bonding/exchange reaction. Influenced by temperature, concentration and solvent.

- Discriminated by D_2O exchange

δ of Activate Hydrogens

Compound	δ	Compound	δ
Alcohol	0.5-5.5	Aromatic thiol	3-4
Phenol (intramolecular hydrogen bond)	10.5-16	Sulfonic acid	11-12
Phenol	4-8	Amine	0.4-3.5
Ene-ol(intramolecular hydrogen bond)	15-19	Aromatic amine	2.9-4.8
Carboxylic acid	10-13	Primary amide	5-6.5
Oxime	7.4-10.2	Secondary amide	6-8.2
Thiol	0.9-2.5	Aromatic amide	7.8-9.4

3.   General rules for coupling and first-order spectrum
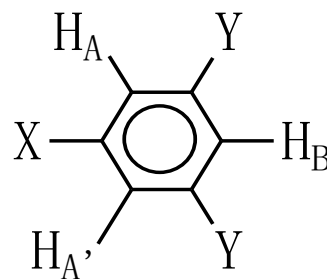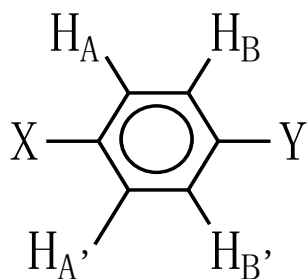
3.1 Nucleus equivalence

- **Chemical equivalence (different peaks)**

- **Magnetic equivalence (different splittings)**
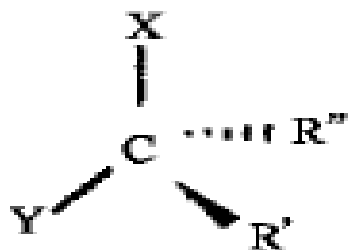
Chemical equivalence

Two atoms or groups are chemically equivalent if two atoms or radicals are exchanged by rapid rotation or symmetry.

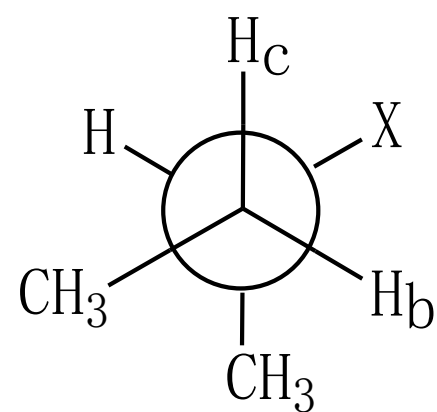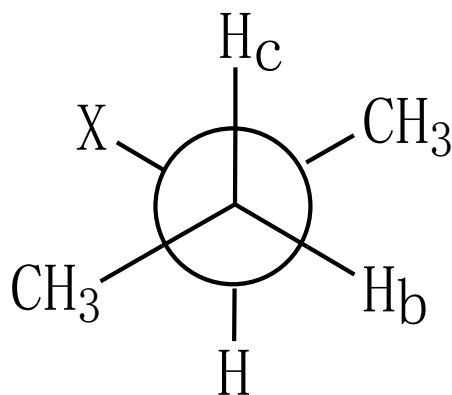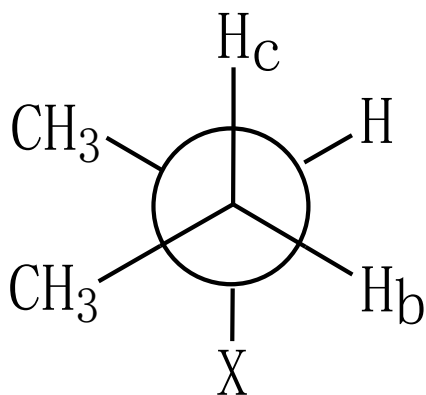# Symmetry exchange

Symmetry axis exchange

Symmetry plane exchange

■ **General rules:**

☐ Methyl H or same groups on saturated C are chemically equivalent ;

☐ H of the fixed CH_2 on the ring are chemically inequivalent ;

☐ H of CH_2 attached to the chiral C are chemically inequivalent ;

☐ H/same groups on the same atom whose single bond cannot rotate freely are chemically inequivalent.

CH$_2$ attached to the chiral C

$$\overset{a}{CH_3} - \overset{\overset{b}{H}}{\underset{\underset{c}{H}}{C}} - \overset{d}{CH} - \overset{f}{\underset{O}{C}} - O - CH_2 - \overset{g}{CH_3}$$

with CH$_3$ (labeled e) on the CH, and O double bonded to C.
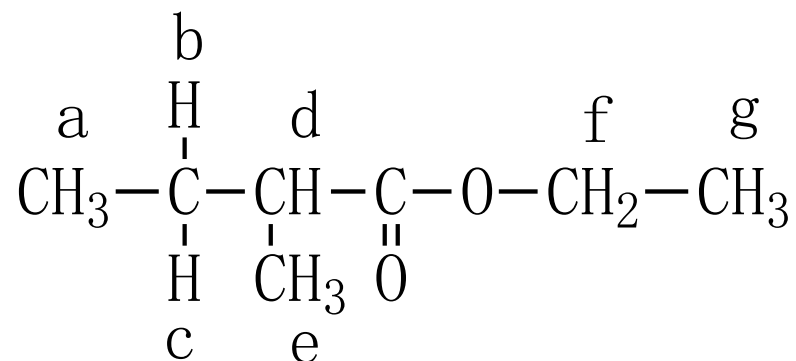
- One NMR signal for chemically equivalent atoms.

- Different NMR signal numbers are corresponding to different chemically inequivalent atoms, respectively.

e.g. 1 : C$\underline{H}_3$-O-C$\underline{H}_3$ **1 signal**

e.g. 2 : C$\underline{H}_3$-C$\underline{H}_2$-Br   **2 signals**

e.g. 3 : (C$\underline{H}_3$)$_2$C$\underline{H}$C$\underline{H}$(C$\underline{H}_3$)$_2$ **2 signals**

e.g. 4 : C$\underline{H}_3$-C$\underline{H}_2$COO-C$\underline{H}_3$ **3 signals**
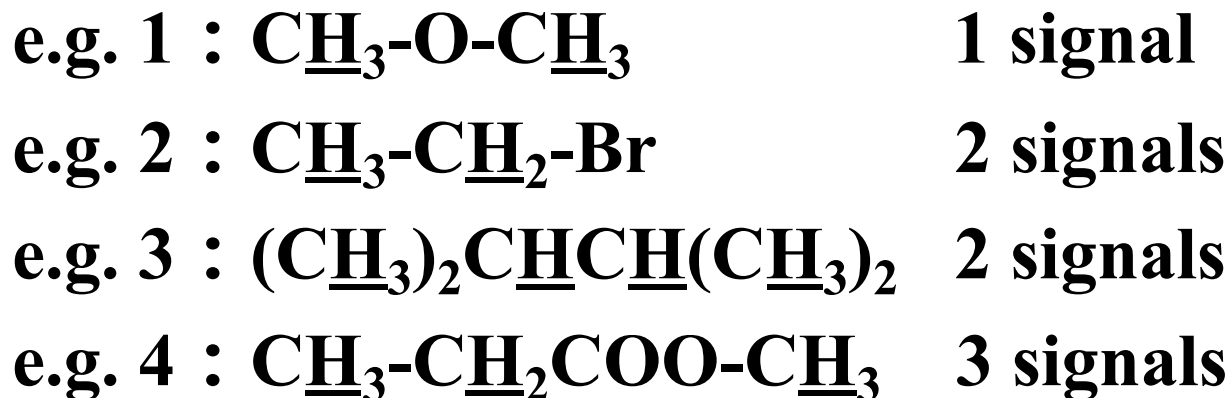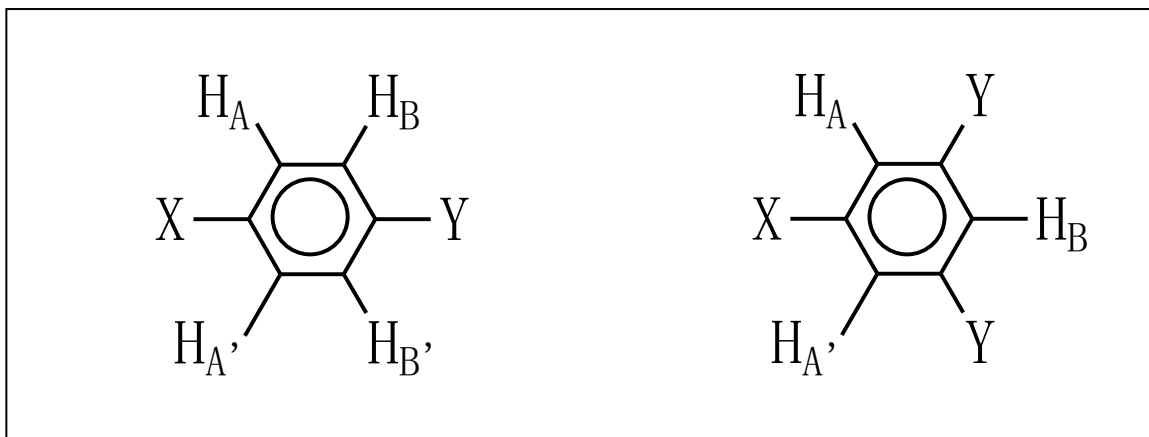
Magnetic equivalence

- Same chemical shift; same coupling splitting and constant.

1,1-difluoroethene   1-chloroethane

3.2 General rules for coupling

- **Coupling with n magnetic equivalent nuclei, splitting to $2nI+1$ peaks , for ^{1}H,^{13}C ($I=1/2$) , then $n+1$ peaks , "$n+1$ rule" 。**

- **Coupling with n magnetic equivalent nuclei and another m magnetic equivalent nuclei , splitting to $(n+1)(m+1)$ peaks.**

- **Intensity of the multiple coupling peaks can be presented as the coefficient of $(a+b)^n$ expansion, n is the number of magnetic equivalent nucleus ;**

- **The center of the splitting peaks is the chemical shift δ. The splitting between the peaks is defined as splitting constant J (Hz) ;**

- **There is coupling between magnetic equivalent nuclei, yet no splitting.**

3.3 First-order spectrum

- **Spectrum complied to the above rules is defined as first-order spectrum.**

- **$\Delta \nu / J > 6$, $\Delta \nu$ is the difference of coupling constant of two coupling nuclei.**

- **$\Delta \nu / J < 6$, not first-order spectrum which is not complied to the rules.**

3.4 Factors that affect the coupling constant

- **Same carbon coupling（$^2J_{\text{H-C-H}}$或 ^2J ）**

- **Adjacent carbon coupling（$^3J_{\text{H-C-C-H}}$或 ^3J ）**

- **Distant coupling**

(1) Same carbon coupling $(\ ^2J \ )$

^2J is a minus number, e.g. :

☐ **Hexane $(\ sp^3 \ )$ $^2J \ = \ -$ 12.6 Hz**

☐ **End-ene $(= CH_2) \ (\ sp^2 \ ) \ \ ^2J = -0.5 \sim -3$ Hz**

(2) Adjacent carbon coupling（^3J）

- **sp^3杂化体系**

  - ☐ **Free rotating single bond，$^3J \approx 7$ Hz。**

  - ☐ **Fixed conformation，$^3J = J_0\cos^2\theta + C$**

    （ 0°<θ<90° ）

  - ☐ $^3J = J_{180}\cos^2\theta + C$ **（ 90°<θ<180° ）**

  - ☐ $J_0: \theta = 0°$ **,** $J_{180}: \theta = 180°$

- **Alkene ^3J: *trans* $\theta = 0°$；*cis* $\theta = 180°$; $^3J_{trans} > ^3J_{cis}$**

- **More electronegativity, lower J.**
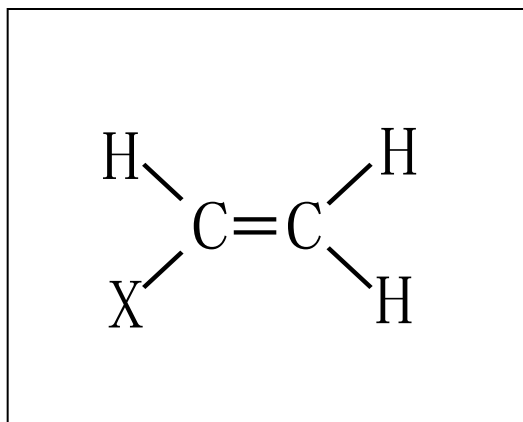
取代基	－Li	－CH_3	－F
$^3J_{顺}$	19.3	10.0	4.7
$^3J_{反}$	23.9	16.8	12.7

(3) Distant coupling

- Coupling between nuclei over 3 chemical bonds

- In π conjugated systems, e.g. alkenes, alkynes, aromatics etc., long distant coupling is commonly observed.
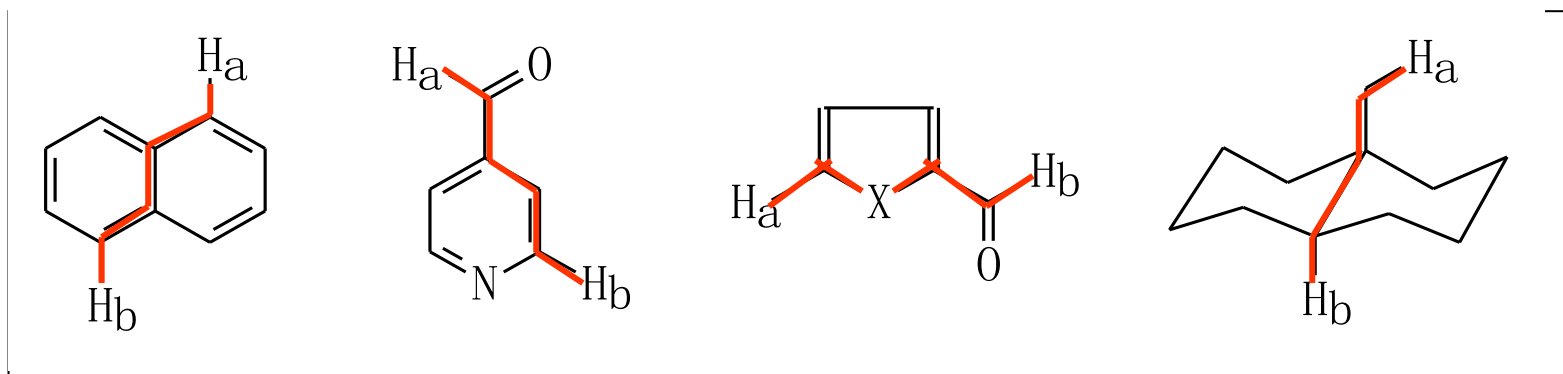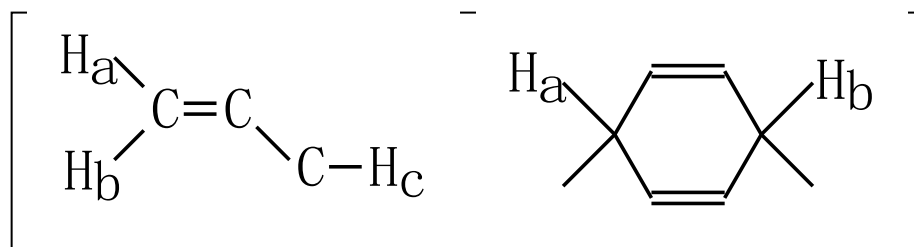
- **Aromatics**

$$J_{ortho} : 6 \sim 10\,Hz \,;\, J_{meta} : 1 \sim 3\,Hz \,;\, J_{para} : 0 \sim 1\,Hz$$

Coupling between H and other elements

Coupling between ^{19}F、 ^{31}P and ^{1}H are more common and important (^{19}F、 ^{31}P, I = ½)，and are complied to n +1 rule.

^{19}F -^{1}H coupling

- **Coupling between ^{19}F and ^{1}H can be observed from 2-5 chemical bonds**

- **In saturated chain alkanes: $^2J_{F-H}$ = 45-80 Hz , $^3J_{F-H}$ = 0-30 Hz , $^4J_{F-H}$ = 0-4 Hz ;**

- **In alkenes: $^2J_{F-H}$ = 70-90 Hz , $^3J_{F-H}$ (trans) = 10-50 Hz , $^3J_{F-H}$ (cis) = –3-20 Hz ;**

- **In aromatics: $^3J_{F-H}$ (ortho) = 6-9 Hz , $^4J_{F-H}$ (meta) = 4-8 Hz , $^5J_{F-H}$ (para) = 0-3 Hz。**

CH$_3$-CH$_2$-F
  b   a

4.13

1.27

F
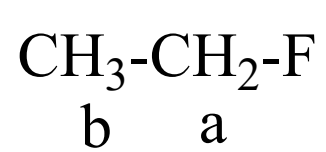
J$_{aF}$=46.7   J$_{aF}$>J$_{bF}$

                          J$_{ab}$=6-8

J$_{bF}$=25.2   J$_{aF}$>>J$_{ab}$

PPM
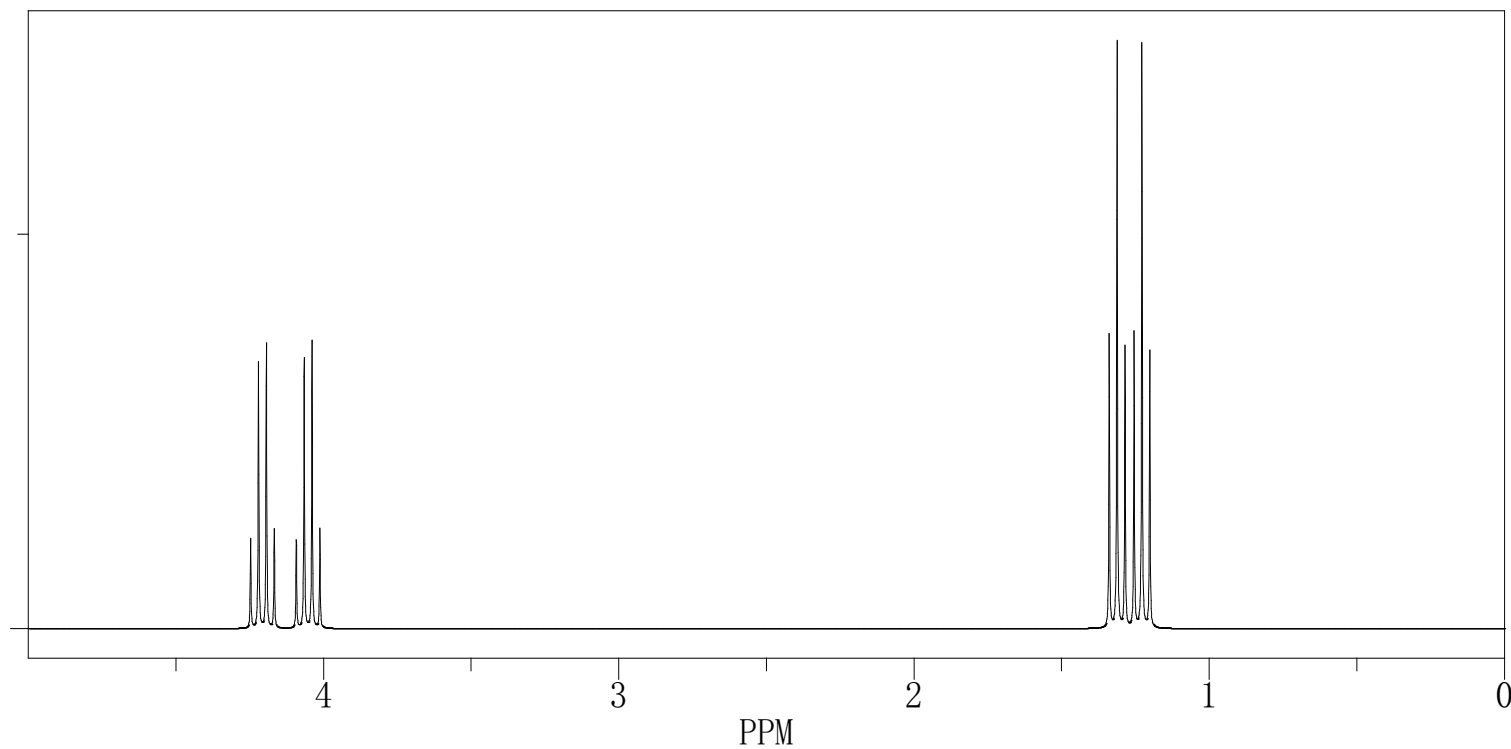
^{31}P -^{1}H coupling

- $^{1}J_{P\text{-}H}$ = 180-200 Hz ;

- Weaker than the H-F coupling