Spectroscopic Methods in Organic Chemistry

CHEM-6124, Organic Chemistry (Minor)

Lectures on NMR

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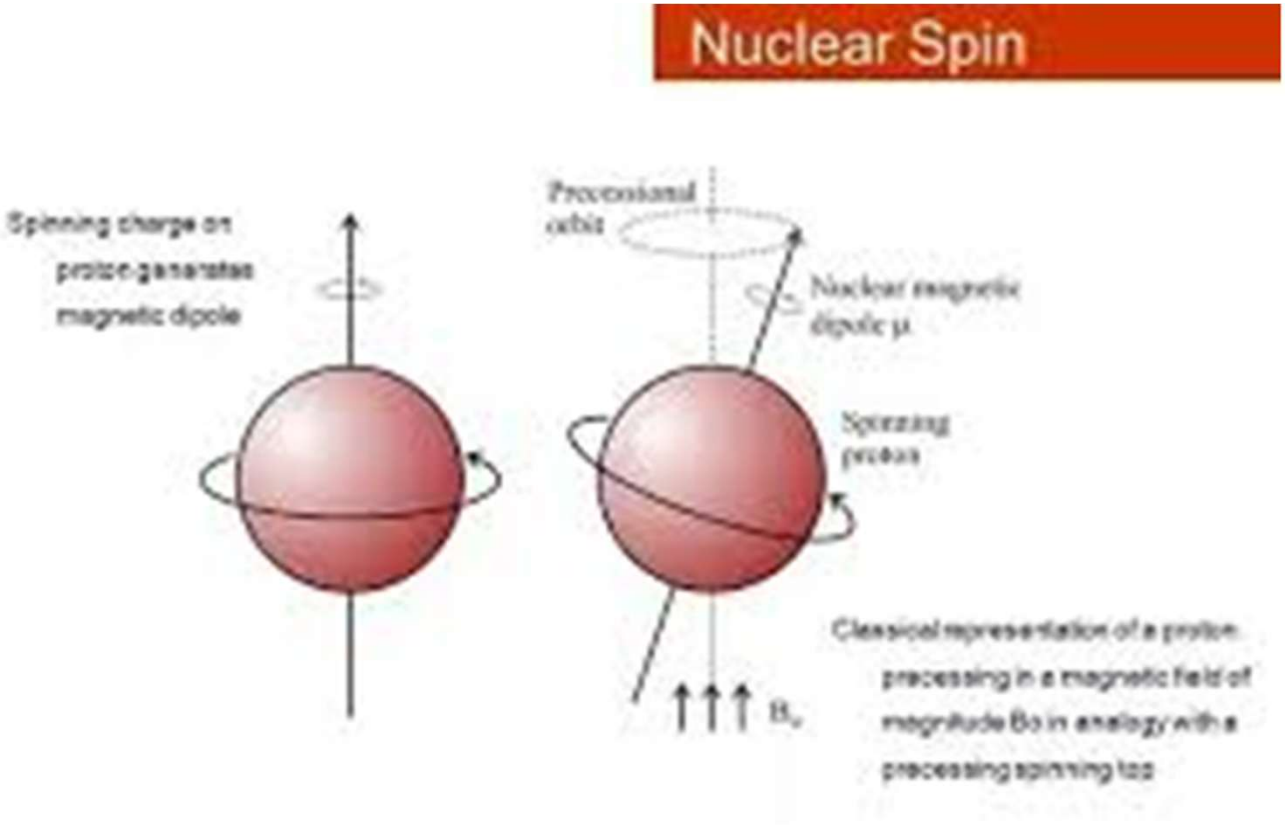
Spectral Band

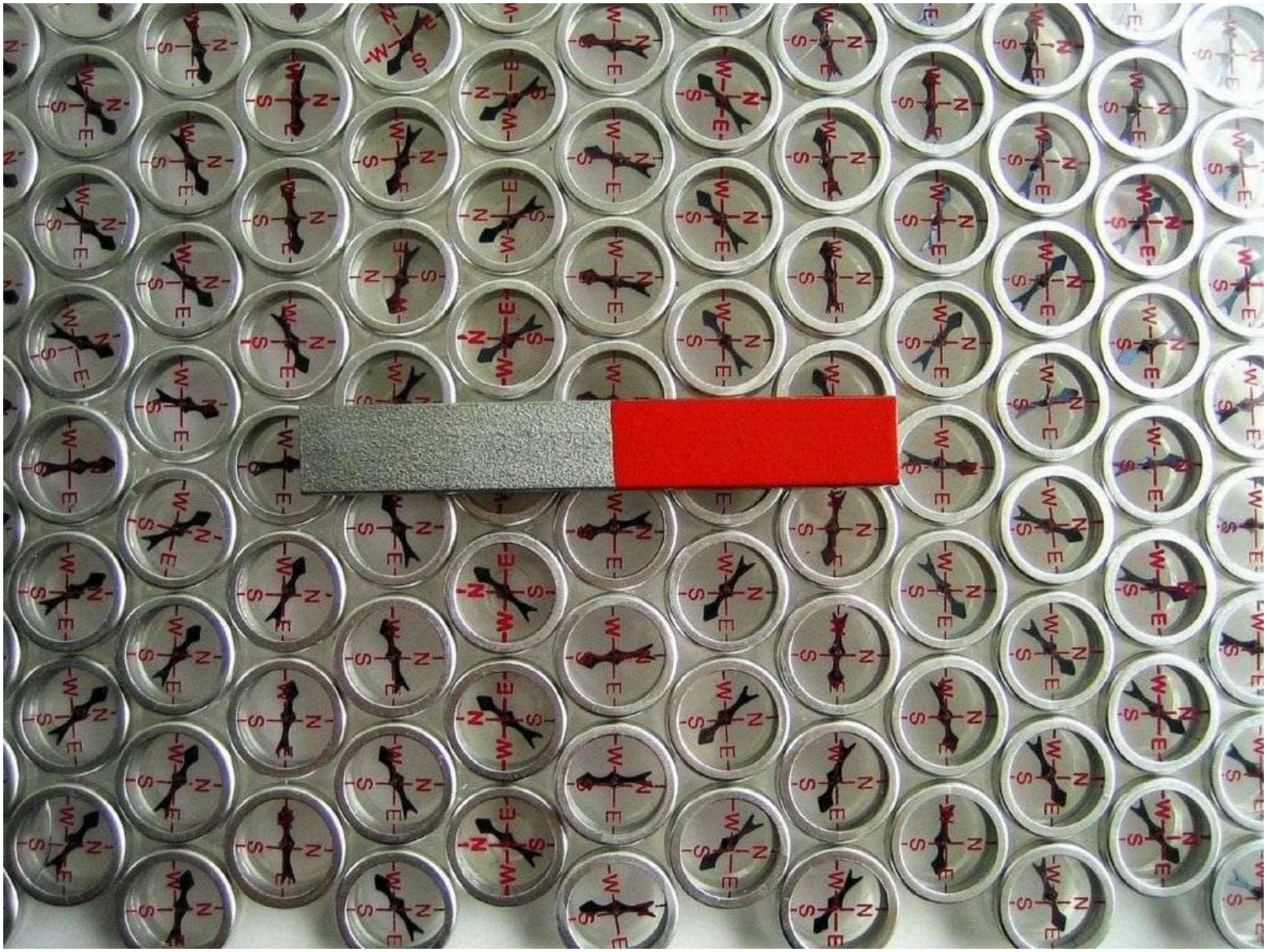
Frequency (ν) = 10^6 (M) to 10^9 (G) Hz

Wavelength (λ) = 300 to 0.3 m

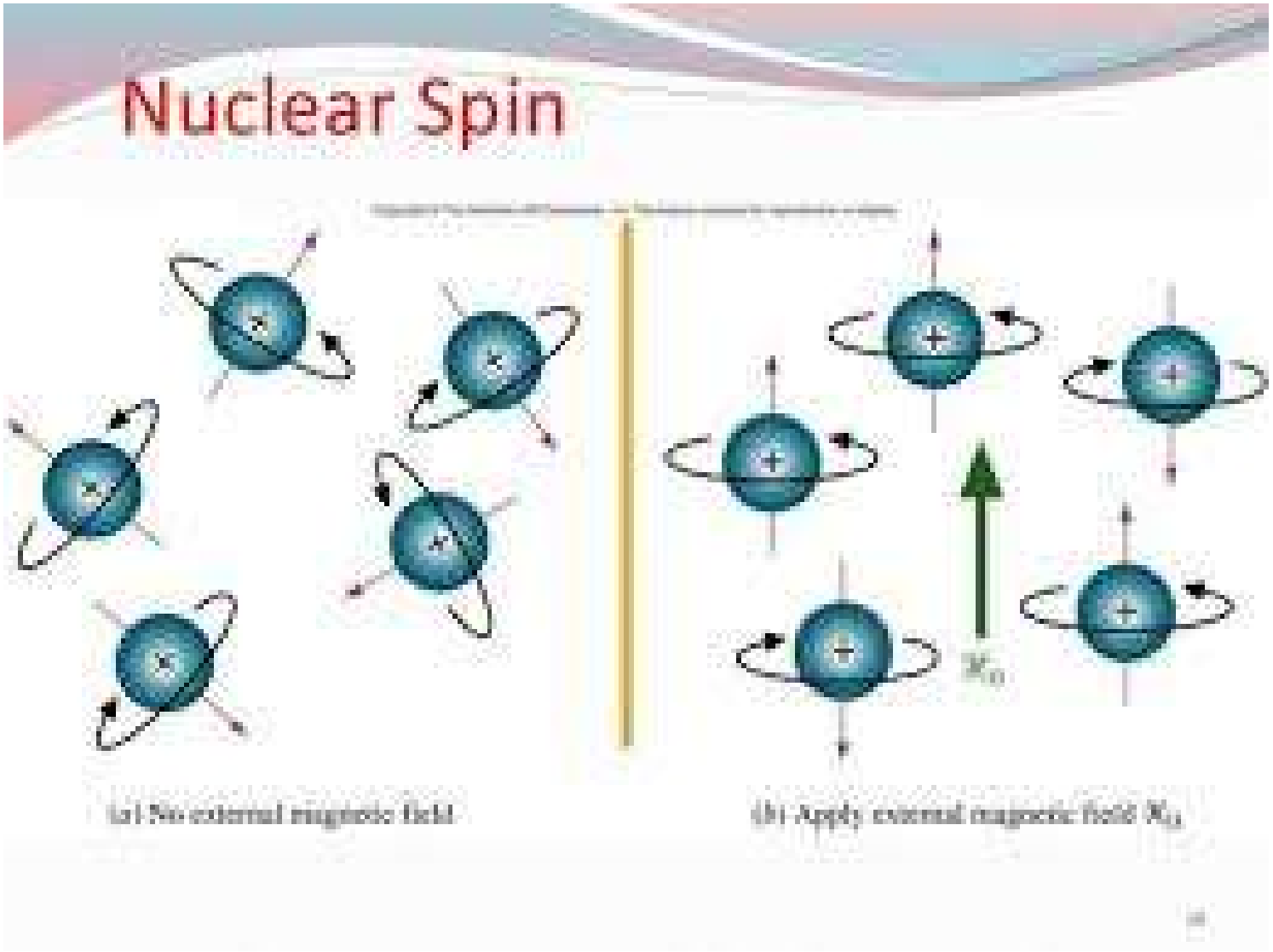
Wave Number = 3.33×10^{-3} to 3.33 m^{-1}



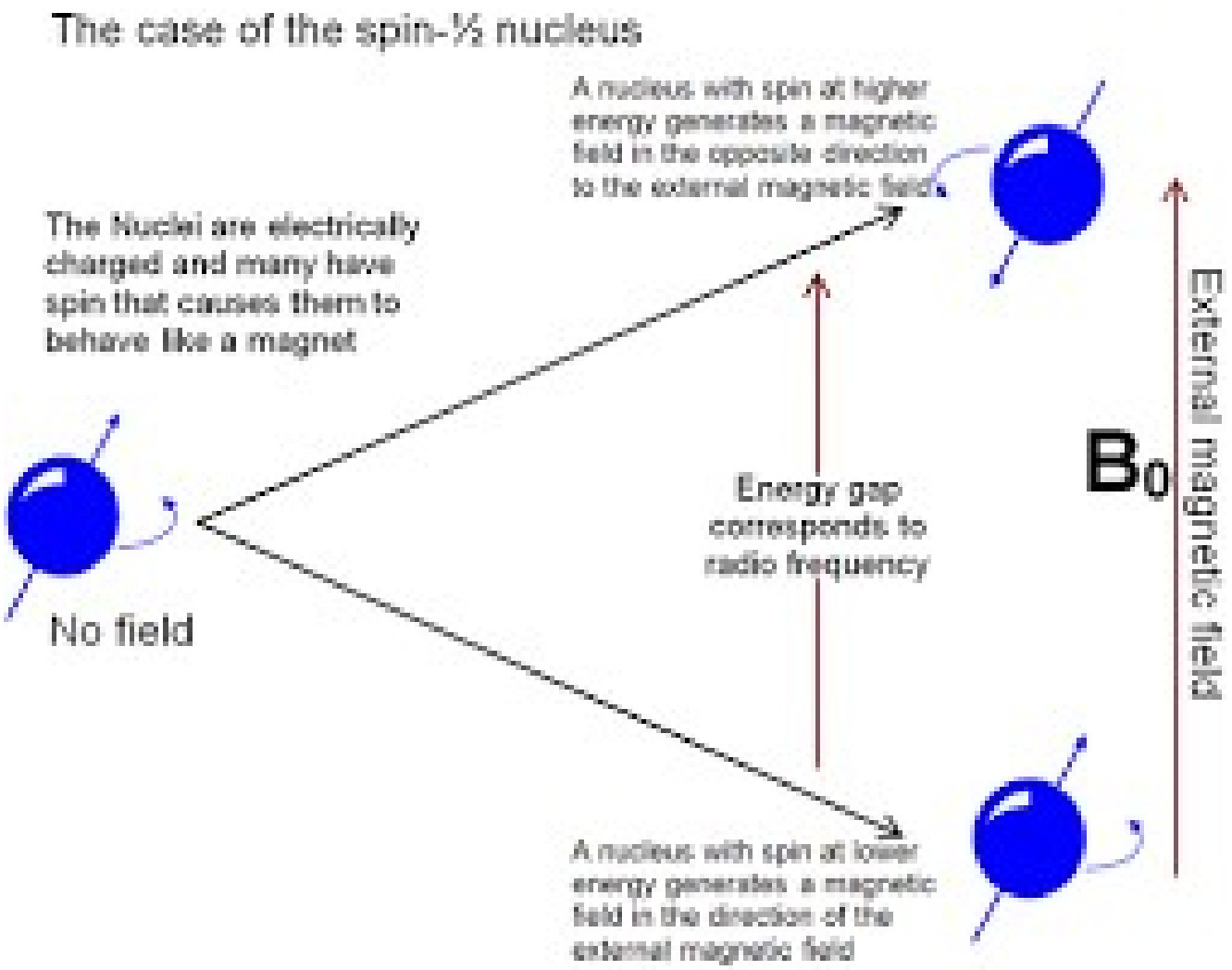
Magnetic Field



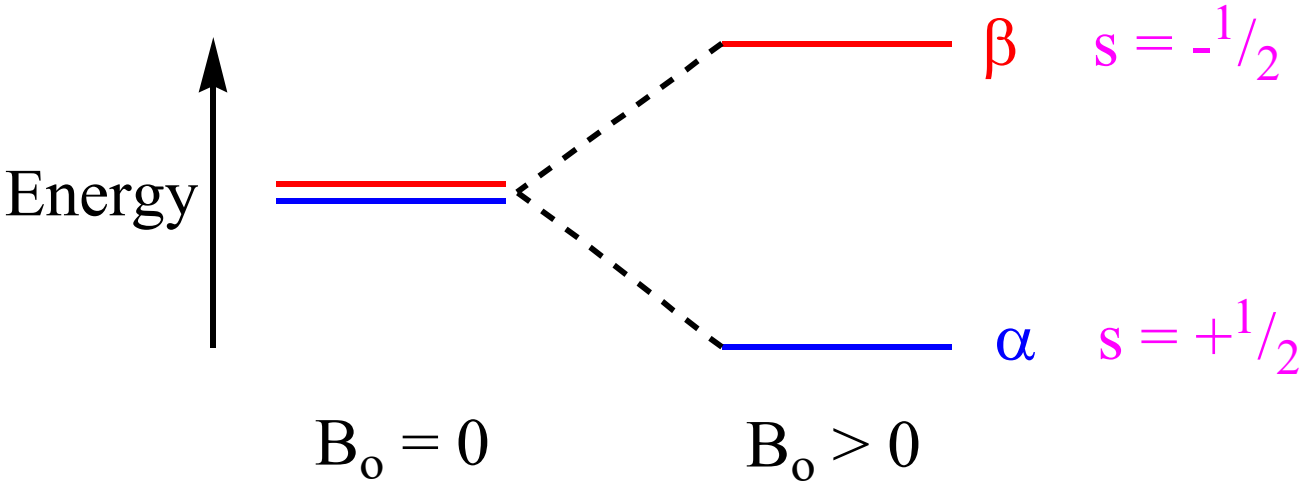
Spectral Band

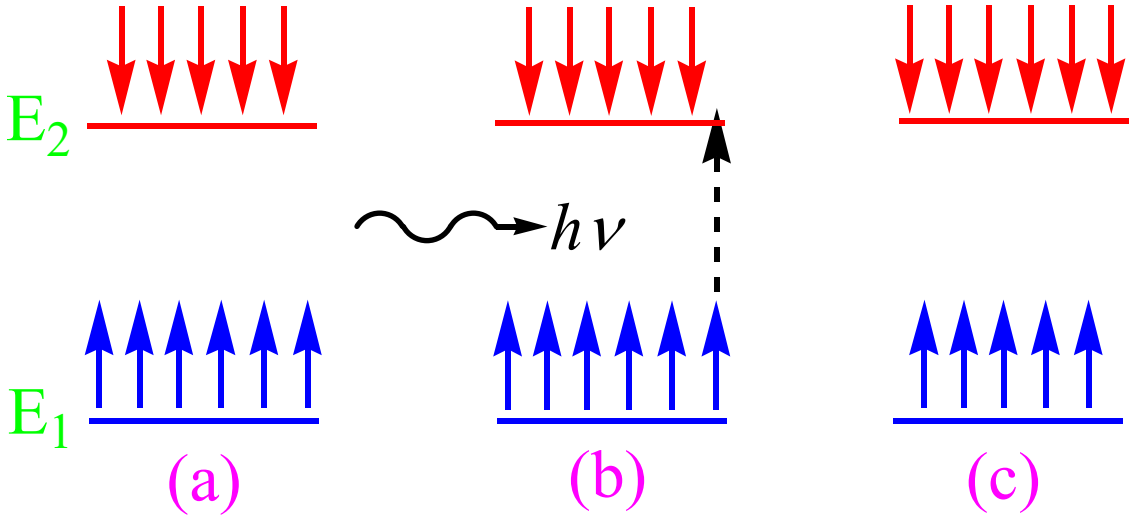


Energy States

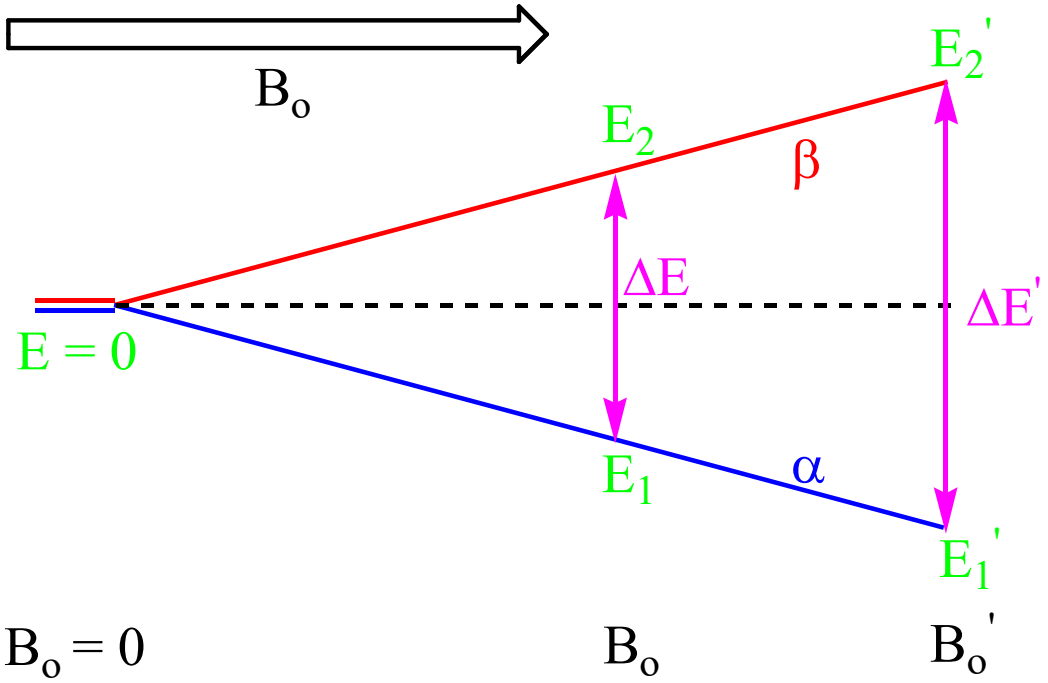


Energy States





Energy States



$\nu \alpha B_o$

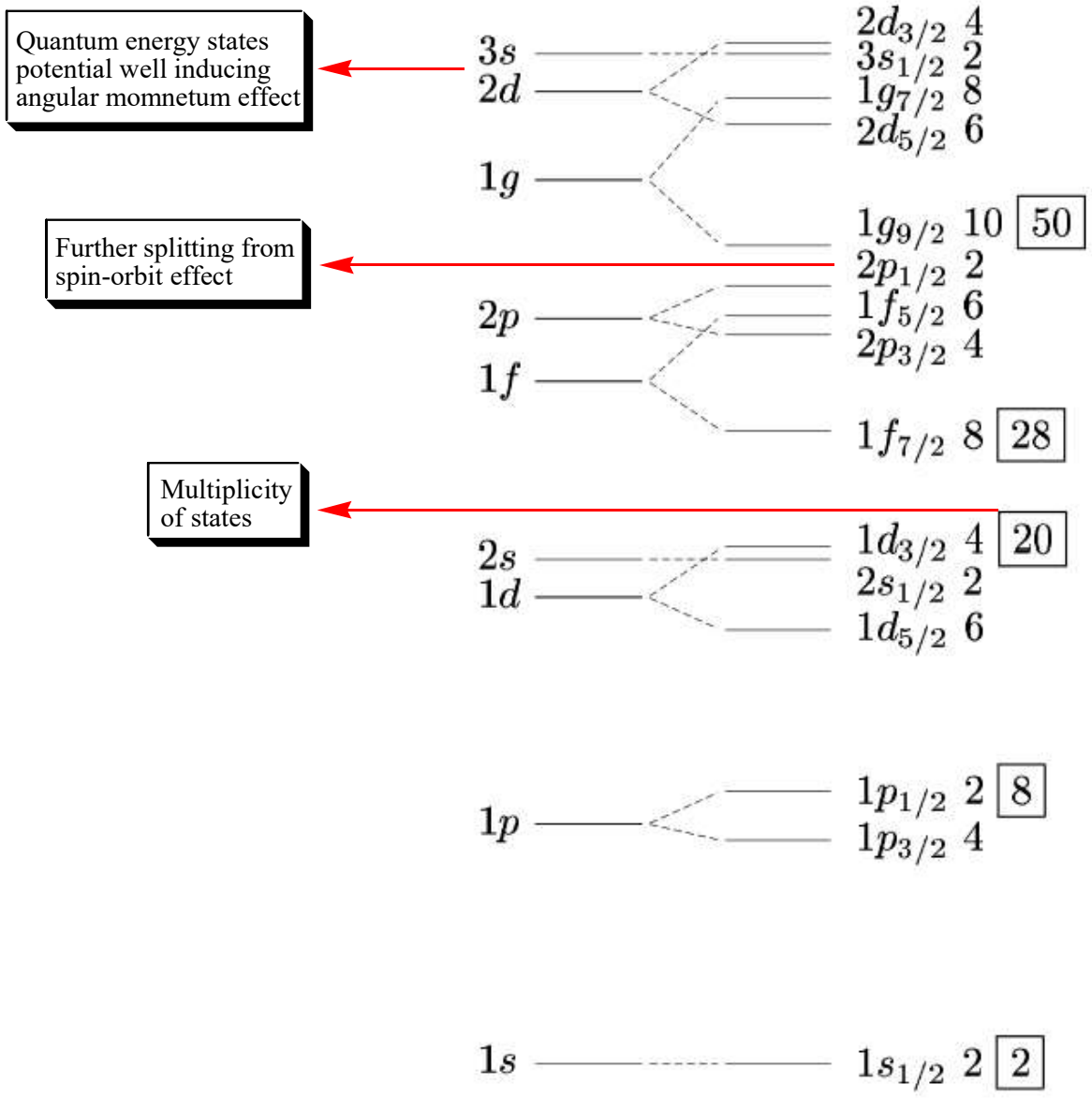
$\nu = (\gamma_n/2\pi) B_o$

$\gamma_n = \nu (2\pi) / B_o$

$\gamma_n / 2\pi = (\nu / B_o)$

Nucleus	γ_n (rad.s^{-1}.T^{-1})	$\gamma_n/2\pi$ (MHz/T)
^{1}H	267.51×10^6	42.58
^{2}H	41.07×10^6	6.54
^{13}C	67.28×10^6	10.71
^{19}F	251.66×10^6	40.05
^{31}P	108.29×10^6	17.24

Nuclear Energy Levels



Nuclear Spin (I)

$$1s_{1/2}^{2} < 1p_{3/2}^{4} < 1p_{1/2}^{2} < 1d_{5/2}^{6} < 2s_{1/2}^{2} <$$
$$1d_{3/2}^{4} < 1f_{7/2}^{8} < 2p_{3/2}^{4} < 1f_{5/2}^{6} < 2p_{1/2}^{2} <$$
$$1g_{9/2}^{10} < 2d_{5/2}^{6} < 1g_{7/2}^{8} < 3s_{1/2}^{2} < 2d_{3/2}^{4} \ \ldots$$

$I = i_p + i_n$ when I' = odd/fractional number
$I = i_p - i_n$ when I' = even number
$I' = (i_p + i_n) + (l_p + l_n)$

$^{1}H_{1}$

$Z = 1$; $A = 1$

$p = 1$; $n = 0$

$1s_{1/2}^{2}$

$I' = (1/2 + 0) + (0 + 0)$
$I' = 1/2$
$I = 1/2 + 0 = 1/2$

Nuclear Spin (I)

$$1s_{1/2}^{2} < 1p_{3/2}^{4} < 1p_{1/2}^{2} < 1d_{5/2}^{6} < 2s_{1/2}^{2} < 1d_{3/2}^{4} < 1f_{7/2}^{8} < 2p_{3/2}^{4} < 1f_{5/2}^{6} < 2p_{1/2}^{2} < 1g_{9/2}^{10} < 2d_{5/2}^{6} < 1g_{7/2}^{8} < 3s_{1/2}^{2} < 2d_{3/2}^{4} \ldots$$

$^{2}D_{1}$

Z = 1; A = 2

p = 1; n = 1

I' = (1/2 + 1/2) + (0 + 0)

I' = 1

I = 1/2 + 1/2 = 1

$^{13}C_{6}$

Z = 6; A = 13

p = 6; n = 7

I' = (1/2 + 0) + (1 + 0)

I' = 3/2

I = 1/2 + 0 = 1/2

$^{19}F_{9}$

Z = 9; A = 19

p = 9; n = 10

I' = (1/2 + 1) + (2 + 2)

I' = 11/2

I = 1/2 + 1 = 3/2

$^{31}P_{15}$

Z = 15; A = 31

p = 15; n = 16

I' = (1/2 + 0) + (0 + 0)

I' = 1/2

I = 1/2 + 0 = 1/2

Nuclear Spin (I)

$1s_{1/2}^{2} < 1p_{3/2}^{4} < 1p_{1/2}^{2} < 1d_{5/2}^{6} < 2s_{1/2}^{2} < 1d_{3/2}^{4} < 1f_{7/2}^{8} < 2p_{3/2}^{4} < 1f_{5/2}^{6} < 2p_{1/2}^{2} < 1g_{9/2}^{10} < 2d_{5/2}^{6} < 1g_{7/2}^{8} < 3s_{1/2}^{2} < 2d_{3/2}^{4}$ ...

$^{35}Cl_{17}$

Z = 17; A = 35

p = 17; n = 18

I' = (1/2 + 1) + (2 + 2)

I' = 11/2

I = 1/2 + 1 = 3/2

$^{37}Cl_{17}$

Z = 17; A = 37

p = 17; n = 20

I' = (1/2 + 0) + (2 + 0)

I' = 5/2

I = 1/2 + 0 = 1/2

$^{79}Br_{35}$

Z = 35; A = 79

p = 35; n = 44

I' = (3/2 + 2) + (3 + 4)

I' = 21/2

I = 3/2 + 2 = 7/2

$^{81}Br_{35}$

Z = 35; A = 81

p = 35; n = 46

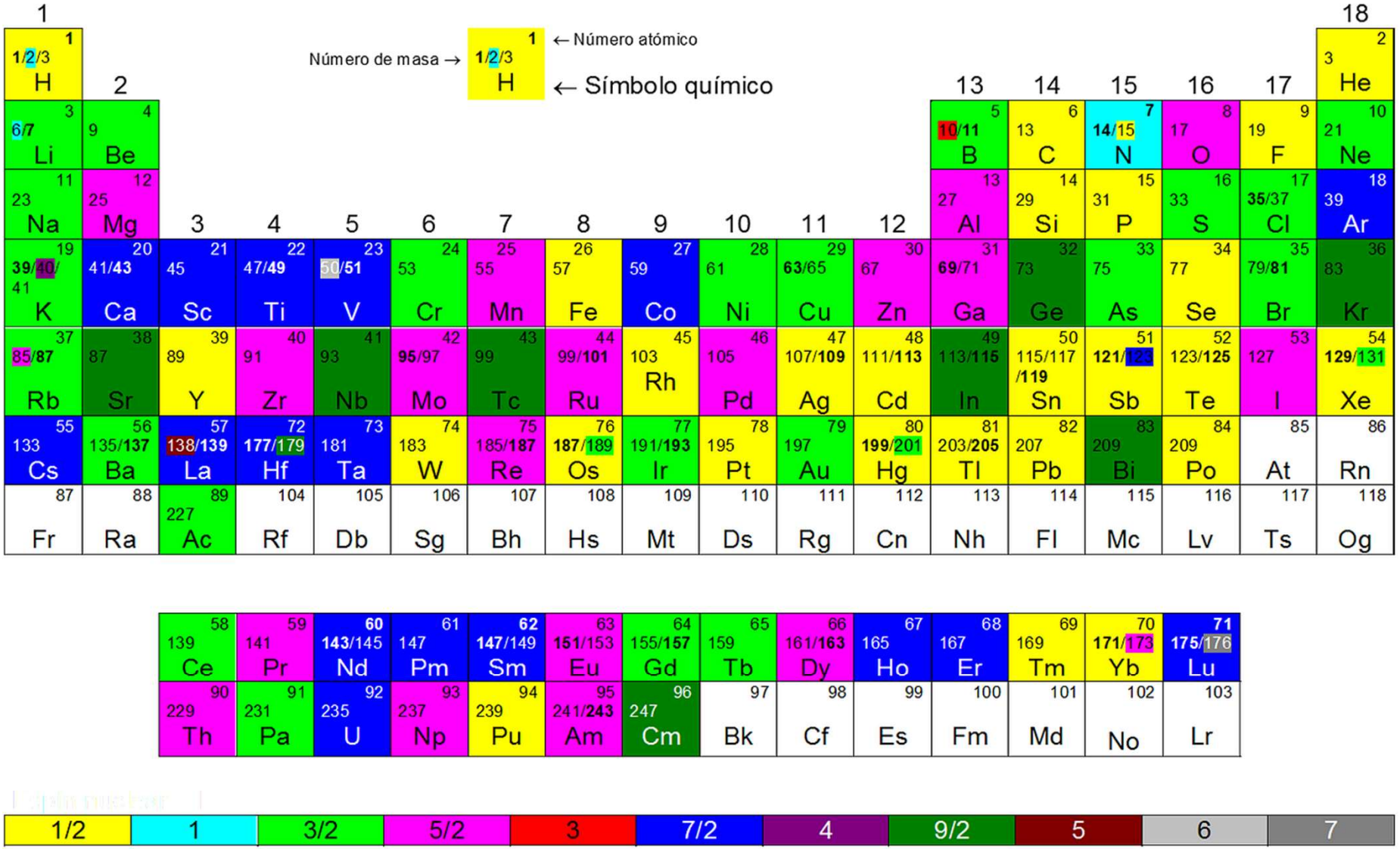
I' = (3/2 + 2) + (3 + 4)

I' = 21/2

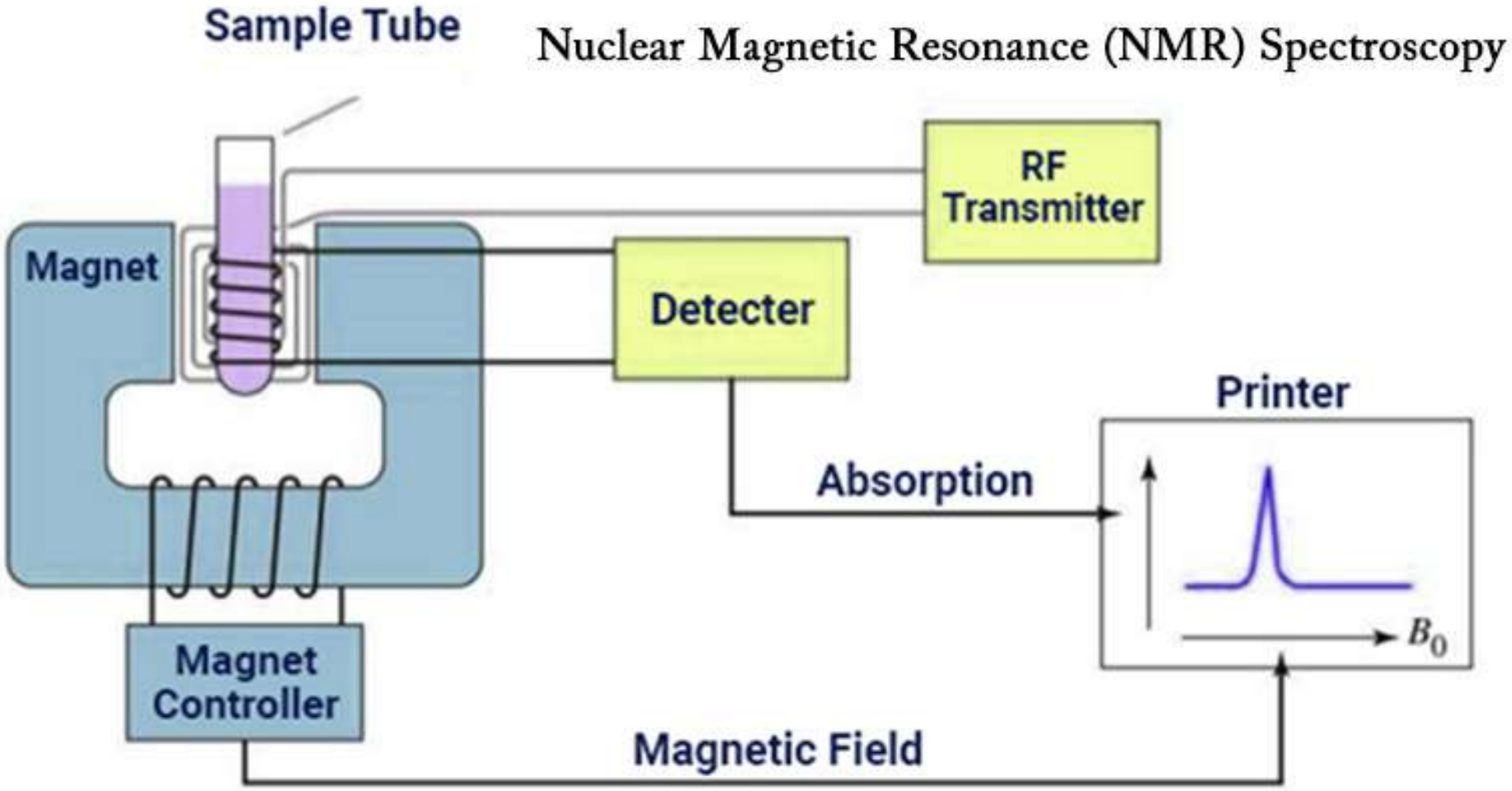
I = 3/2 + 2 = 7/2

Nuclear Spin (Periodic Table)

Tabla periódica de isótopos de RMN.



NMR Spectrophotometer

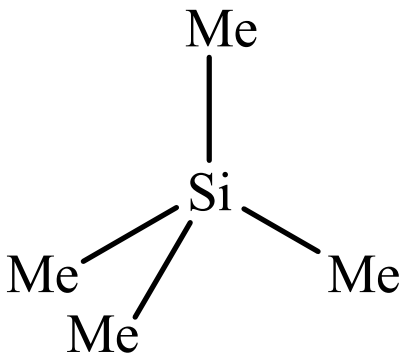


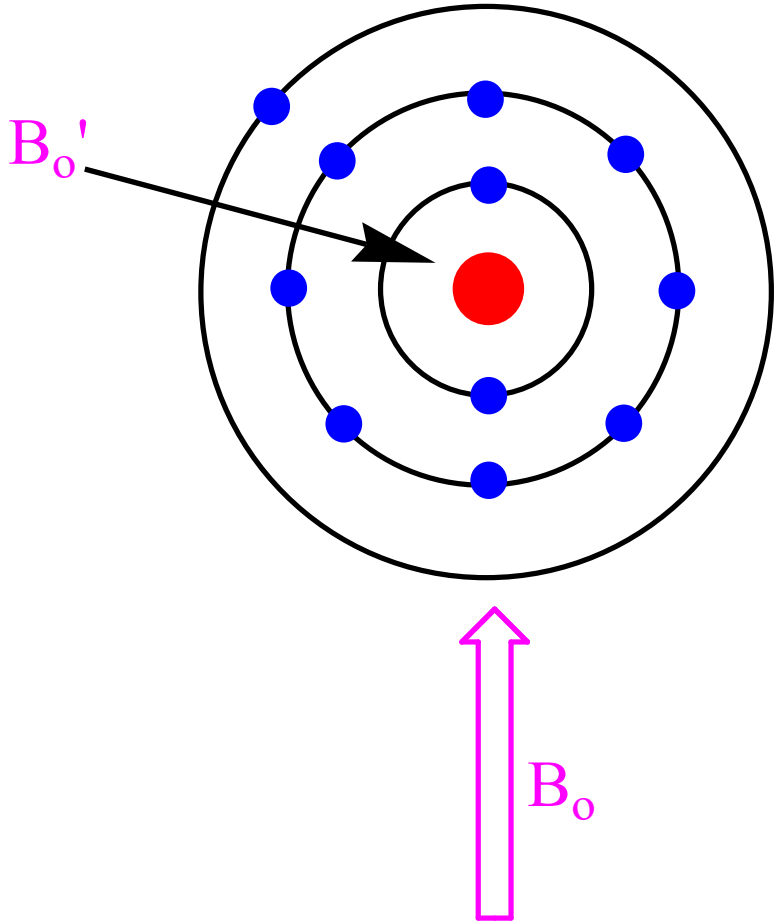
Unit

$$\delta\ (\text{ppm}) = \frac{(\nu_{\text{signal}} - \nu_{\text{TMS}}) \times 10^6}{\nu_{\text{Machine}}\ (\text{MHz})}$$

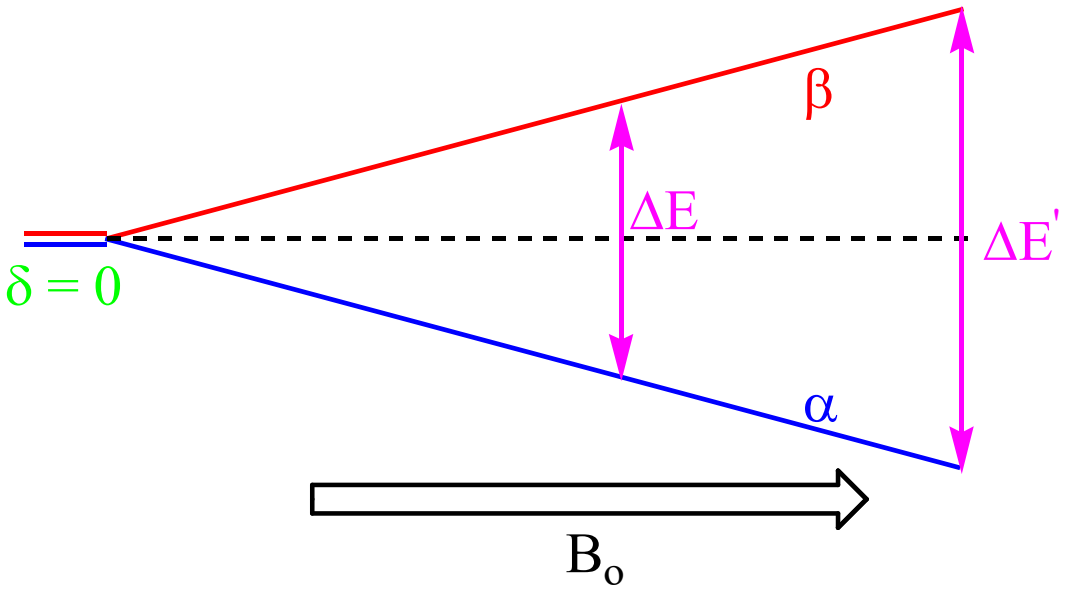
δ = Chemical Shift

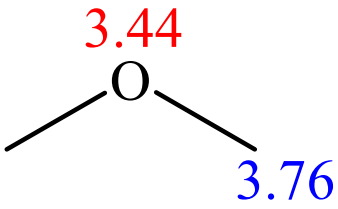
TMS = Tetramethylsilane [Me_4Si]

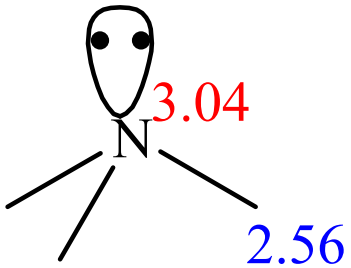




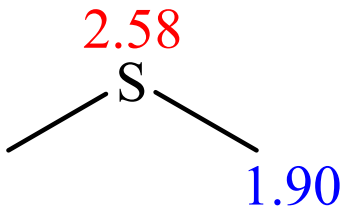
Shielding (+*I*) / Deshielding (-*I*)





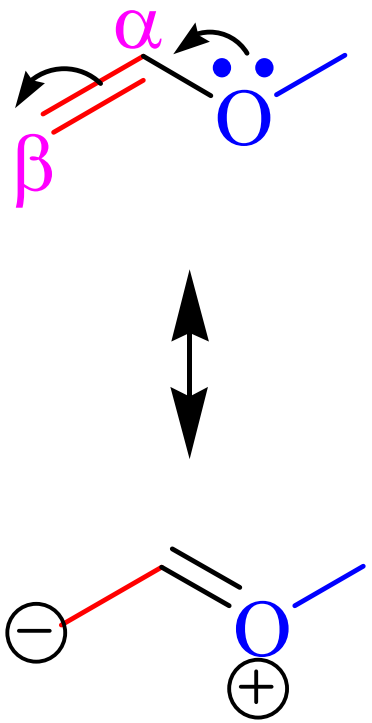


Shielding ⟸ Deshielding ⟹

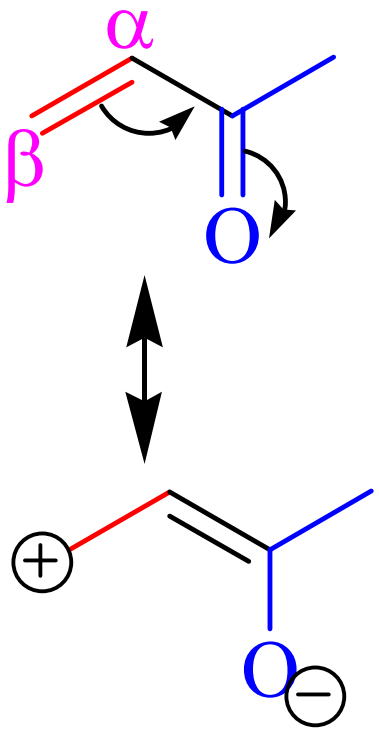


	CH_3F	CH_3Cl	CH_3Br	CH_3I	CH_3C	CH_3H	CH_3Si	CH_3Li
δ (ppm)	4.27	3.06	2.69	2.13	0.86	0.23	0.00	-1.49
E (Pauling)	4.0	3.16	2.96	2.66	2.55	2.20	1.90	0.98

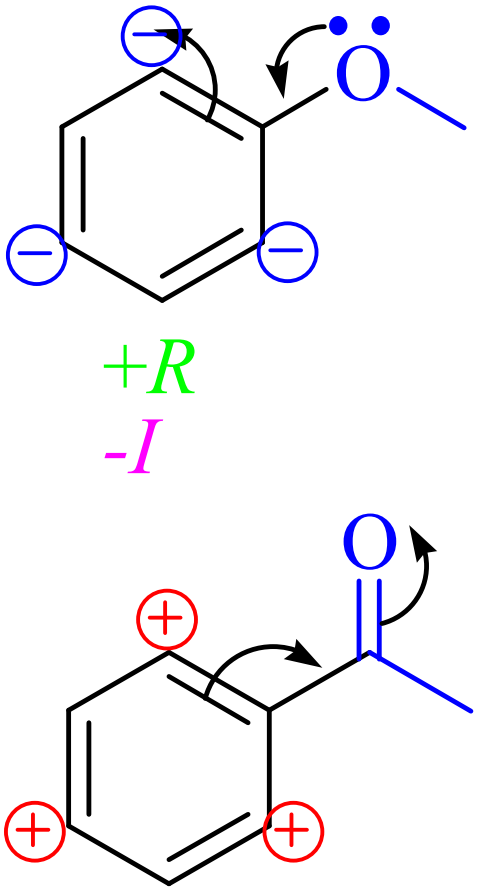
Mesomeric Factor



+*R*
-*I*



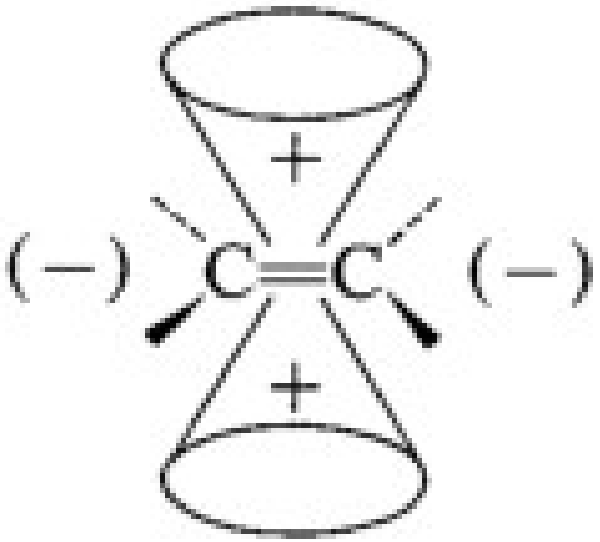
-*R*
-*I*

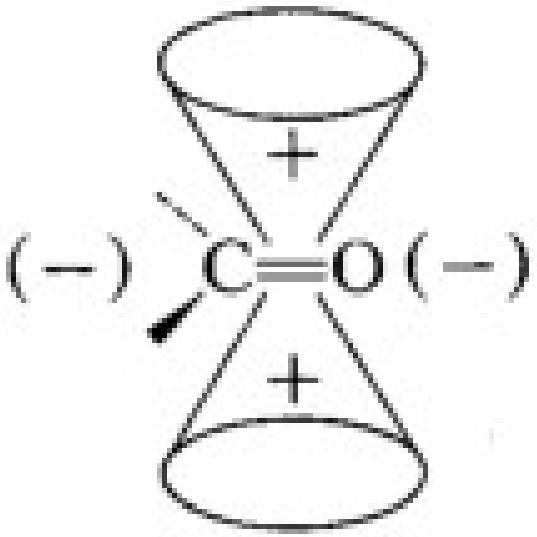


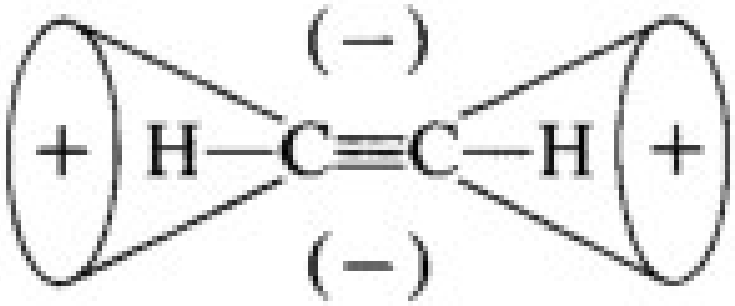
+*R*
-*I*

-*R*
-*I*

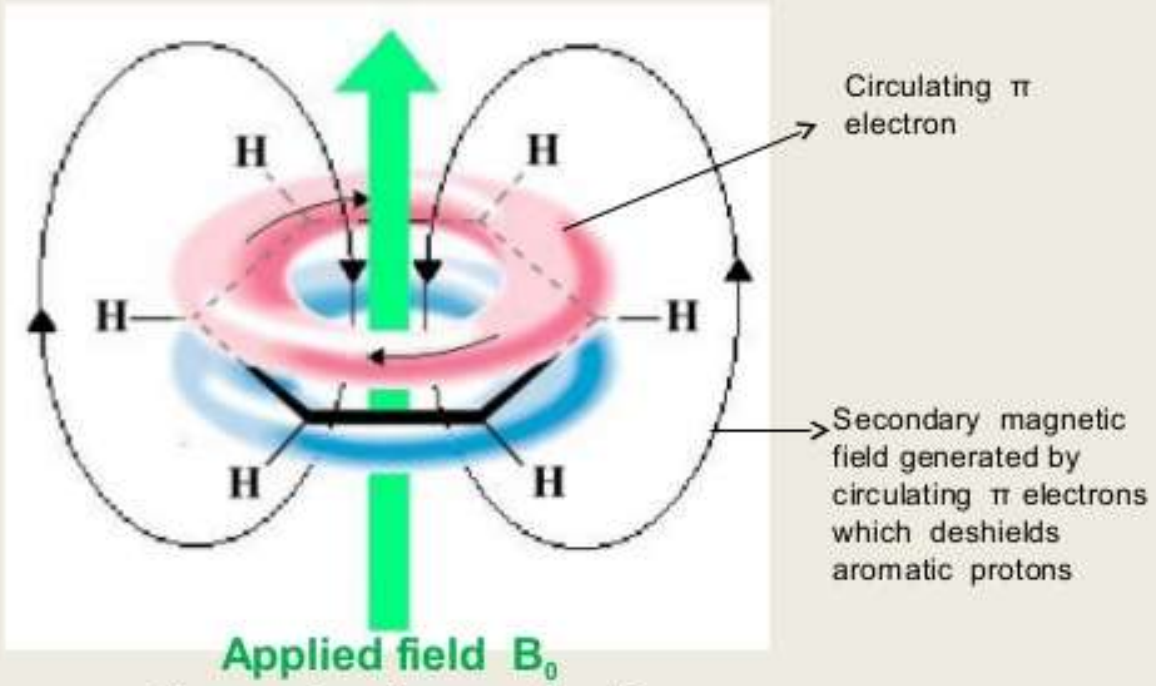
Diamagnetic Anisotropic Effect







Diamagnetic Anisotropy in Benzene



Diamagnetic anisotropy in Benzene

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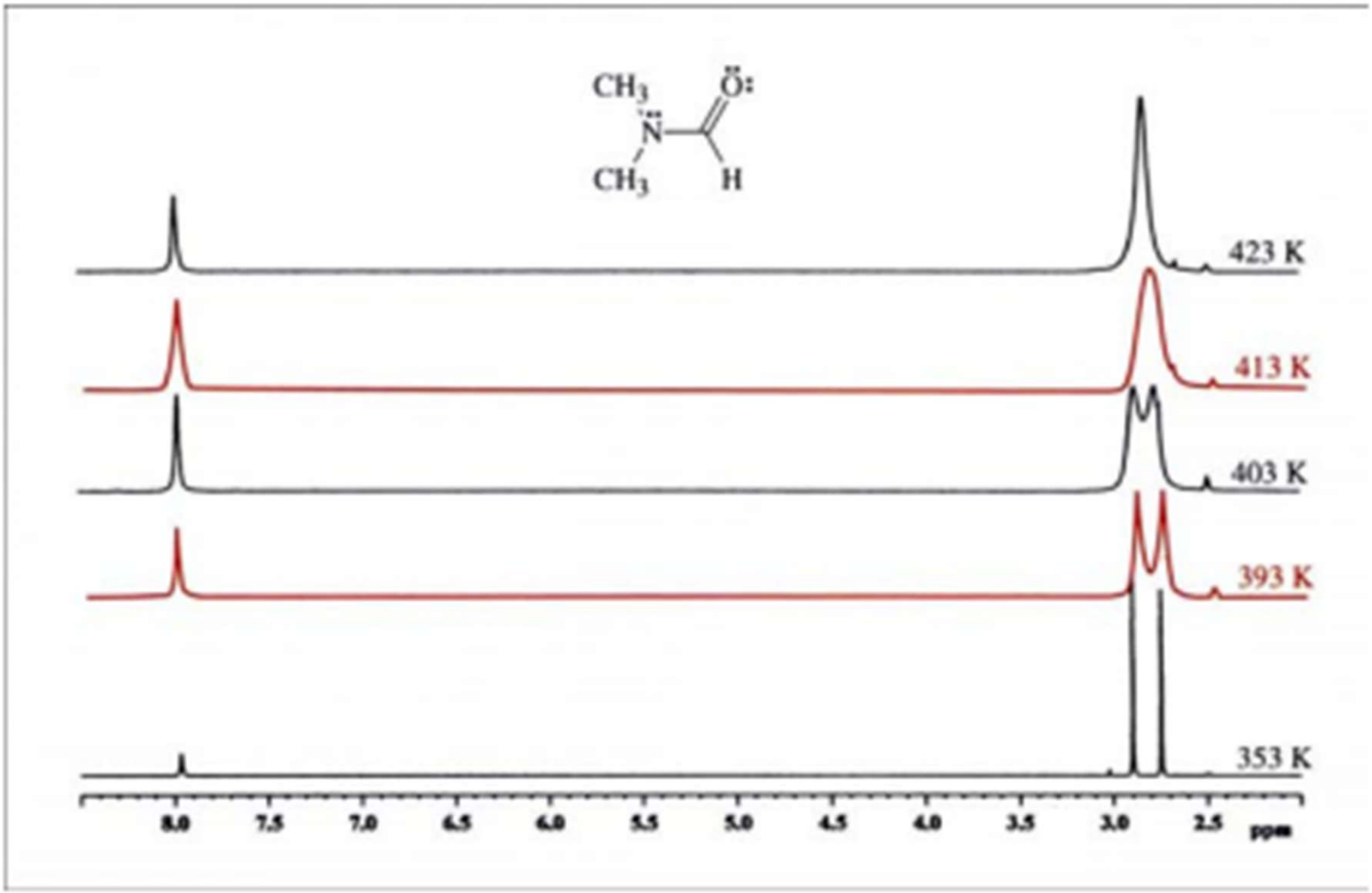
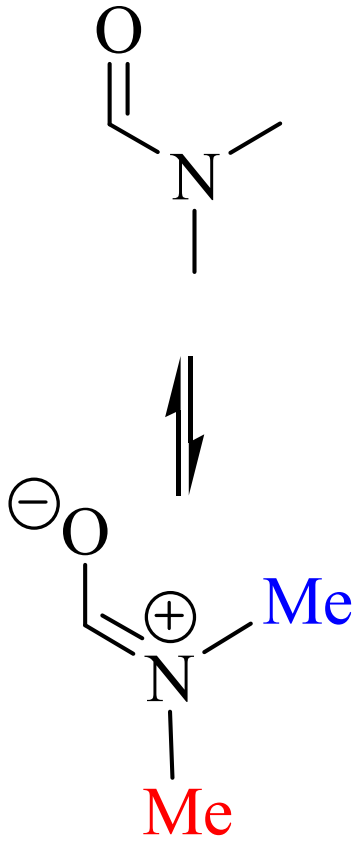
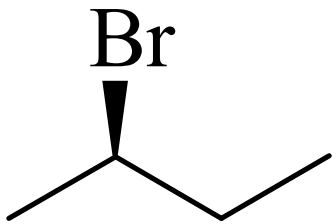
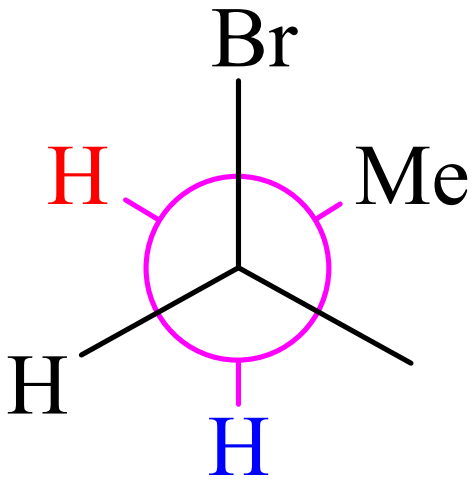
Non-Equivalent Protons



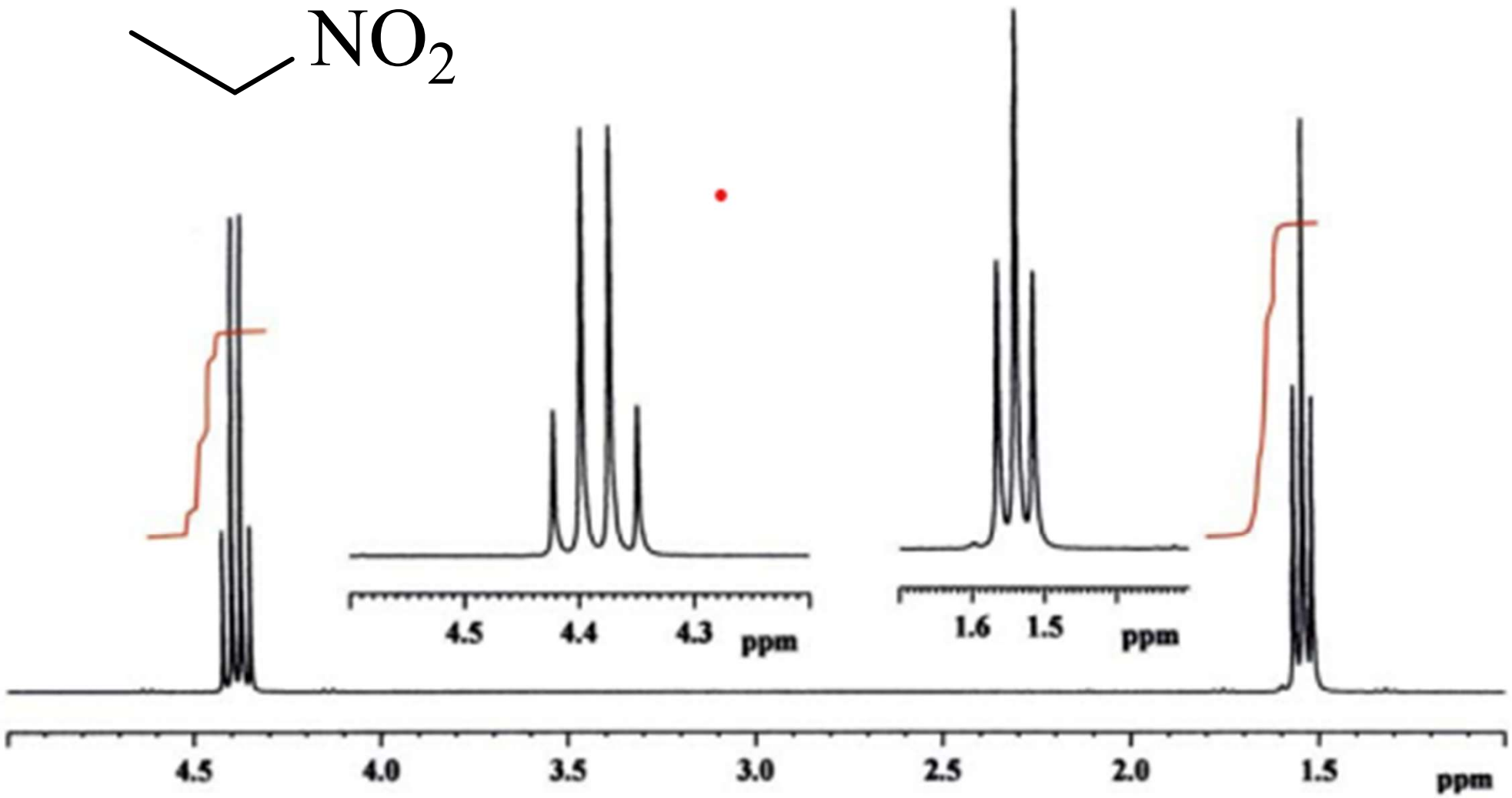


Diastereotopy

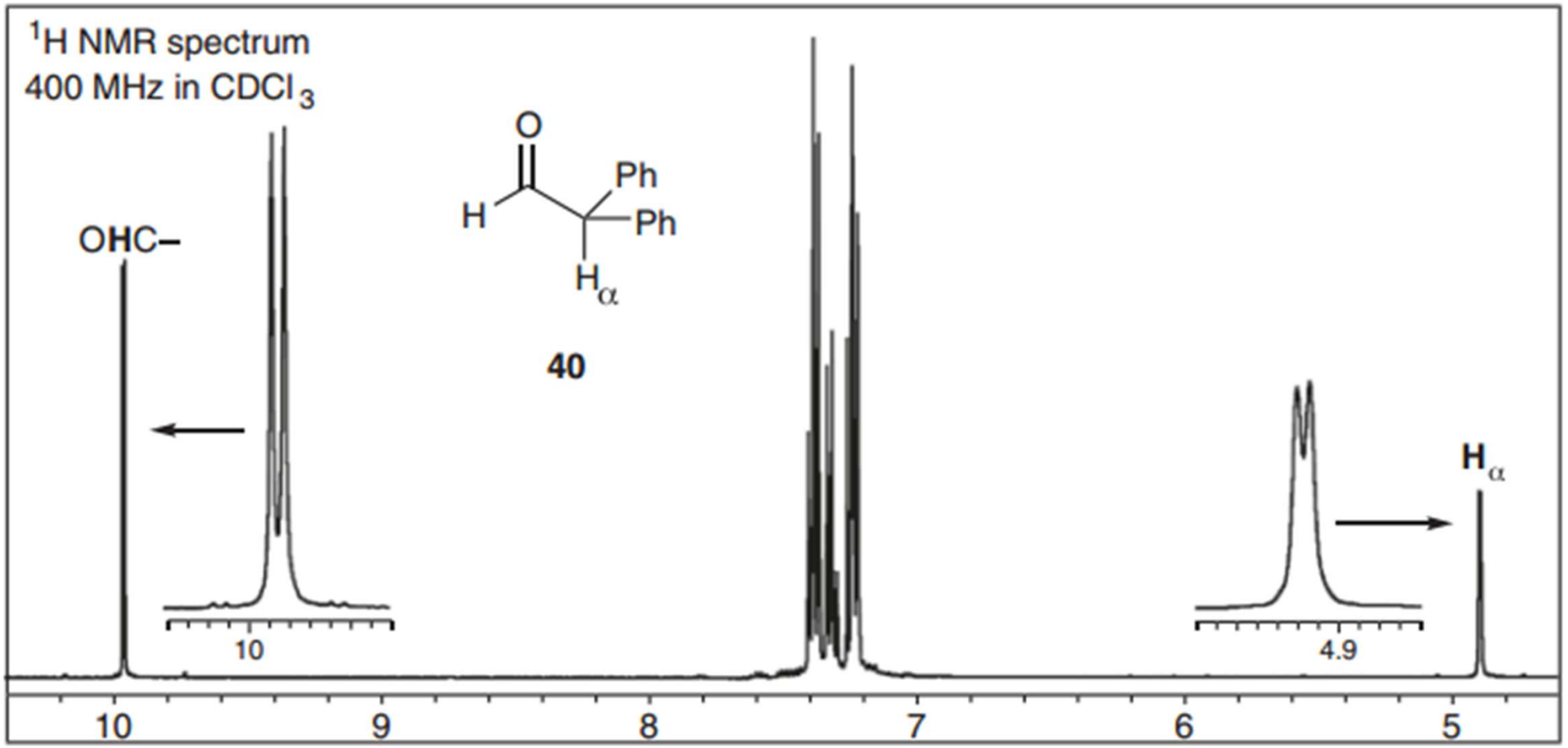




Spin-Spin Splitting



Spin-Spin (^{1}H-^{1}H) Coupling



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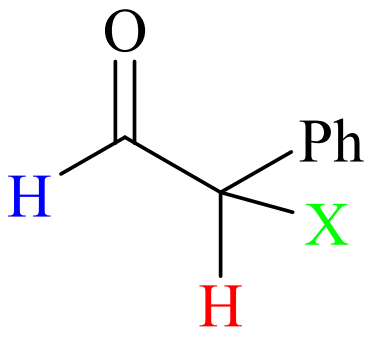

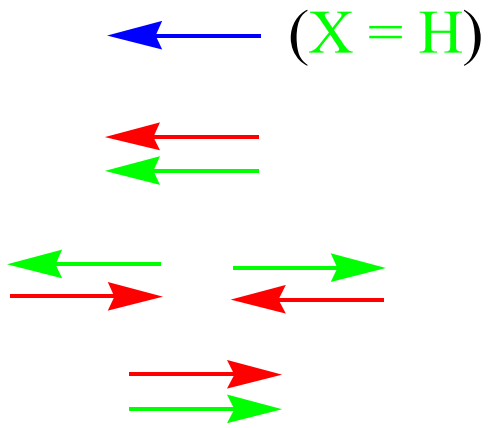

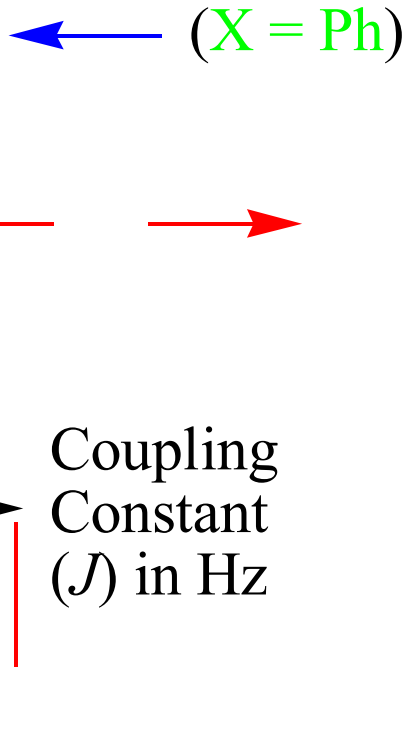

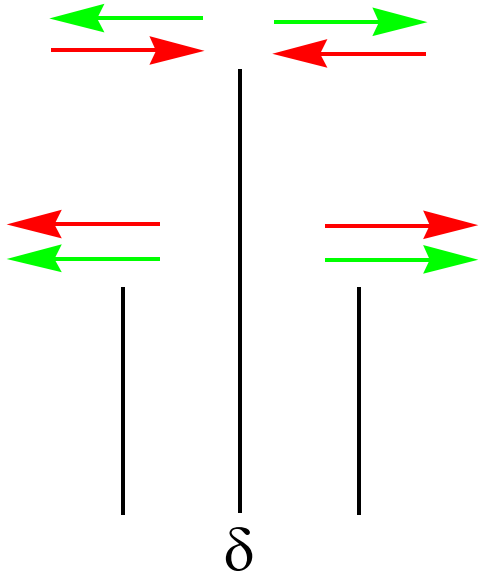

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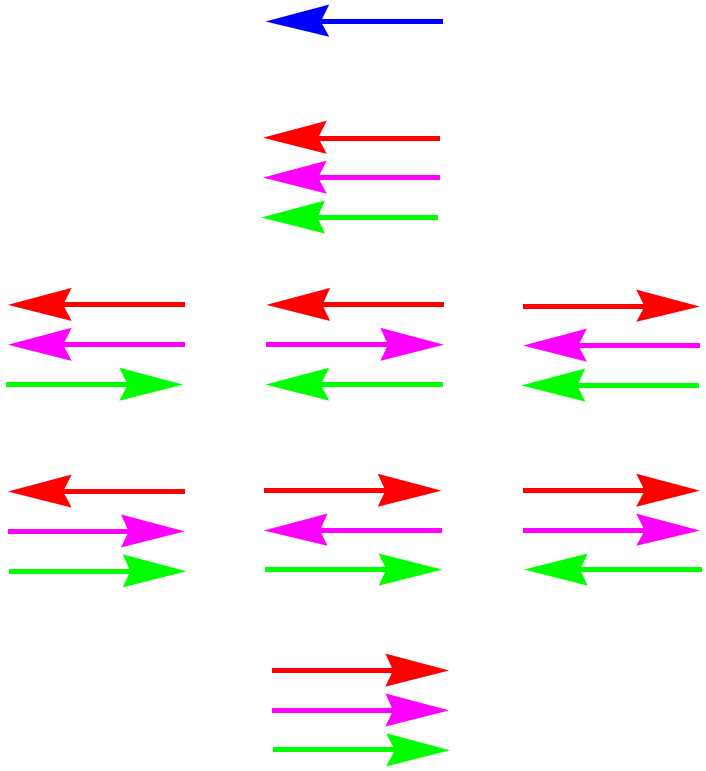
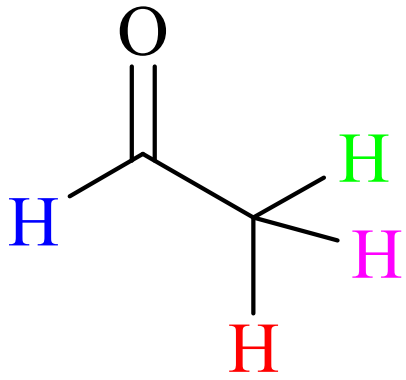
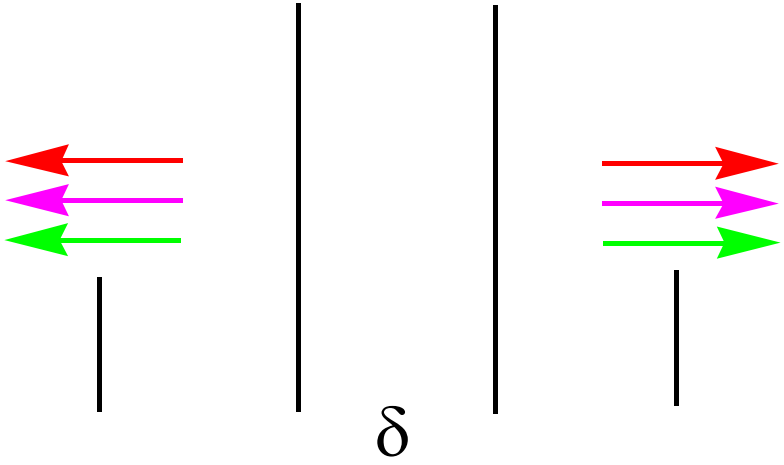
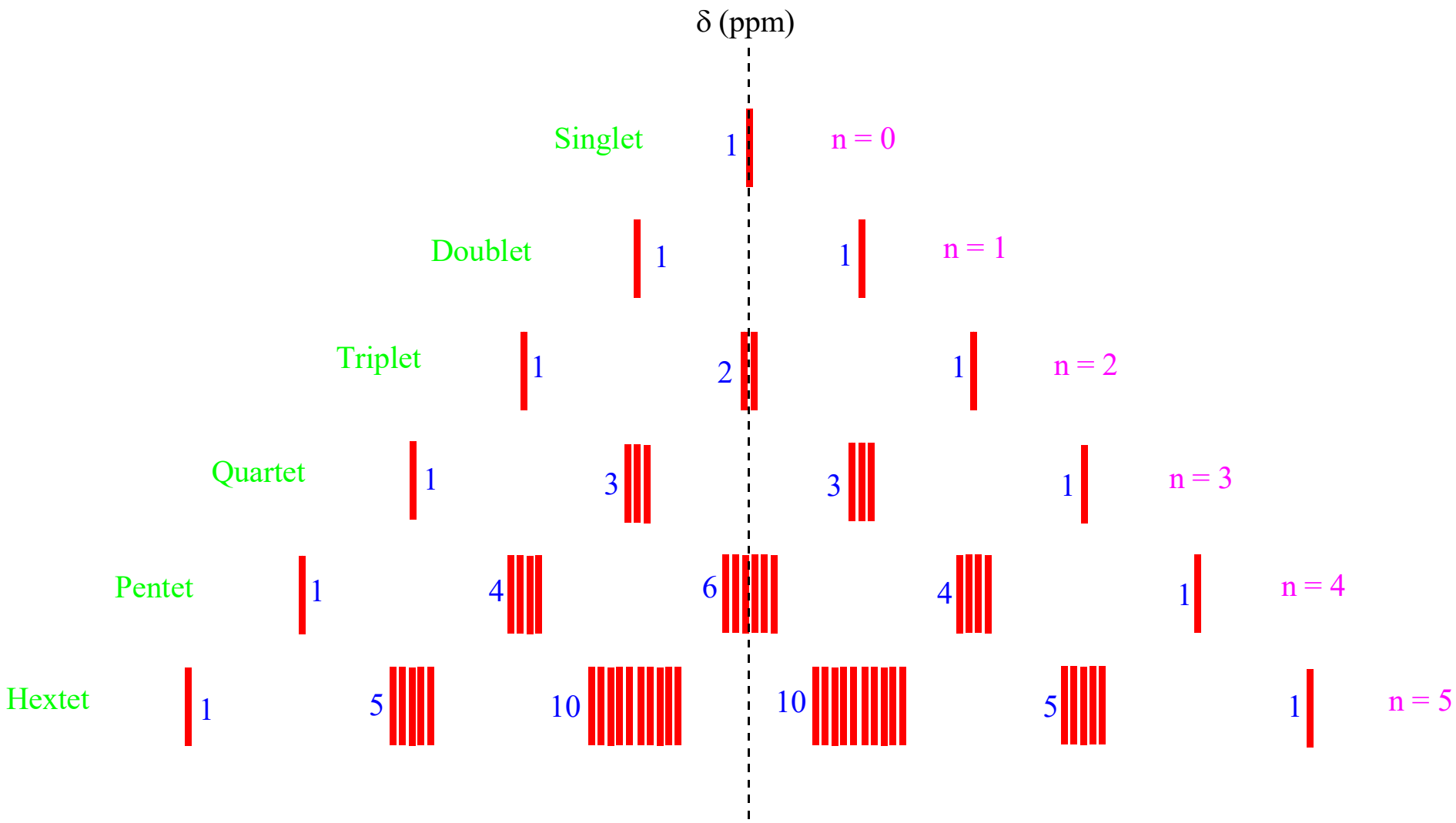


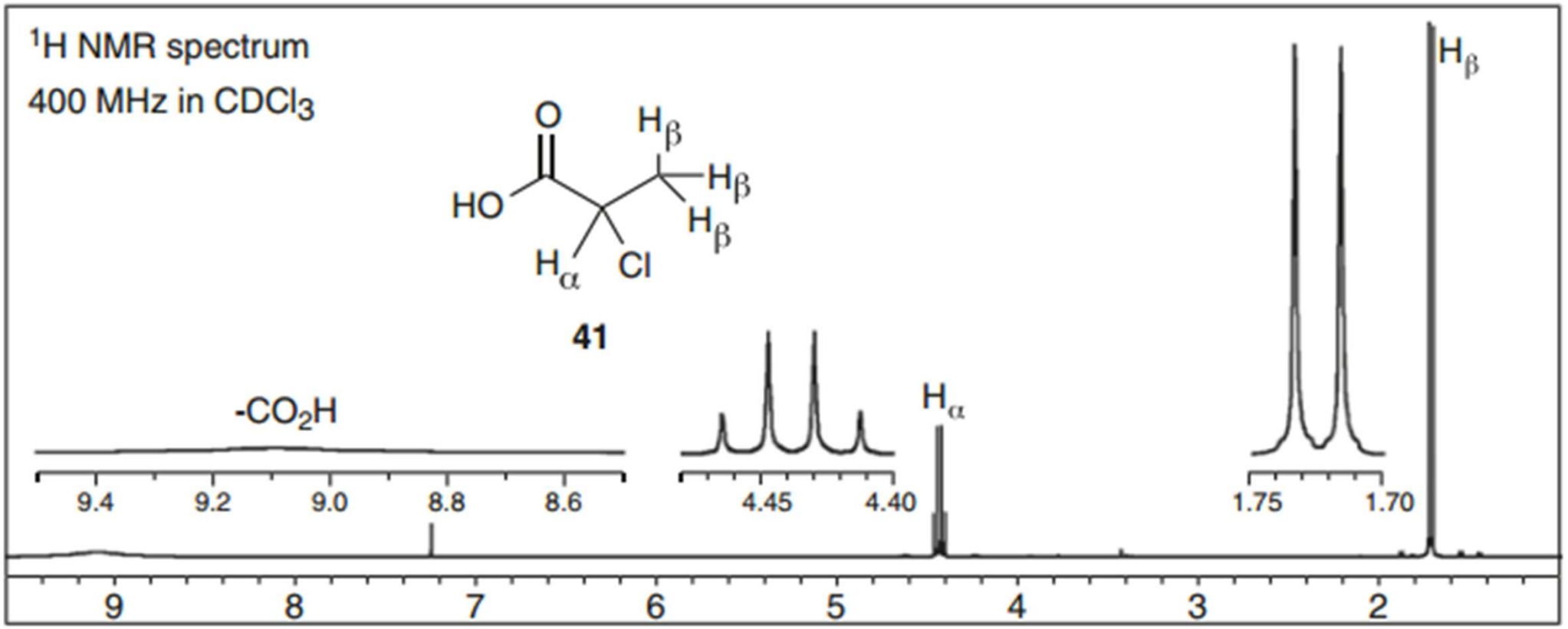




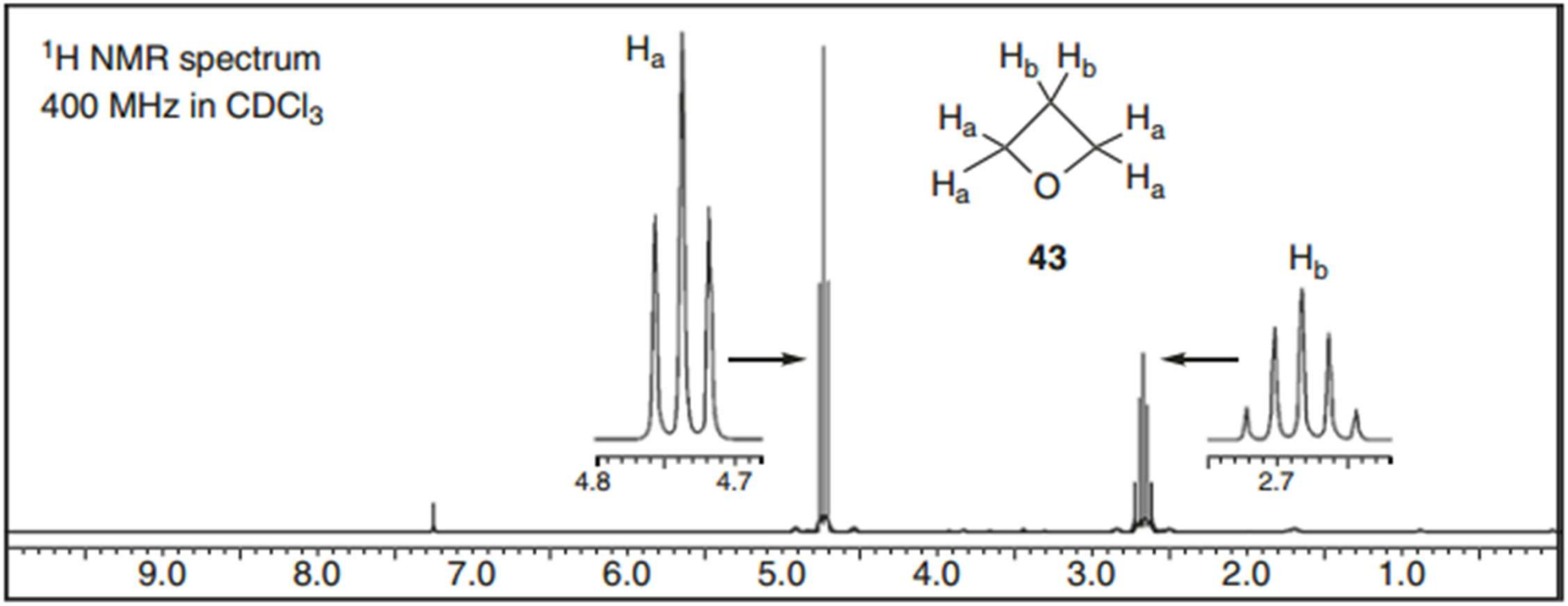
Pascal's Triangle



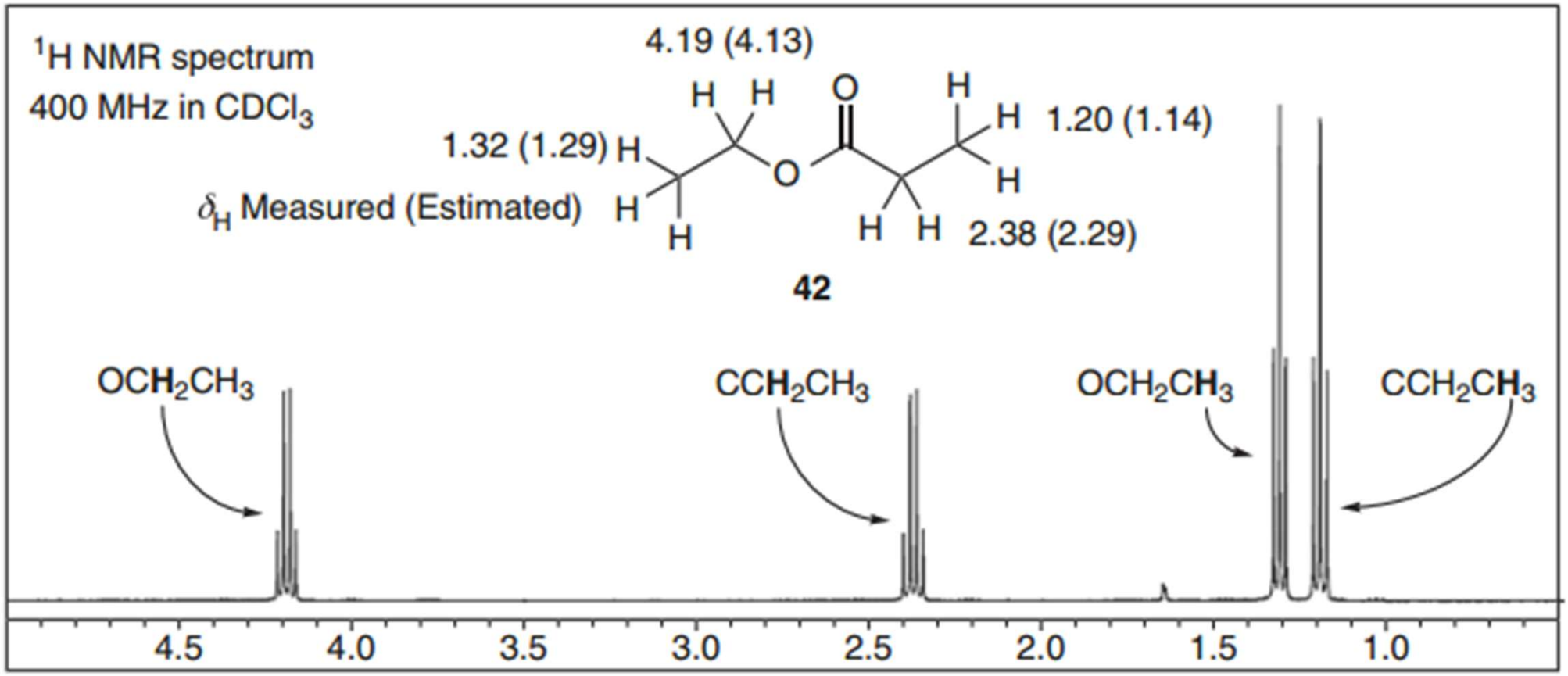
Spin-Spin (^{1}H-^{1}H) Coupling



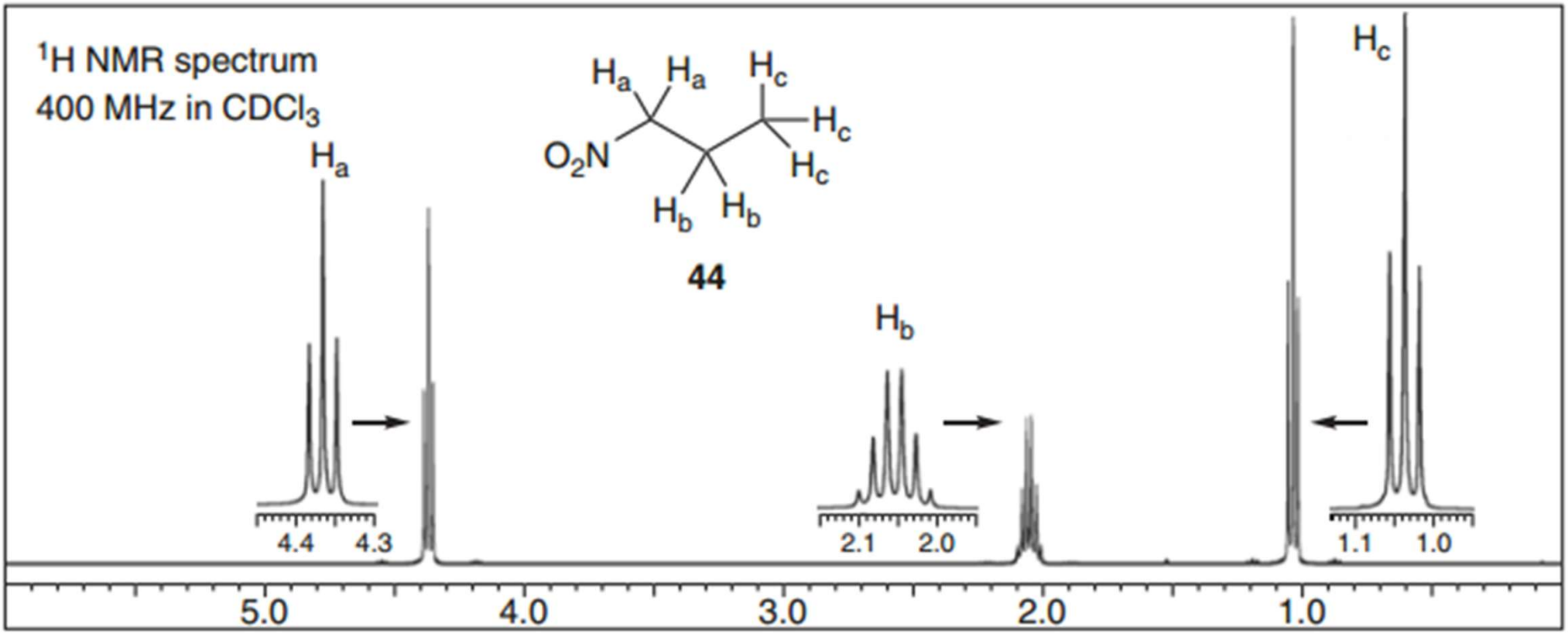
Spin-Spin (^{1}H-^{1}H) Coupling



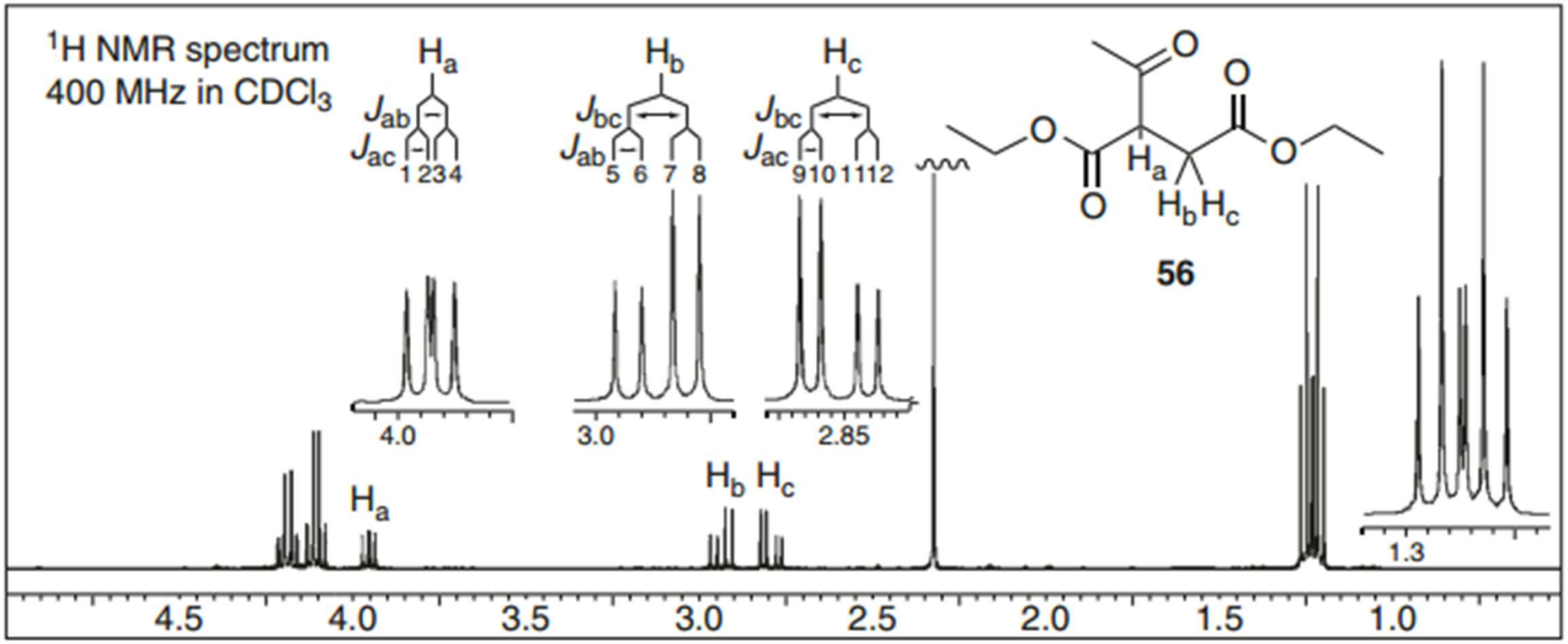
Spin-Spin (^{1}H-^{1}H) Coupling



Spin-Spin (^{1}H-^{1}H) Coupling



Spin Spin (^{1}H-^{1}H) Coupling



Coupling Constants

1. Geminal Coupling Constant (J^2) 8 - 20 Hz

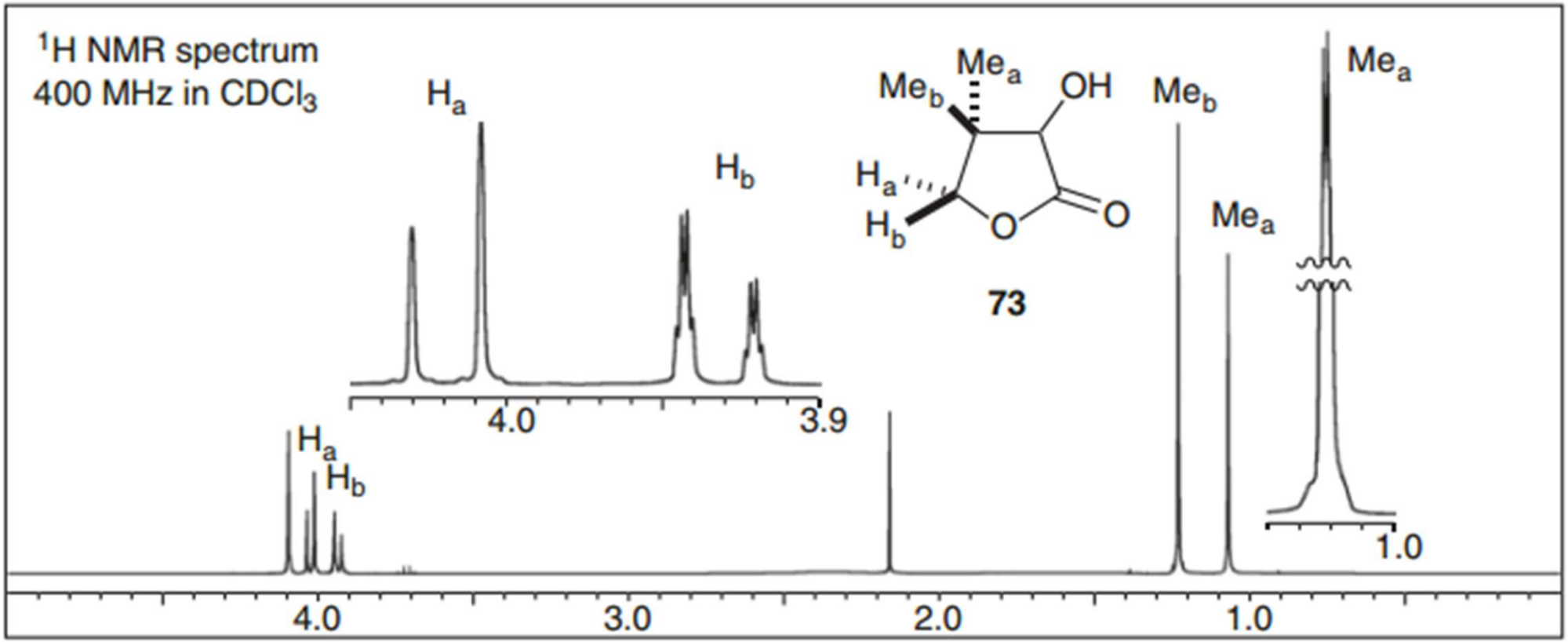
2. Vicinal Coupling Constant (J^3) 2 - 10 Hz

3. Allylic Coupling Constant (J^4) 2 - 4 Hz

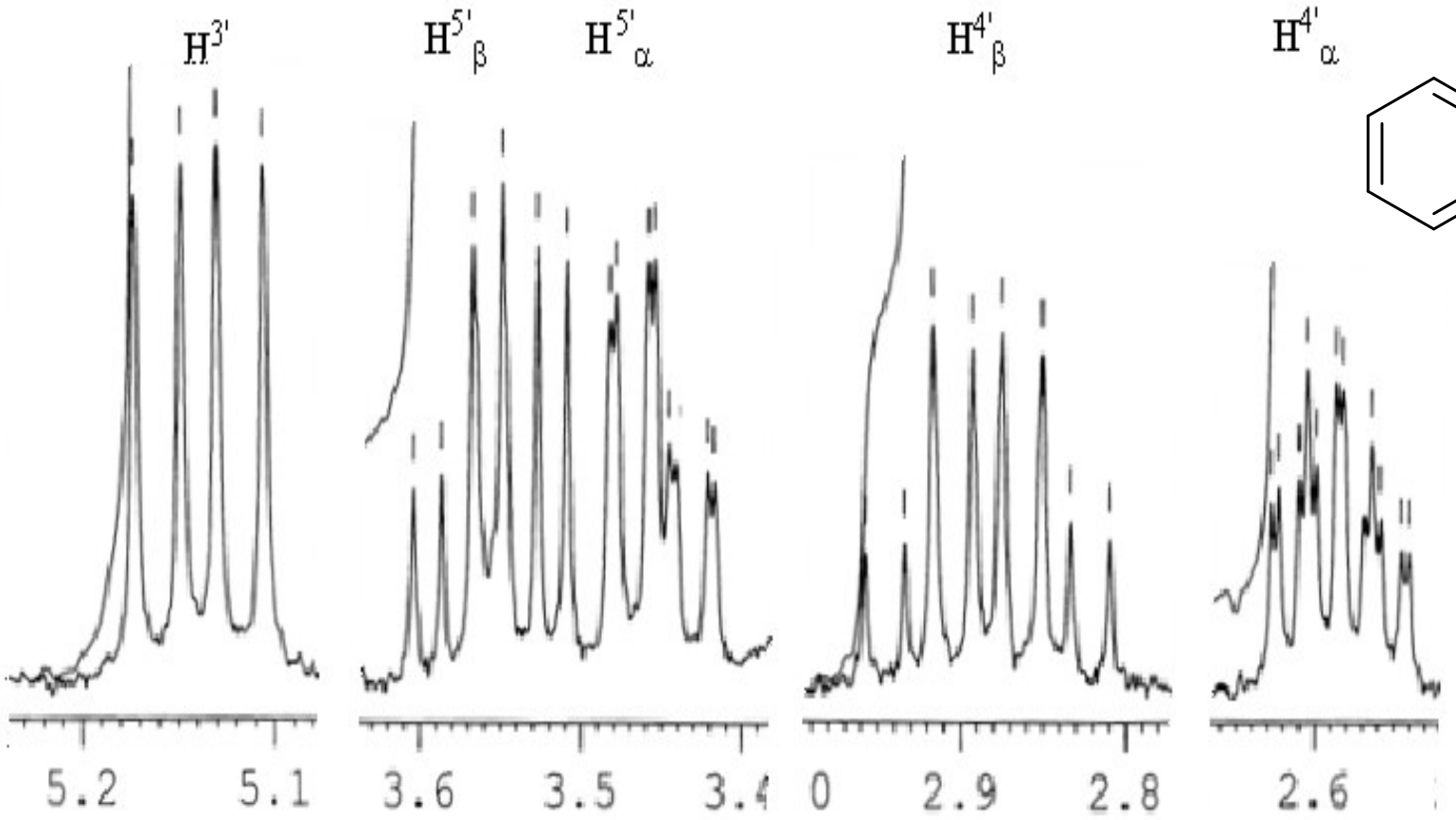
4. Homoallylic Coupling Constant (J^5) 0.5 - 2 Hz

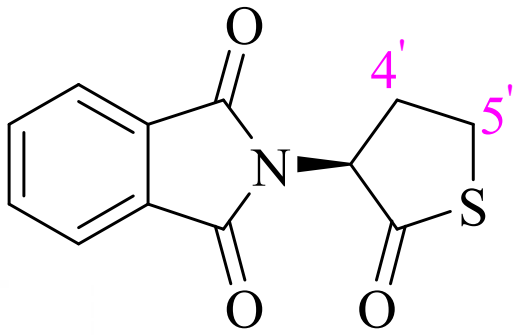
5. Long Range Coupling Constant (J^x) below 1 Hz

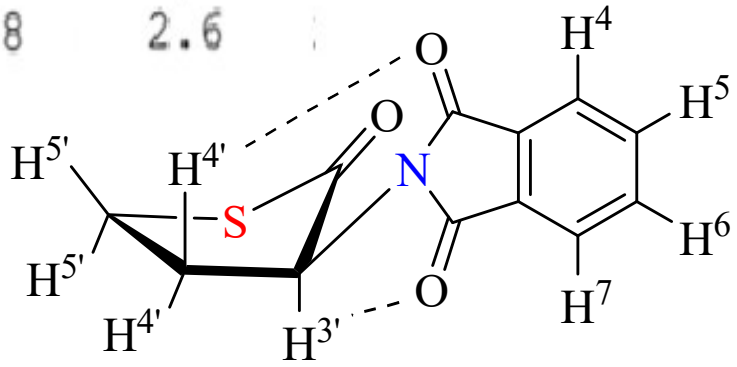
Geminal Coupling (J^2)



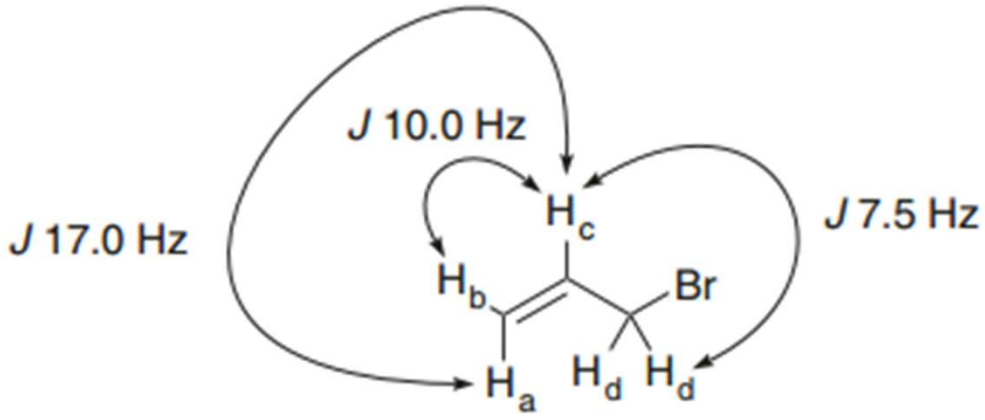
Geminal Coupling & Diastereotopy



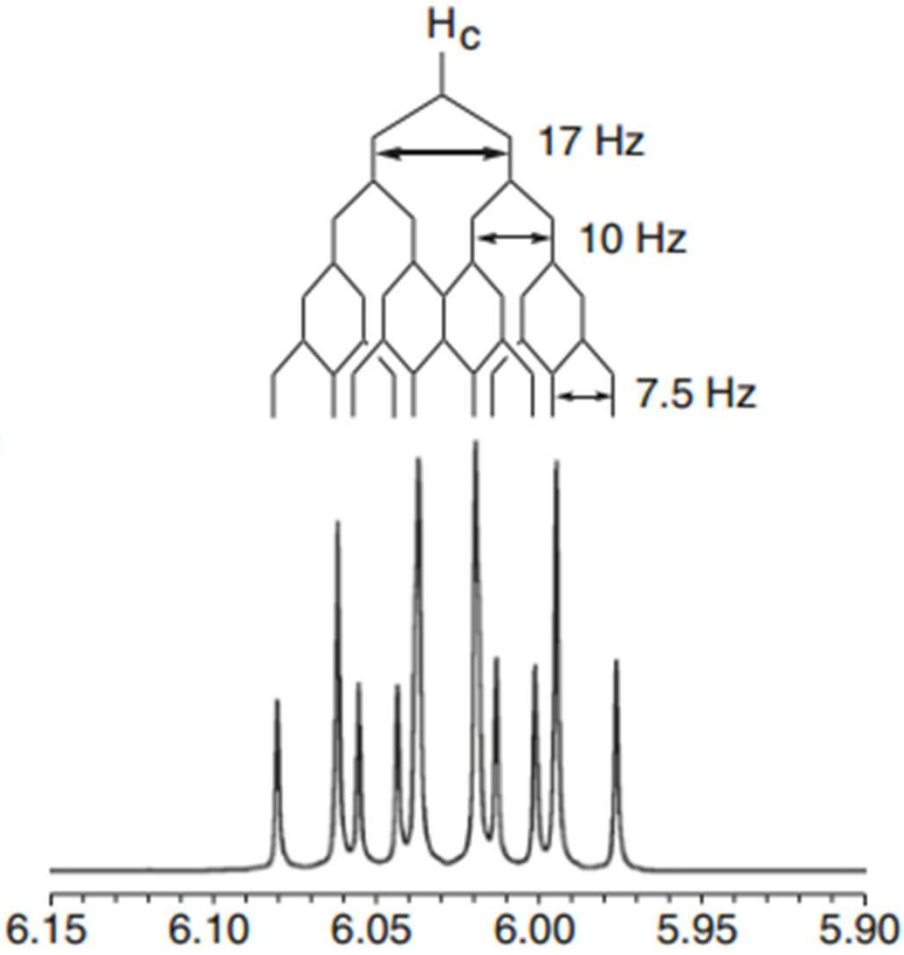




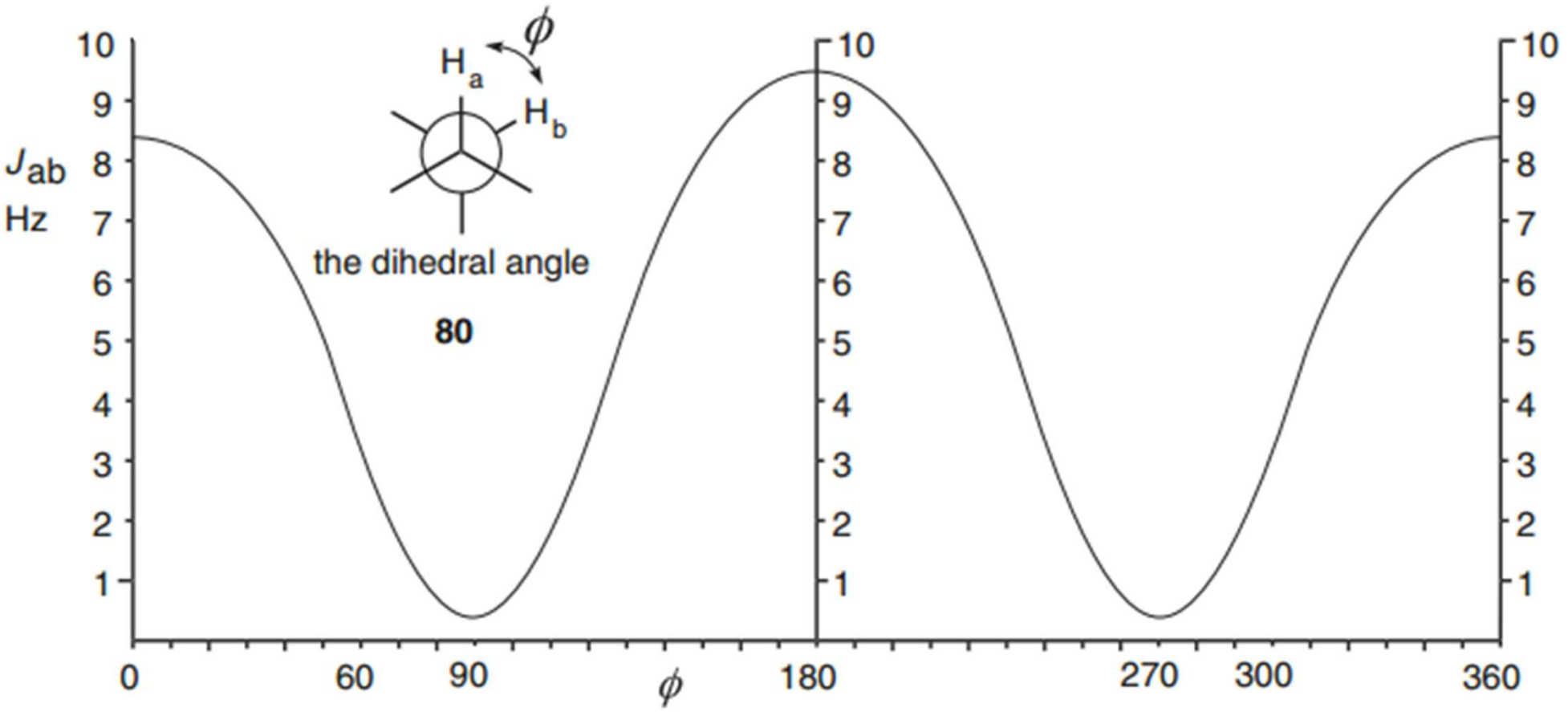
Vicinal (J^3) / allylic Coupling (J^4)



46



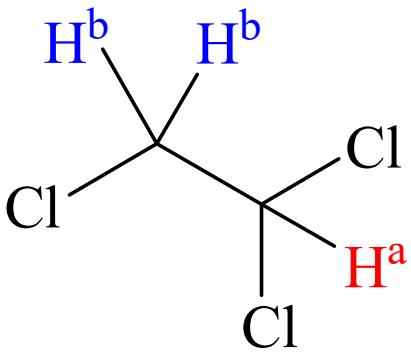
Karplus Equation (J^3)

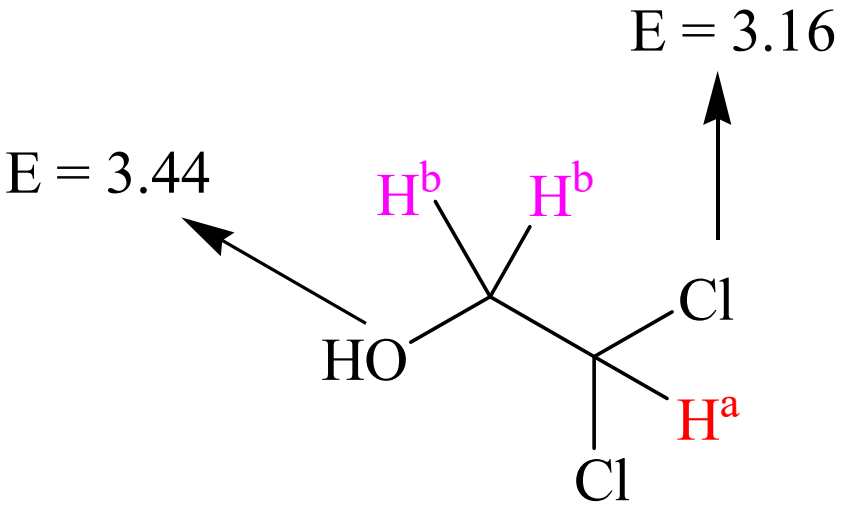


$$J^3 = 8.5 \cos^2 \theta - 0.28 \ \text{(Hz)} \qquad 90^o > \theta > 0^o$$

$$J^3 = 9.5 \cos^2 \theta - 0.28 \ \text{(Hz)} \qquad 180^o > \theta > 90^o$$

Electronegativity *vs* J^3

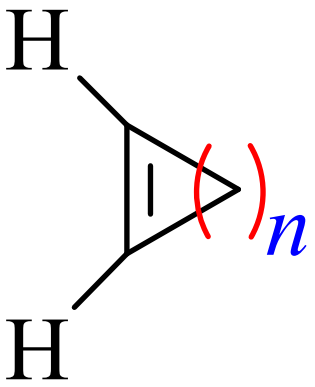


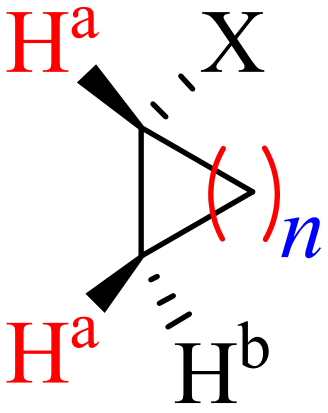


J_{ab} = 7.9 - (0.7 ΔE)
= 7.9 - [0.7 (3 x 0.61)]
= 6.62 Hz

J_{ab} = 7.9 - (0.7 ΔE)
= 7.9 - 0.7 [(2 x 0.61) + 0.89]
= 5.79 Hz

Ring Size *vs* J^2

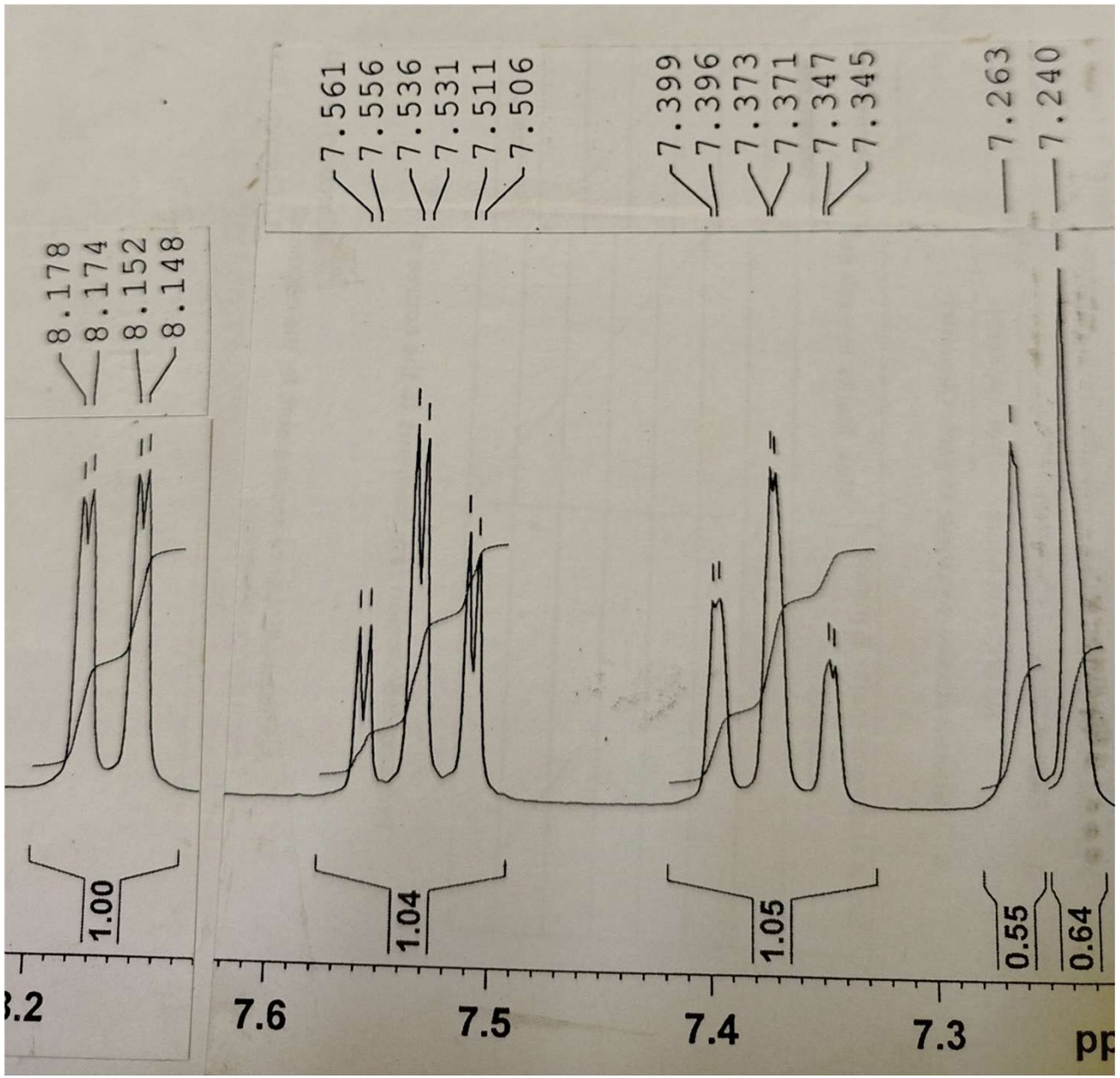


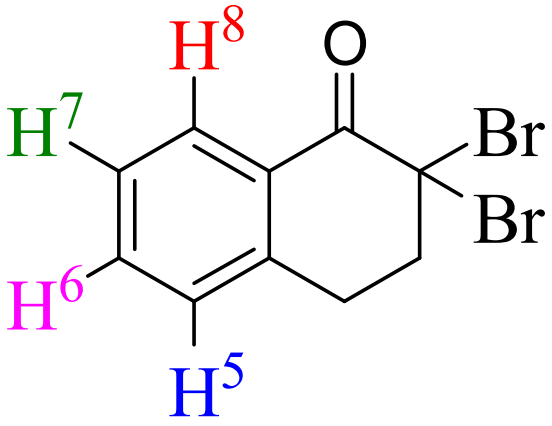


n	J^3
1	0.5 - 1.5
2	2.5 - 3.7
3	5.1 - 7.0
4	8.8 - 11.0
5	9.0 - 12.6
6	10.0 - 13.0

n	J^3_{aa}	J^3_{ab}
1	8 - 13	5 - 10
2	5 - 11	2 - 11
3	1 - 9	1 - 9
4	10 - 13	2 - 5

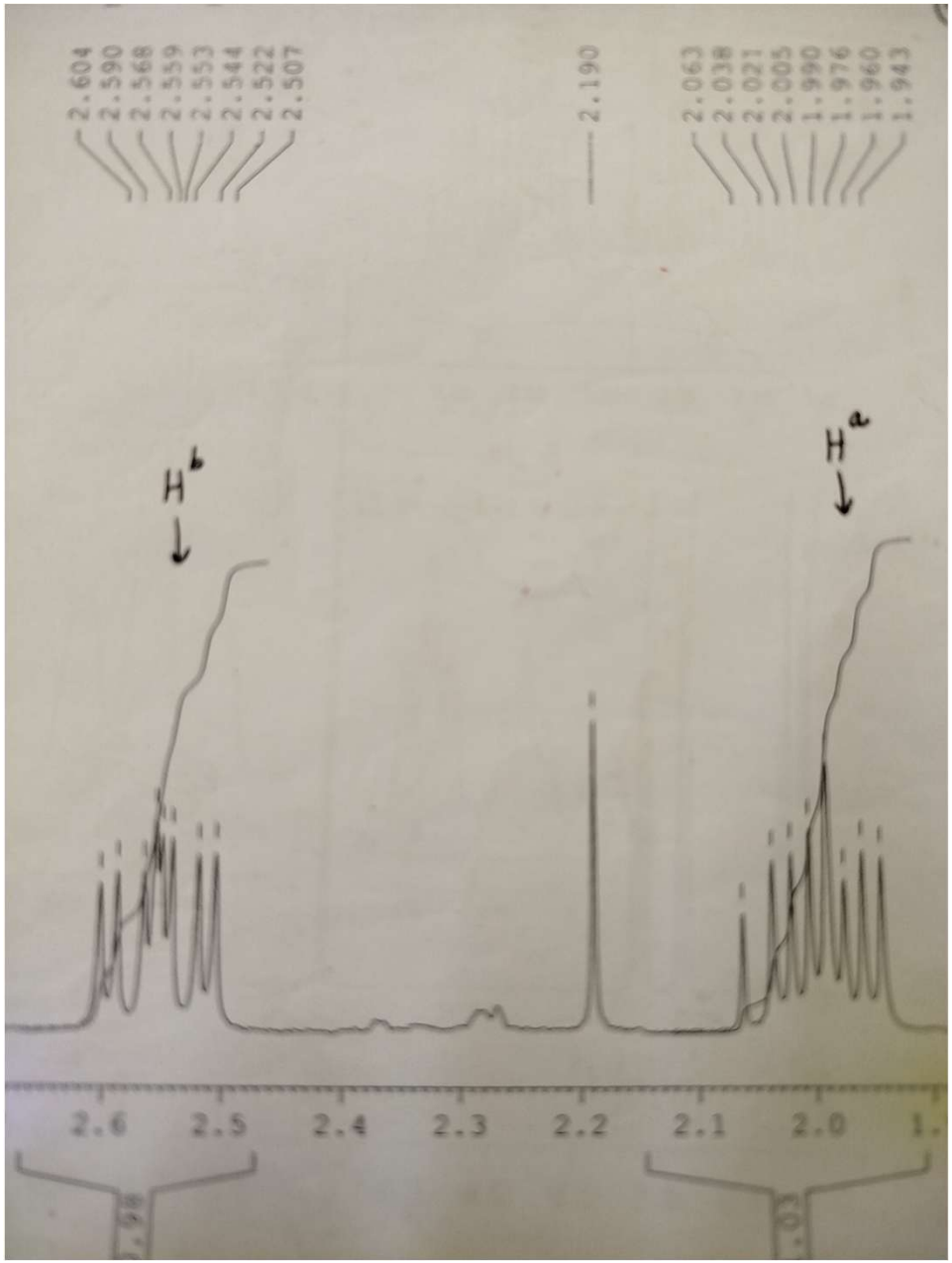
Calculating Coupling Constant(s)

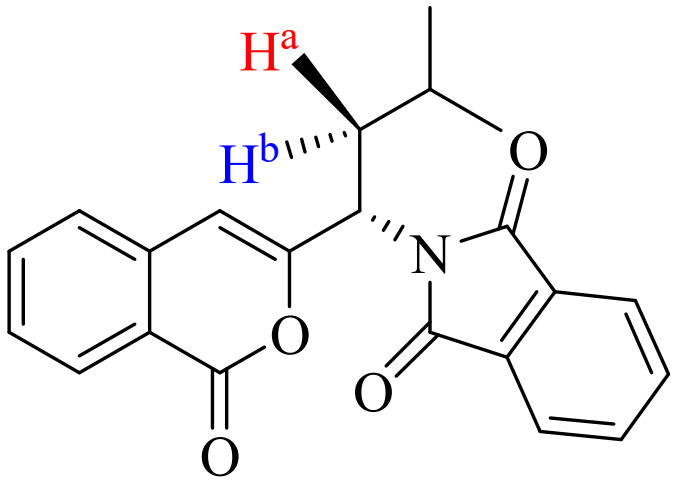




300 MHz ($CDCl_3$)

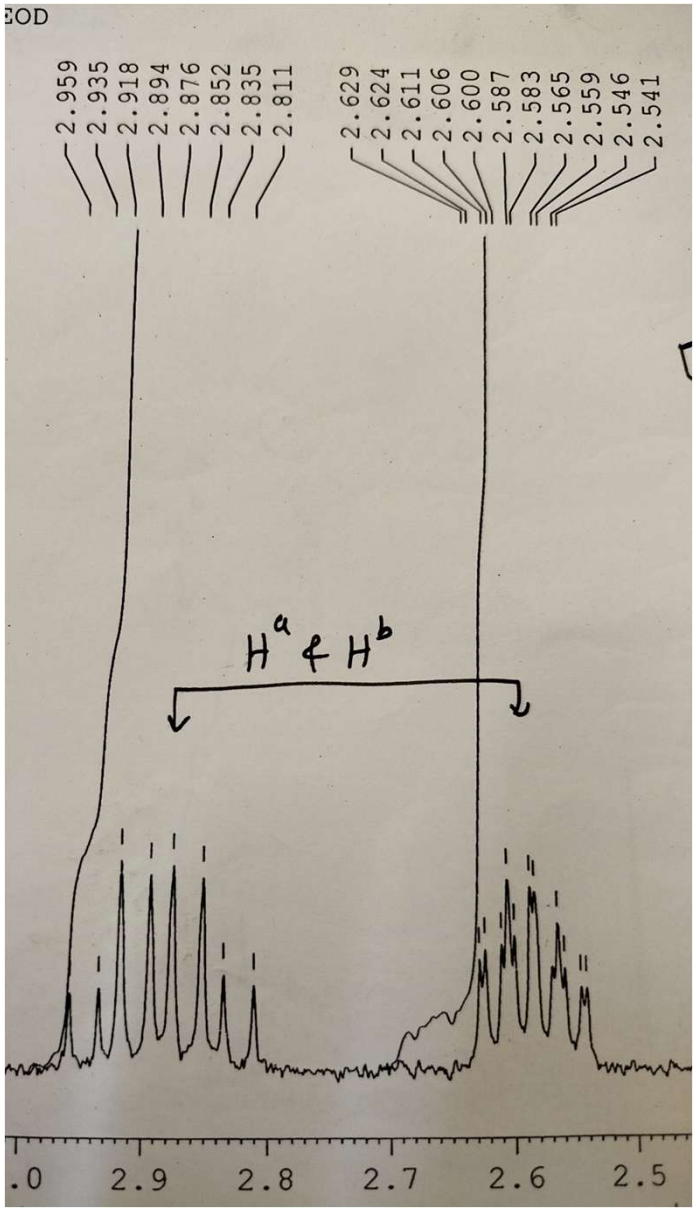
Calculating Coupling Constant(s)

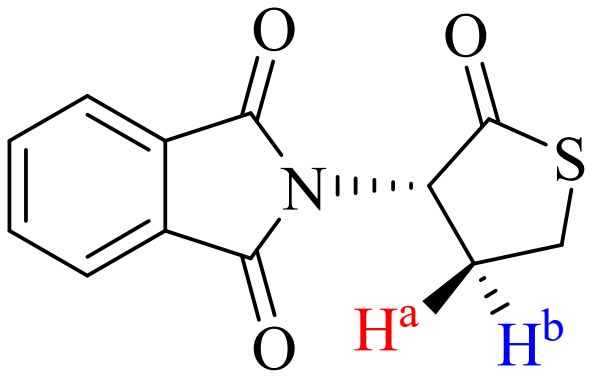




300 MHz ($CDCl_3$)

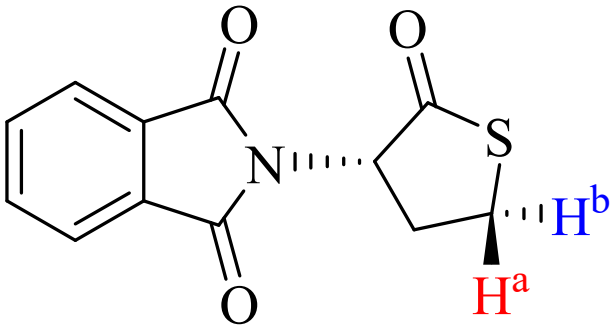
Calculating Coupling Constant(s)





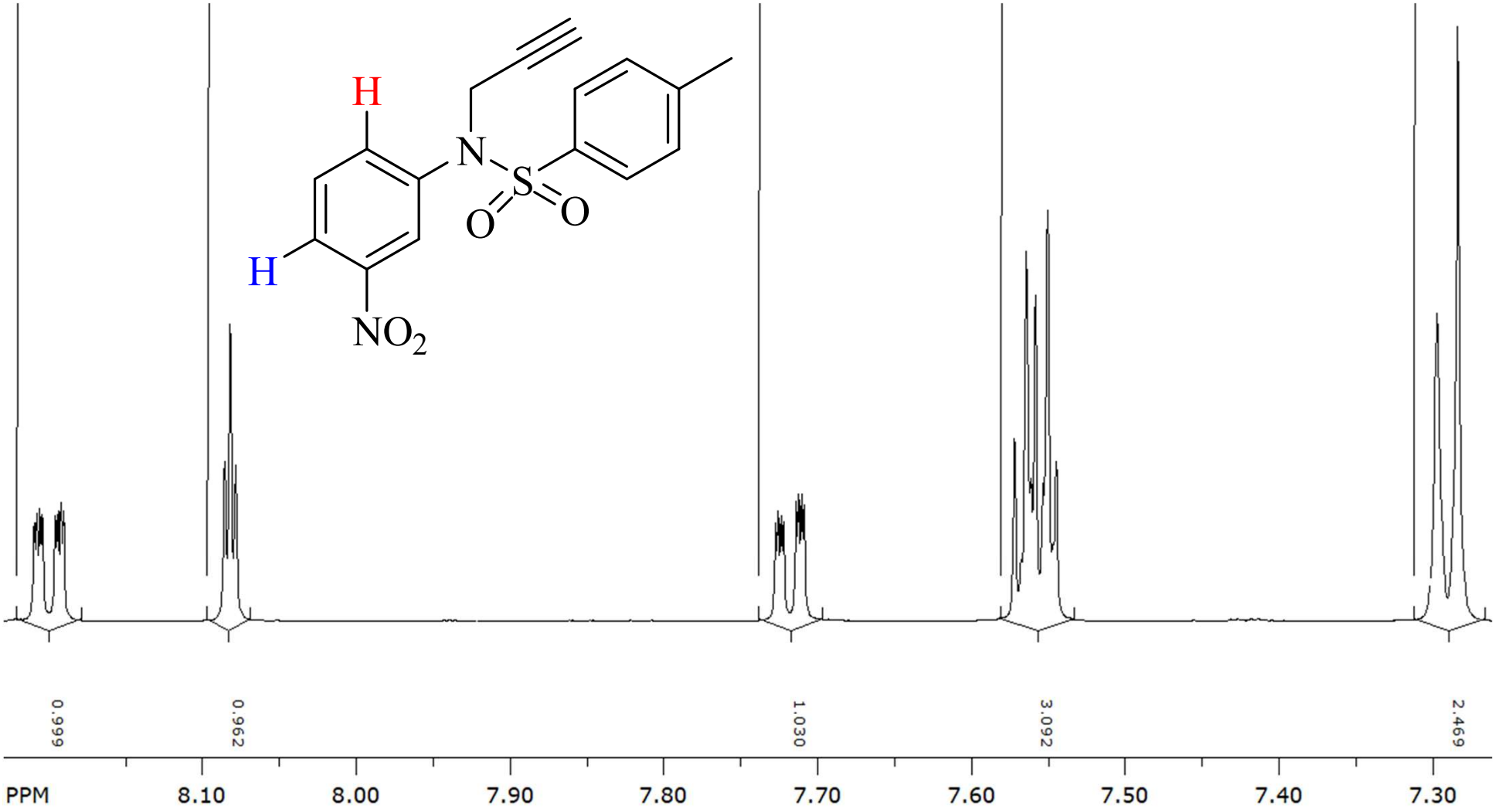
300 MHz ($CDCl_3$)

Calculating Coupling Constant(s)

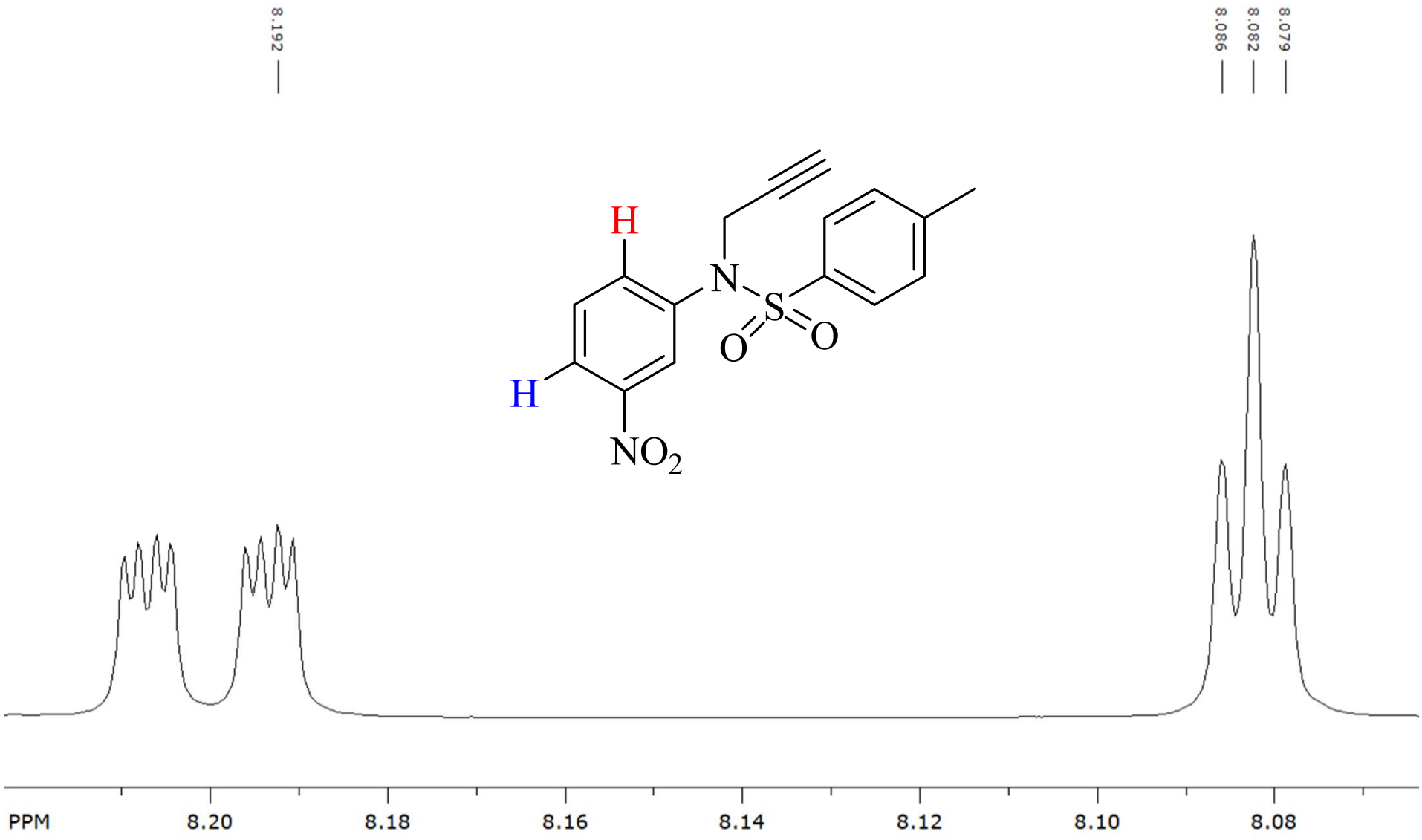


300 MHz ($CDCl_3$)

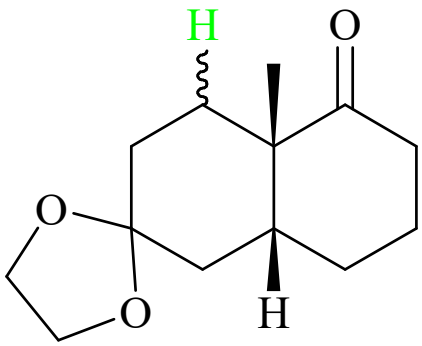
Integration

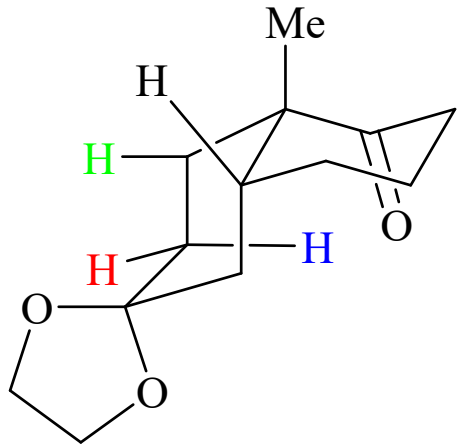


Integration

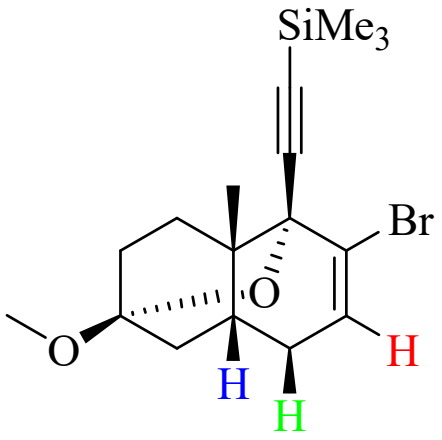


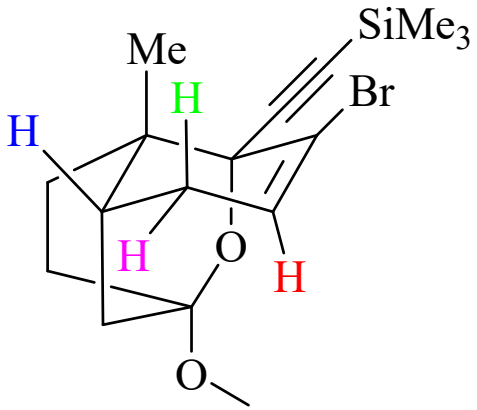
Working Out *J*



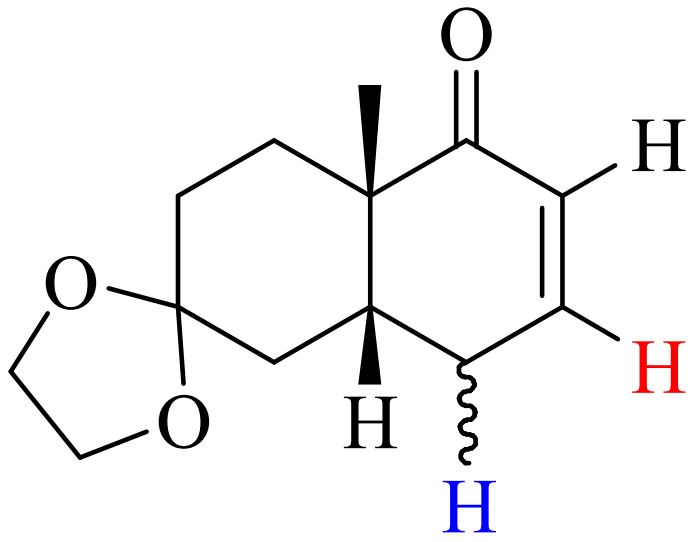


Working Out *J*





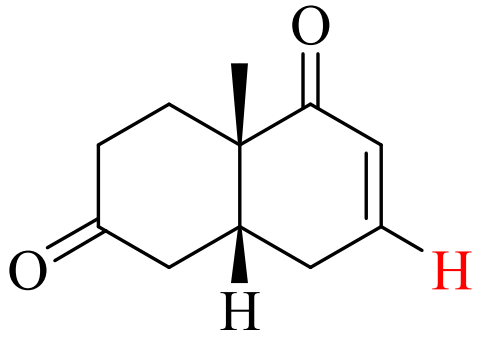
Working Out Splitting Pattern



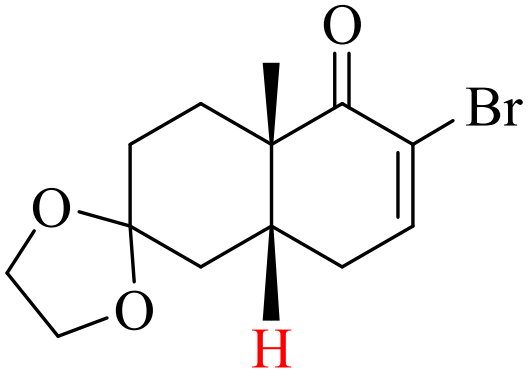
H = 2.72 (1H, dddd, J = -19.8, 2.7, 2.7, 2.7 Hz)

H = 6.67 (1H, dddd, J = 10.2, 5.7, 2.4, 1.5 Hz)

Working Out Splitting Pattern



H = 6.74 (1H, dddd, J = 10.2, 5.4, 1.2, 1.2 Hz)



H = 2.29 (1H, dddd, J = 12.3, 5.4, 1.2, 1.2 Hz)

Predicting δ of a ^1H

Table 4.23 ^1H Chemical shifts in methyl, methylene and methine groups

	Methyl protons	δ_H	Methylene protons	δ_H	Methine protons	δ_H
C	R–CH_3	0.9	R–CH_2–R	1.4	R–CHR_2	1.5
	C=C–C–CH_3	1.1	C=C–C–CH_2–R	1.7		
	O–C–CH_3	1.3	O–C–CH_2–R	1.9	O–C–CHR_2	2.0
	N–C–CH_3	1.1	N–C–CH_2–R	1.4		
	O_2N–C–CH_3	1.6	O_2N–C–CH_2–R	2.1		
	C=C–CH_3	1.6	C=C–CH_2–R	2.3		
	Ar–CH_3	2.3	Ar–CH_2–R	2.7	Ar–CHR_2	3.0
	O=CC=C–CH_3	2.0	O=CC=C–CH_2–R	2.4		
	O=CC(CH_3)=C	1.8	O=CC(CH_2–R)=C	2.4		
	C≡C–CH_3	1.8	C≡C–CH_2–R	2.2	C≡C–CHR_2	2.6
	RCO–CH_3	2.2	RCO–CH_2–R	2.4	RCO–CHR_2	2.7
	ArCO–CH_3	2.6	ArCO–CH_2–R	2.9	ArCO–CHR_2	3.3
	ROOC–CH_3	2.0	ROOC–CH_2–R	2.2	ROOC–CHR_2	2.5
	ArOOC–CH_3	2.4	ArOOC–CH_2–R	2.6		
	N–CO–CH_3	2.0	N–CO–CH_2–R	2.2	N–CO–CHR_2	2.4
	N≡C–CH_3	2.0	N≡C–CH_2–R	2.3	N≡C–CHR_2	2.7
N	N–CH_3	2.3	N–CH_2–R	2.5	N–CHR_2	2.8
	ArN–CH_3	3.0	ArN–CH_2	3.5		
	RCON–CH_3	2.9	RCON–CH_2–R	3.2	RCO–N–CHR_2	4.0
	N^+–CH_3	3.3	N^+–CH_2–R	3.3		
	O_2N–CH_3	4.3	O_2N–CH_2–R	4.4	O_2N–CHR_2	4.7

Predicting δ of a ^{1}H

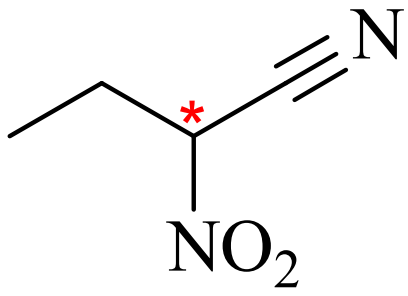
Estimation of ^{1}H Chemical Shifts in Alkanes

$$\text{For } R^1R^2R^3C{-}H, \quad \delta_H = 1.50 + \sum z_i \qquad (4.23)$$

Table 4.24 Substituent constants z for Eq. (4.23)

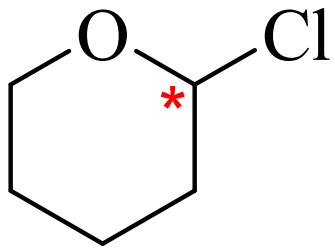
R^i	z	R^i	z	R^i	z	R^i	z
H–	−0.3	CH_2=CH–	0.8	NC–	1.2	AcO–	2.7
Alkyl–	0.0	Ph–	1.3	H_2N–	1.0	Cl–	2.0
CH_2=$CHCH_2$–	0.2	HC≡C–	0.9	O_2N–	3.0	Br–	1.9
$MeCOCH_2$–	0.2	OHC–	1.2	HO–	1.7	I–	1.4
$HOCH_2$–	0.3	MeCO–	1.2	MeO–	1.5	MeS–	1.0
$ClCH_2$–	0.5	RO_2C–	0.8	PhO–	2.3	Me_3Si–	0.7

Predicting δ of a ^1H



$\delta_H = 1.50 + 0\ (Et) + 1.20\ (CN) + 3.0\ (NO_2)$

$\delta_H = 5.70$ ppm

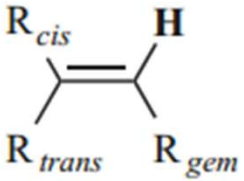


$\delta_H = 1.50 + 0\ (Et) + 1.50\ (OR) + 2.0\ (Cl)$

$\delta_H = 5.00$ ppm

Predicting δ of a ^{1}H

Estimation of ^{1}H Chemical Shifts in Alkenes

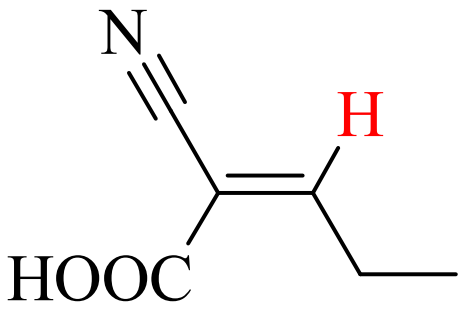


$$\delta_H = 5.25 + \Sigma z_{gem} + \Sigma z_{cis} + \Sigma z_{trans} \quad (4.24)$$

Table 4.26 Substituent constants z for Eq. (4.24)

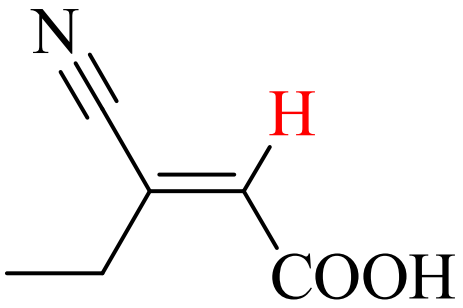
	Substituent R	z_{gem}	z_{cis}	z_{trans}
H	H–	0	0	0
C	Alkyl–	0.45	–0.22	–0.28
	Ring-alkyl–[a]	0.69	–0.25	–0.28
	N≡CCH_2– or $RCOCH_2$–	0.69	–0.08	–0.06
	$ArCH_2$–	1.05	–0.29	–0.32
	R_2NCH_2–	0.58	–0.10	–0.08
	$ROCH_2$–	0.64	–0.10	–0.02
	$HalCH_2$–	0.70	0.11	–0.04
	$RSCH_2$–	0.71	–0.13	–0.22
	Isolated RCH=CH–	1.00	–0.09	–0.23
	Conjugated CH=CH–[b]	1.24	0.02	–0.05
	Ar–	1.38	0.36	–0.07
	OHC–	1.02	0.95	1.17
	Isolated RCO–	1.10	1.12	0.87
	Conjugated RCO–[b]	1.06	0.91	0.74
	Isolated HO_2C–	0.97	1.41	0.71

Predicting δ of a ^{1}H



$\delta_H = 5.25 + 0.45$ (*gem*) $+ 0.75$ (*cis*) $+ 0.71$ (*trans*)

$\delta_H = 7.16$ ppm

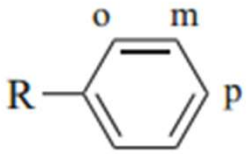


$\delta_H = 5.25 + 0.97$ (*gem*) $+ 0.75$ (*cis*) $- 0.28$ (*trans*)

$\delta_H = 6.69$ ppm

Predicting δ of a ^1H

Estimation of ^1H chemical shifts in substituted benzenes

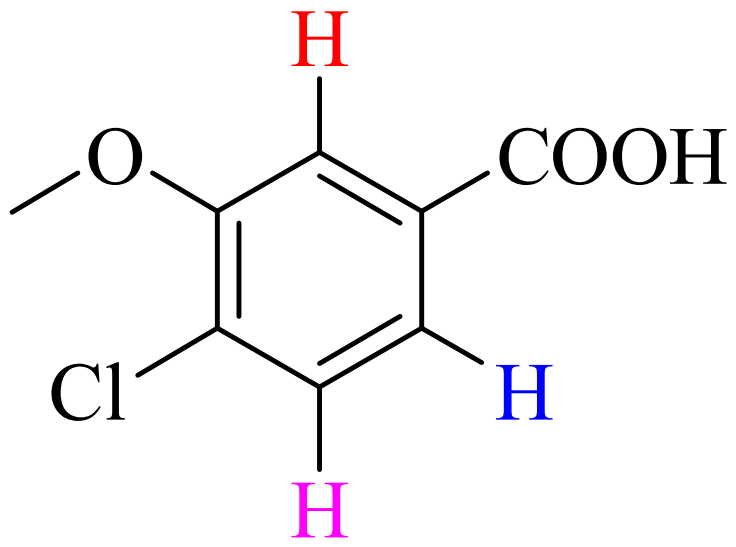


$$\delta_H = 7.27 + \Sigma z_i \qquad (4.25)$$

Table 4.29 Substituent constants z for Eq. (4.25)

	Substituent R	z_{ortho}	z_{meta}	z_{para}
H	H–	0	0	0
C	Me–	–0.20	–0.12	–0.22
	Et–	–0.14	–0.06	–0.17
	Pr^i–	–0.13	–0.08	–0.18
	Bu^t–	–0.02	–0.08	–0.21
	H_2NCH_2– or $HOCH_2$–CH_2–	–0.07	–0.07	–0.07
	$ClCH_2$–	0.00	0.00	0.00
	F_3C–	0.32	0.14	0.20
	Cl_3C–	0.64	0.13	0.10
	CH_2=CH–	0.06	–0.03	–0.10
	Ph–	0.37	0.20	0.10
	OHC–	0.56	0.22	0.29
	MeCO–	0.62	0.14	0.21
	H_2NCO–	0.61	0.10	0.17

Predicting δ of a ^1H



$\delta_H = 7.27 + 0.85\ (COOH) - 0.48\ (OMe) - 0.02\ (Cl)$

$\delta_H = 7.62$ ppm

$\delta_H = 7.27 + 0.85\ (COOH) - 0.44\ (OMe) - 0.02\ (Cl)$

$\delta_H = 7.66$ ppm

$\delta_H = 7.27 + 0.18\ (COOH) - 0.09\ (OMe) + 0.03\ (Cl)$

$\delta_H = 7.39$ ppm

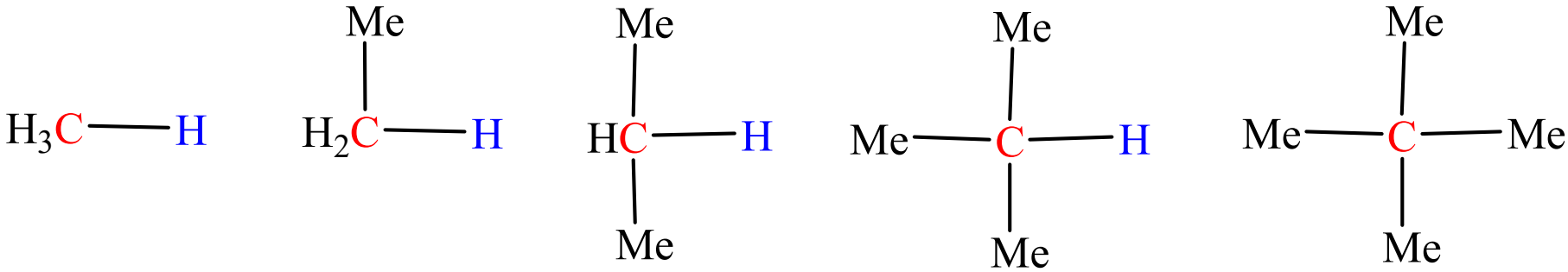
Predicting δ of a ^{1}H

Table 4.31 ^{1}H Chemical shifts of protons attached to elements other than carbon[a]

	Structure	δ_H		Structure	δ_H
NH	RNH_2 and R_2NH	0.5–4.5	OH	Monomeric H_2O	~1.5
	$ArNH_2$ and ArNHR	3–6		Suspended H_2O	~4.7
	$RCONH_2$ and RCONHR	5–12		ROH	0.5–4.5
	Pyrrole NH	7–12		ArOH	4.5–10
				RCO_2H	9–15
SiH	Me_3SiH	4.0		$R_2C{=}NOH$	9–12
	Ar_3SiH	~5.5	Intramolecularly H-bonded OH		7–16
SnH	R_3SnH	~5.3	SH	RSH	1–2
PH	$(RO)_2P(=O)H$	~6.8[b]		ArSH	3–4

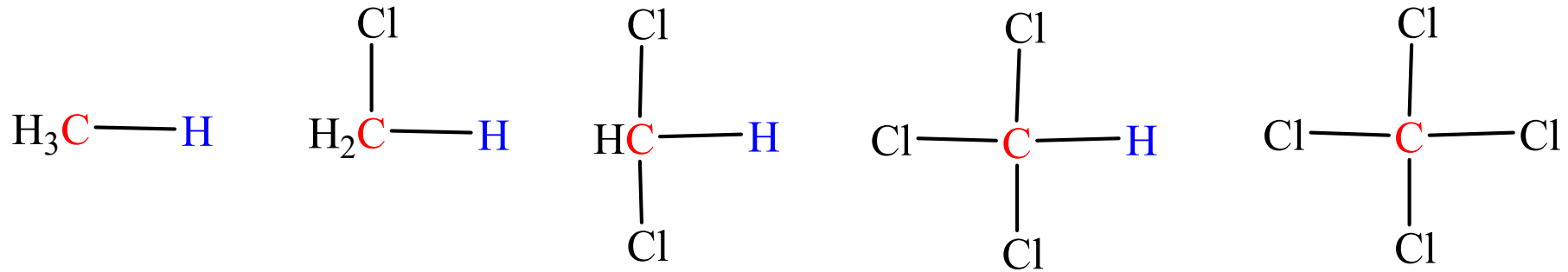
^{13}C NMR (δ)

δ (ppm) -2.3 8.4 15.9 25.0 27.7



δ (ppm) 0.23 0.86 1.33 1.68

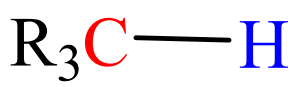
δ (ppm) -2.3 24.9 54.0 77.2 96.1



δ (ppm) 0.23 3.06 5.33 7.24

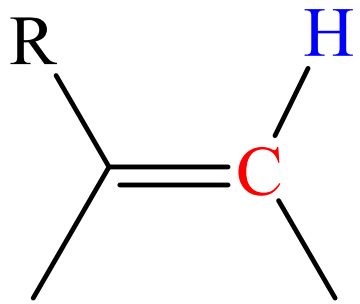
^{13}C NMR (δ)

δ (ppm) 10-100



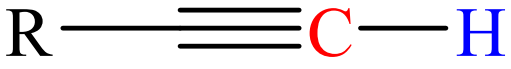
δ (ppm) 1.0-4.0

120-140

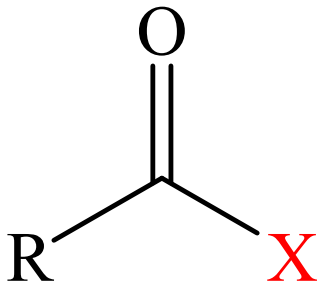


δ (ppm) 5.25-6.5

65-80



δ (ppm) 1.0-2.5



X	δ (ppm)
H	190-220
R / Ar	190-220
OH	170-180
OR	165-175
Cl/Br/I	155-160
NH_2	145-155

^{13}C NMR

Broad Band ^{13}C-NMR = $CH_3 + CH_2 + CH + C$

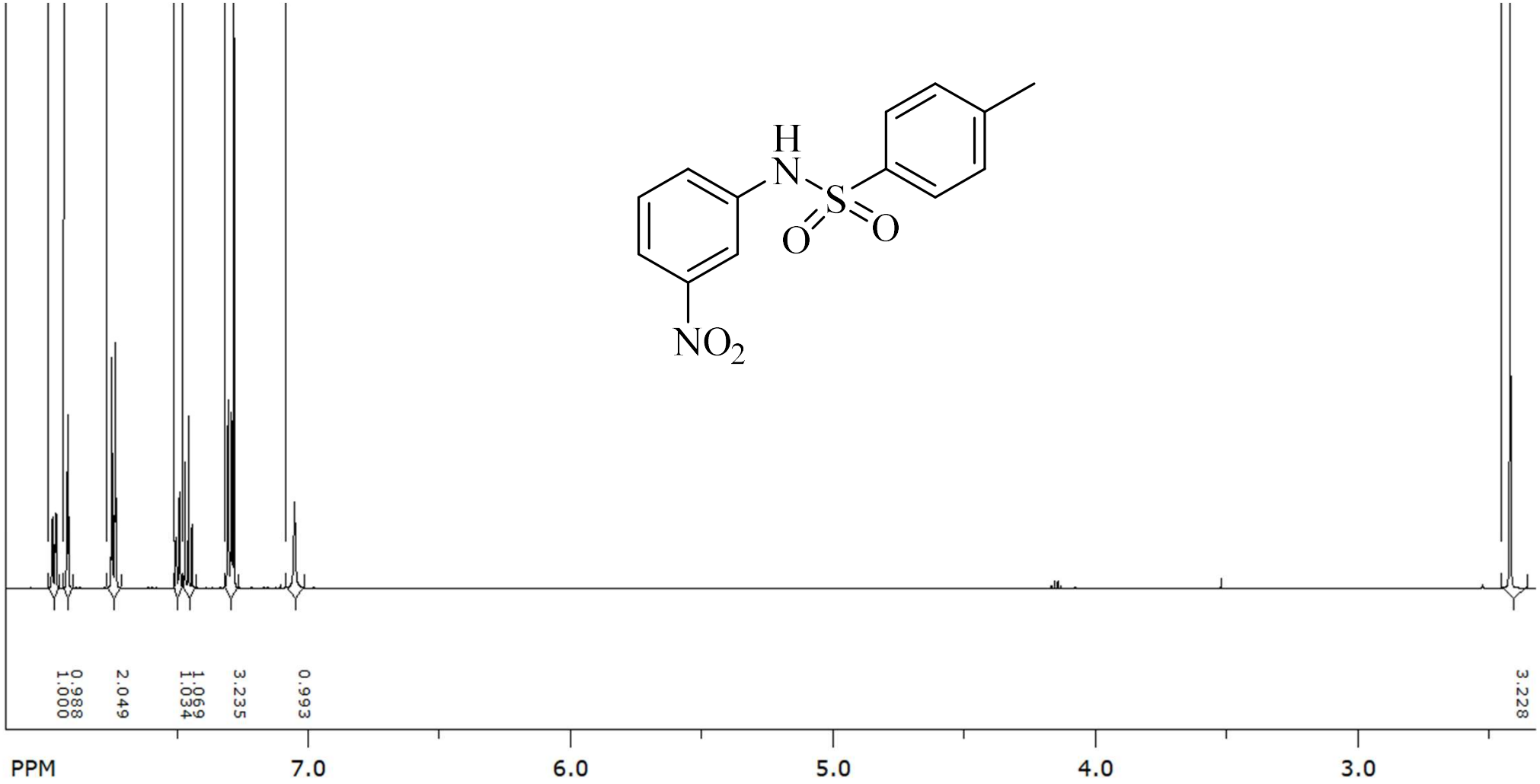
DEPT-45° ^{13}C-NMR = $CH_3 + CH_2 + CH$

DEPT-90° ^{13}C-NMR = CH

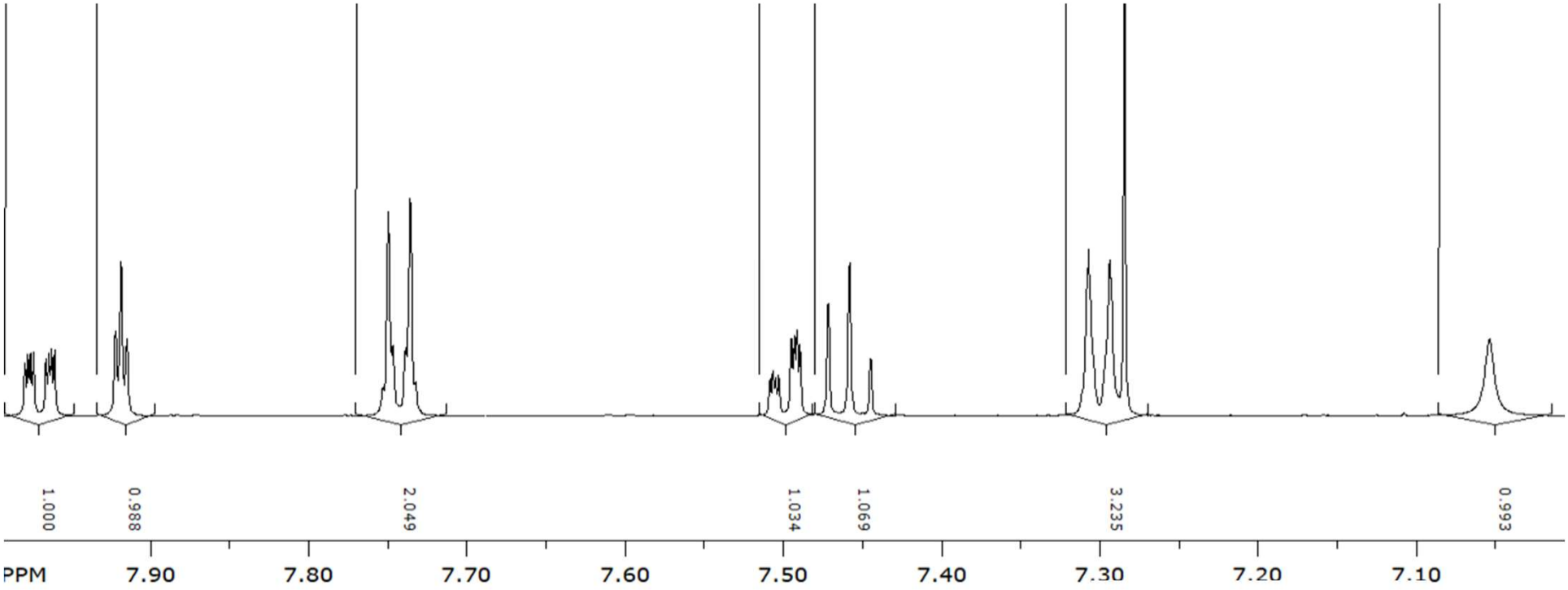
DEPT-135° ^{13}C-NMR = $CH_3 + CH$ (+ve Phase) + CH_2 (-ve Phase)

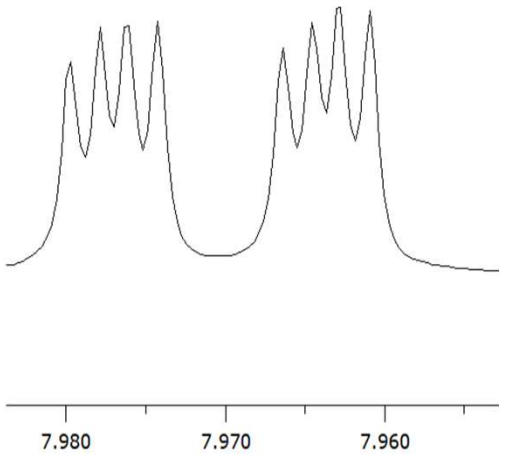
DEPT = Distortionless Enhancement by Polarization Transfer

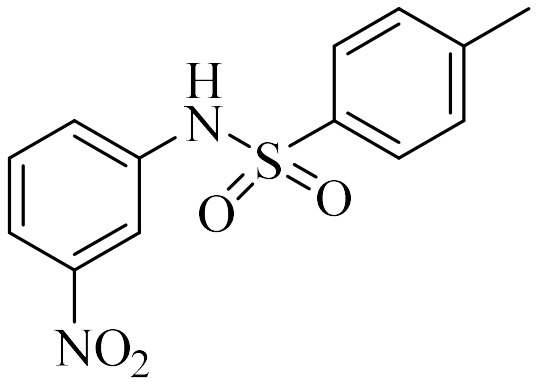
Application

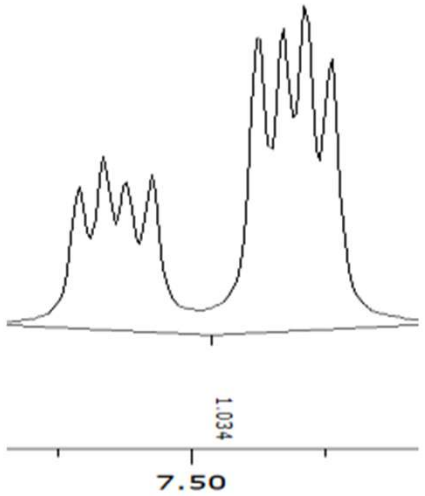


Application

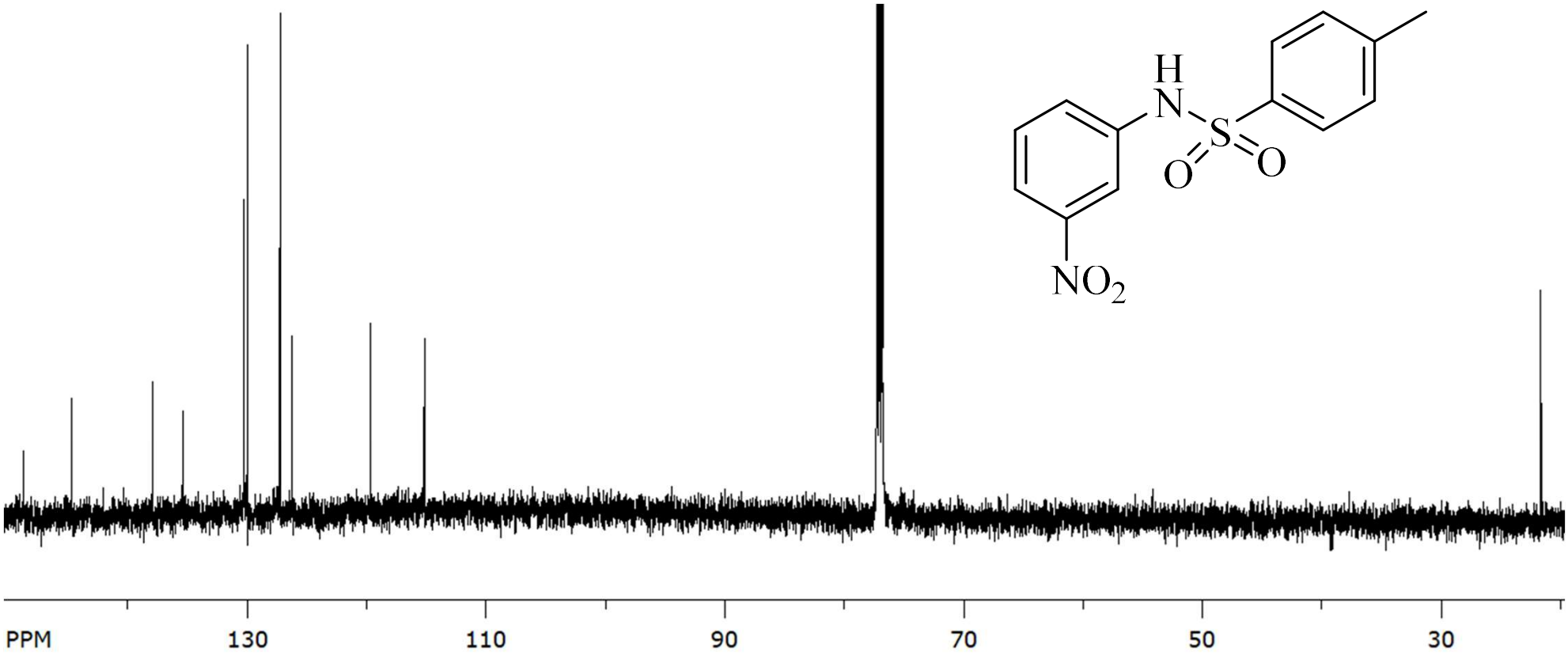




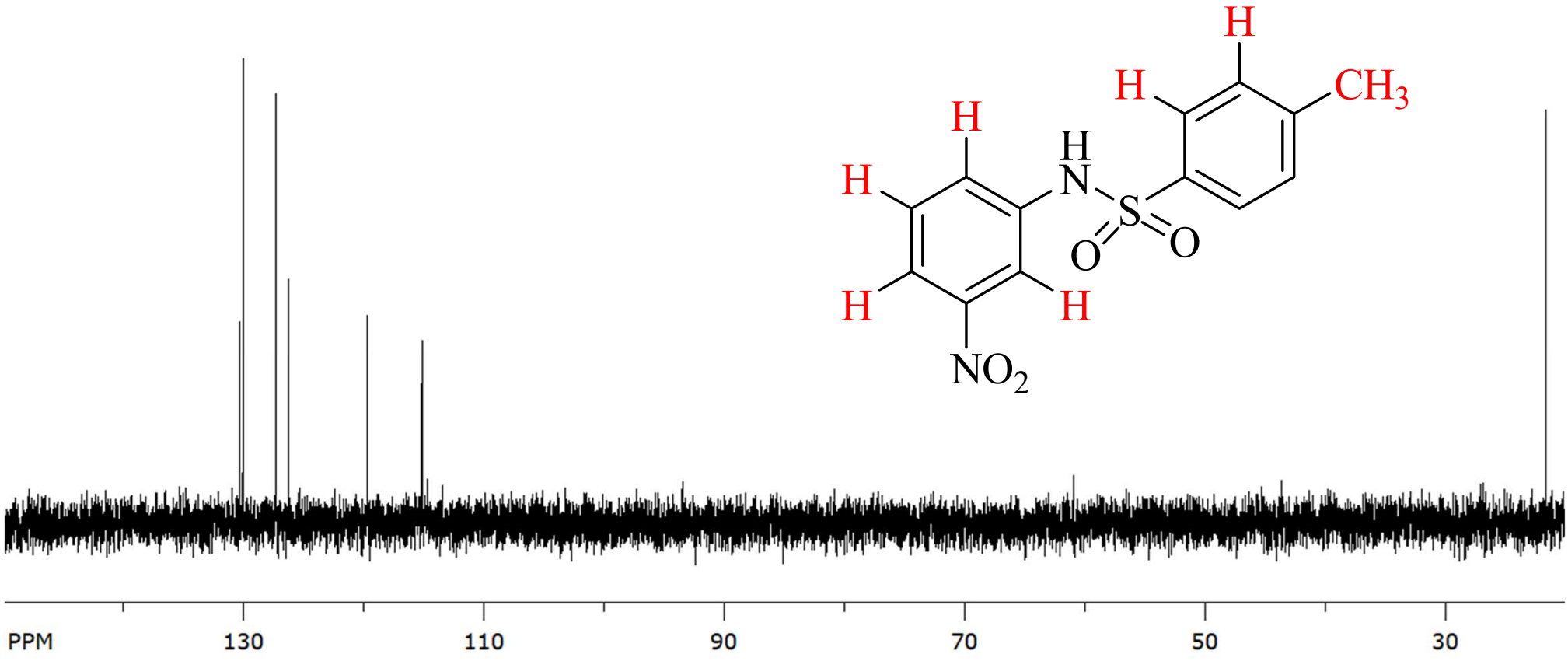




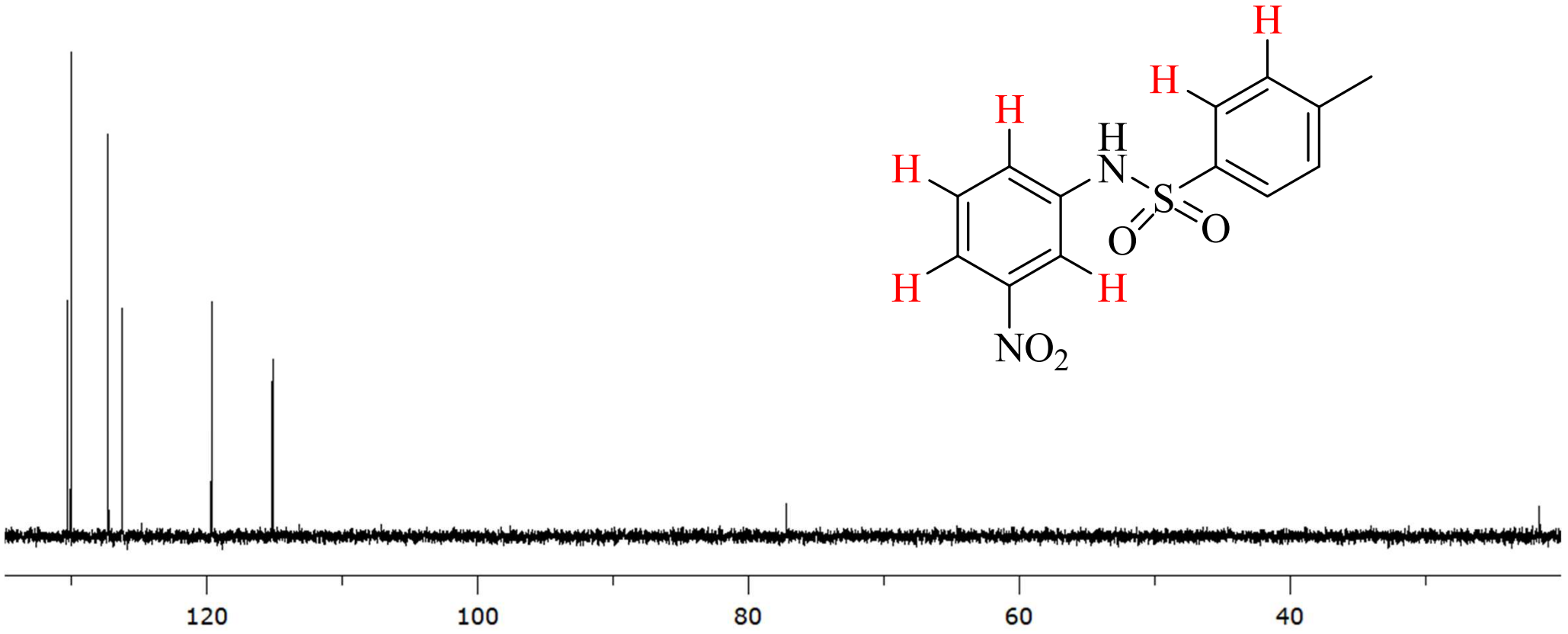
Application (BB)



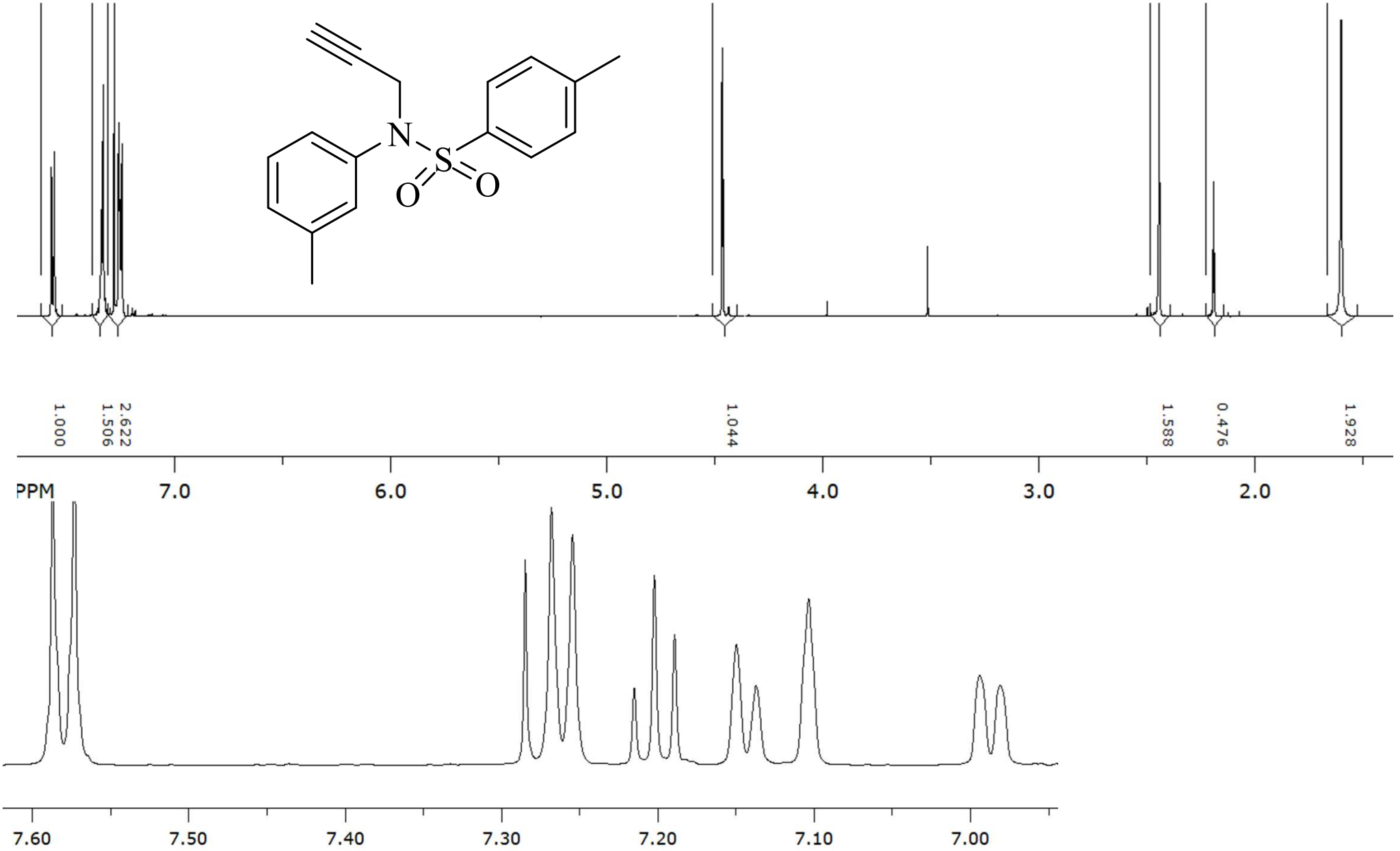
Application (DEPT-45)



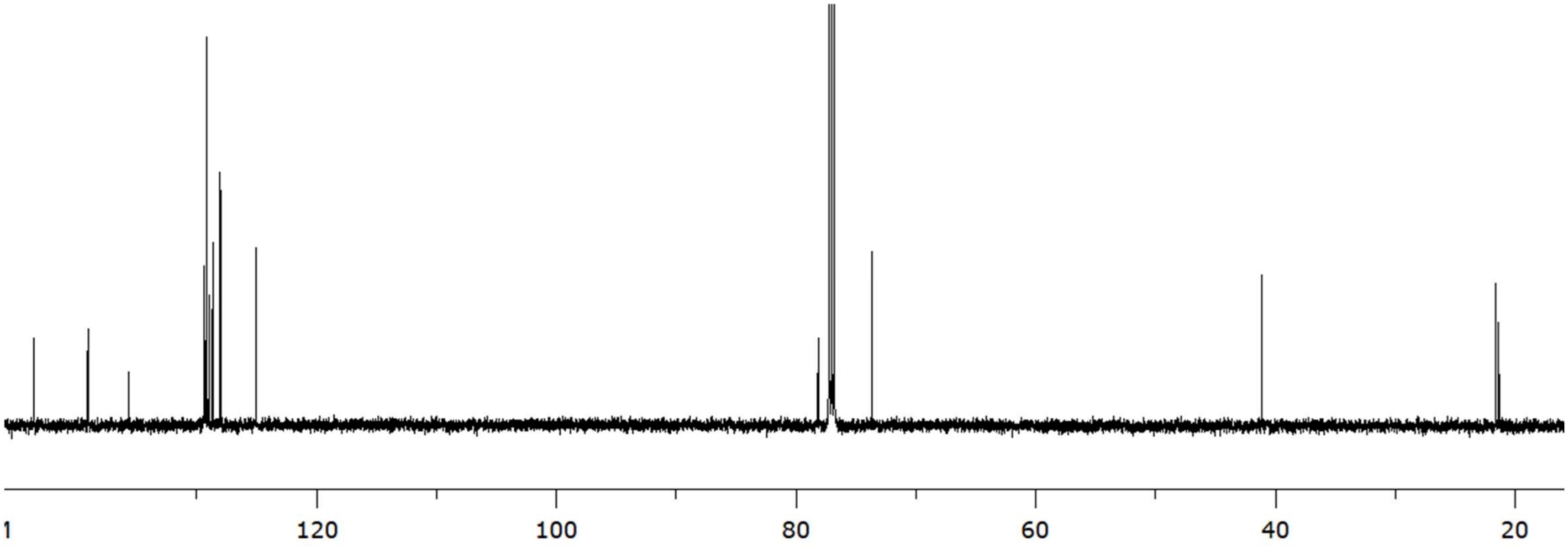
Application (DEPT-90)

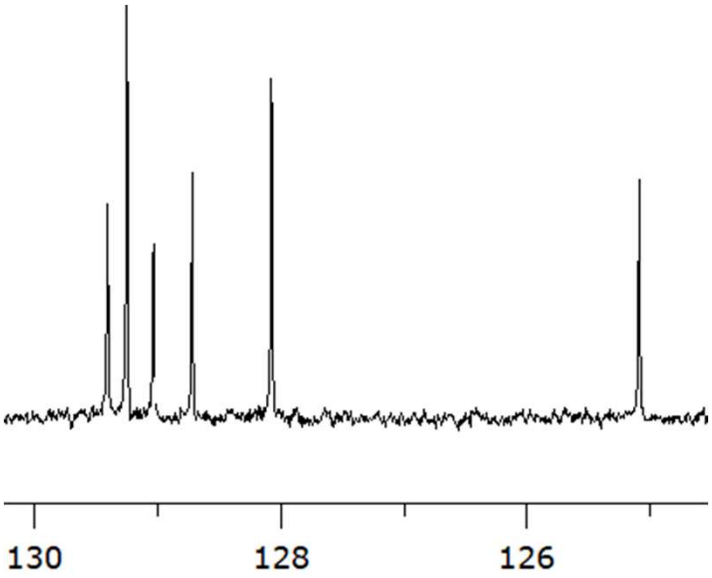


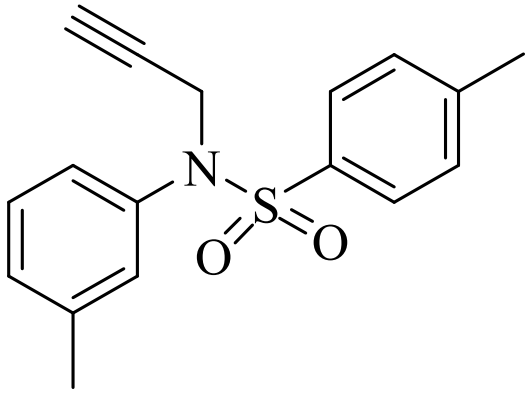
Application-II



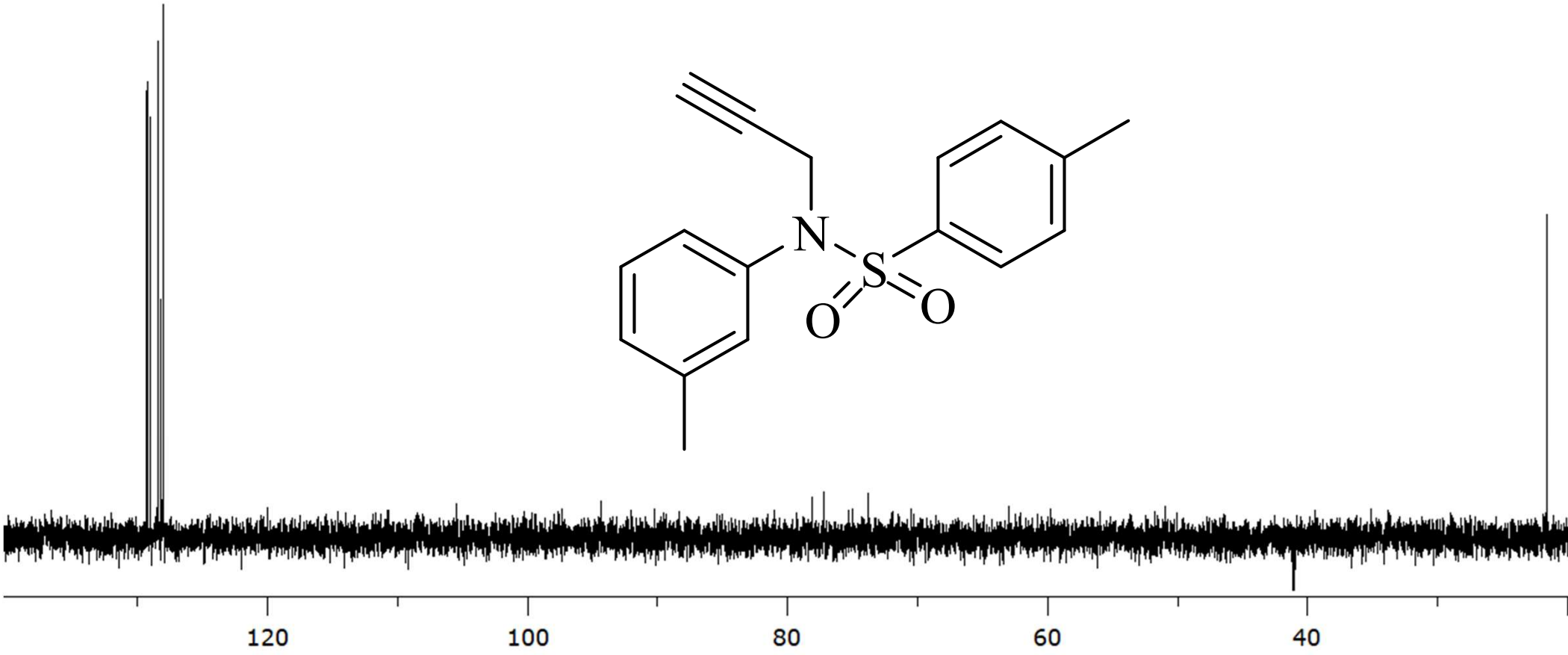
Application (BB)



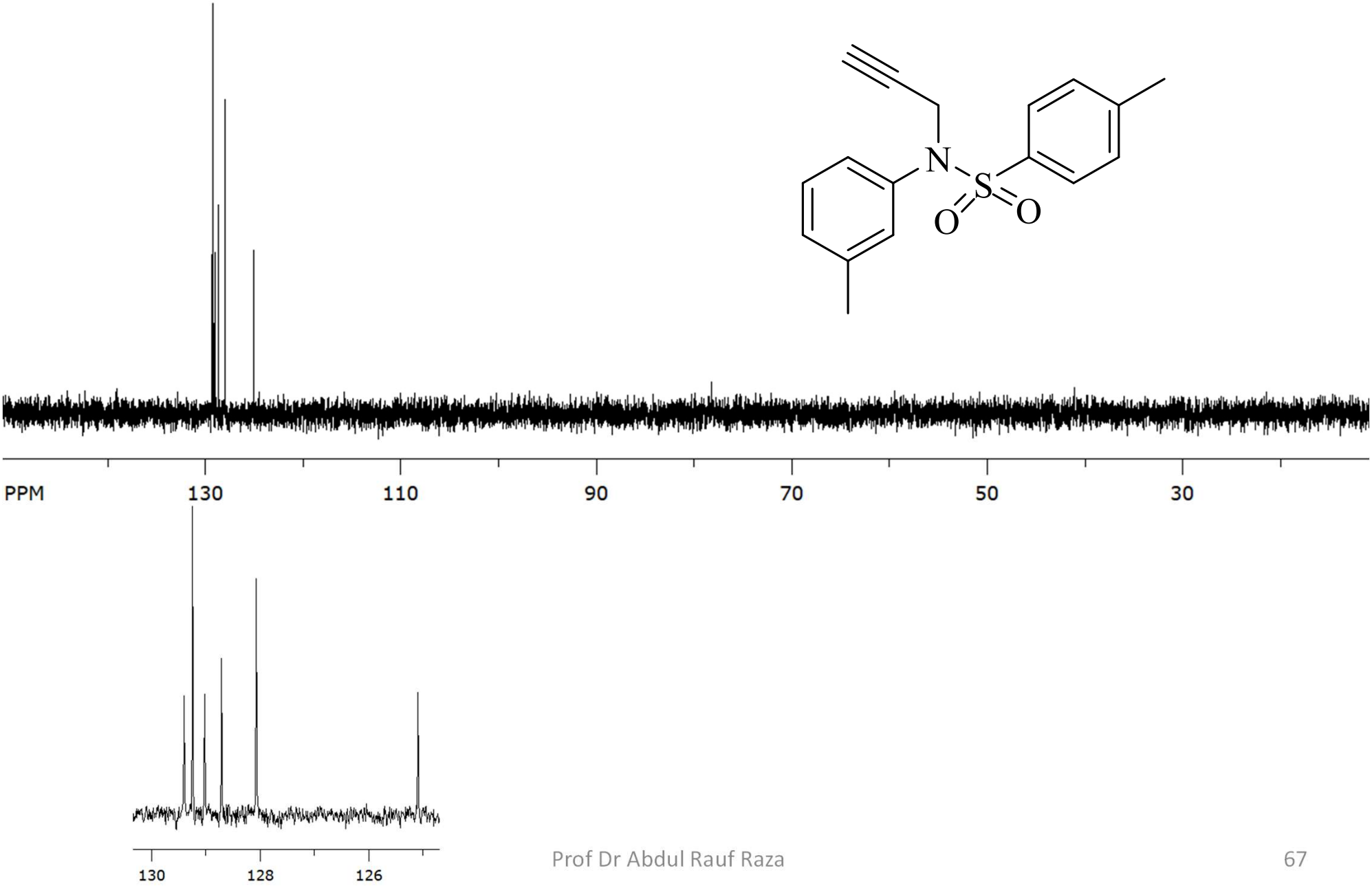




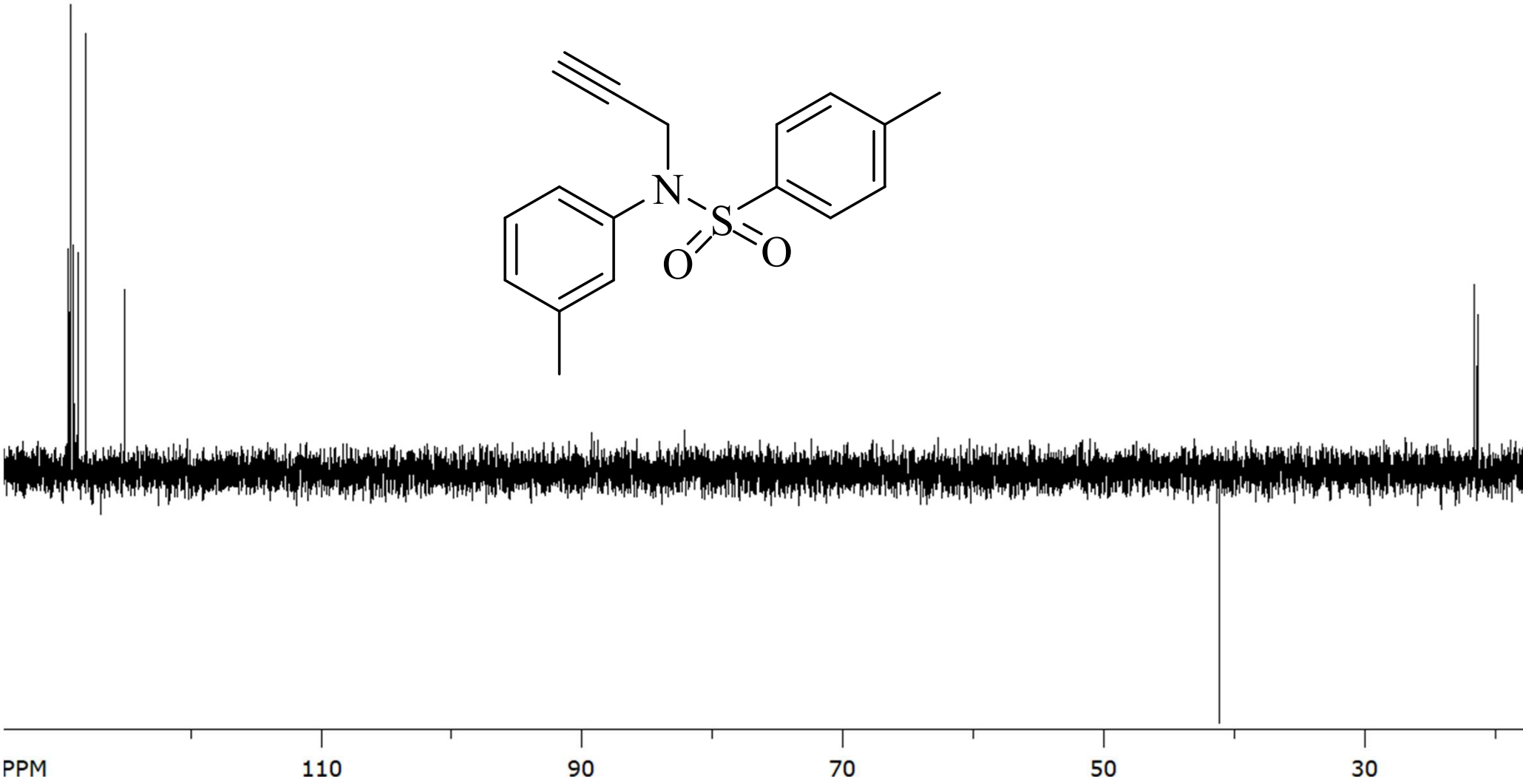
Application (DEPT-45)



Application (DEPT-90)

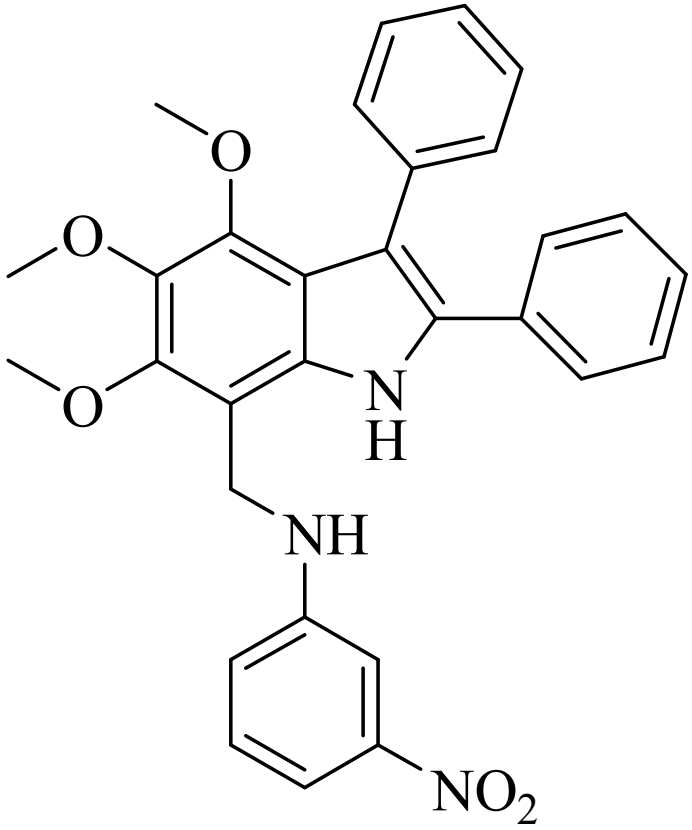


Application (DEPT-135)



Double Bond Equivalent

Double bond equivalent (DBE) = $C_n - (H_n/2) - (X_n/2) + (N_n/2) + 1$

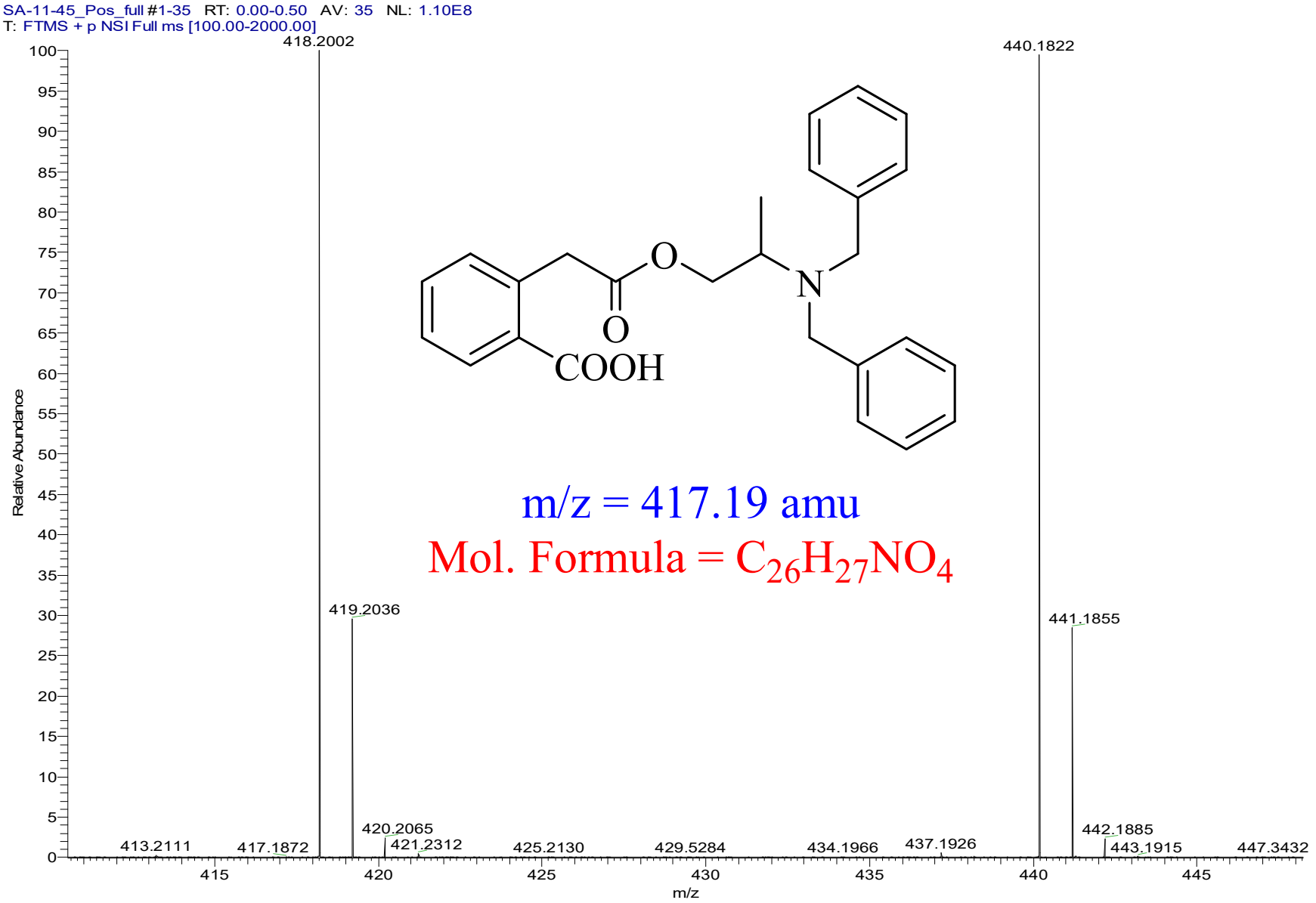


Mol. Formula = $C_{30}H_{27}N_3O_5$

DBE = 30 - (27/2) - (0/2) + (3/2) + 1

DBE = 19

Calculating Number of Cs



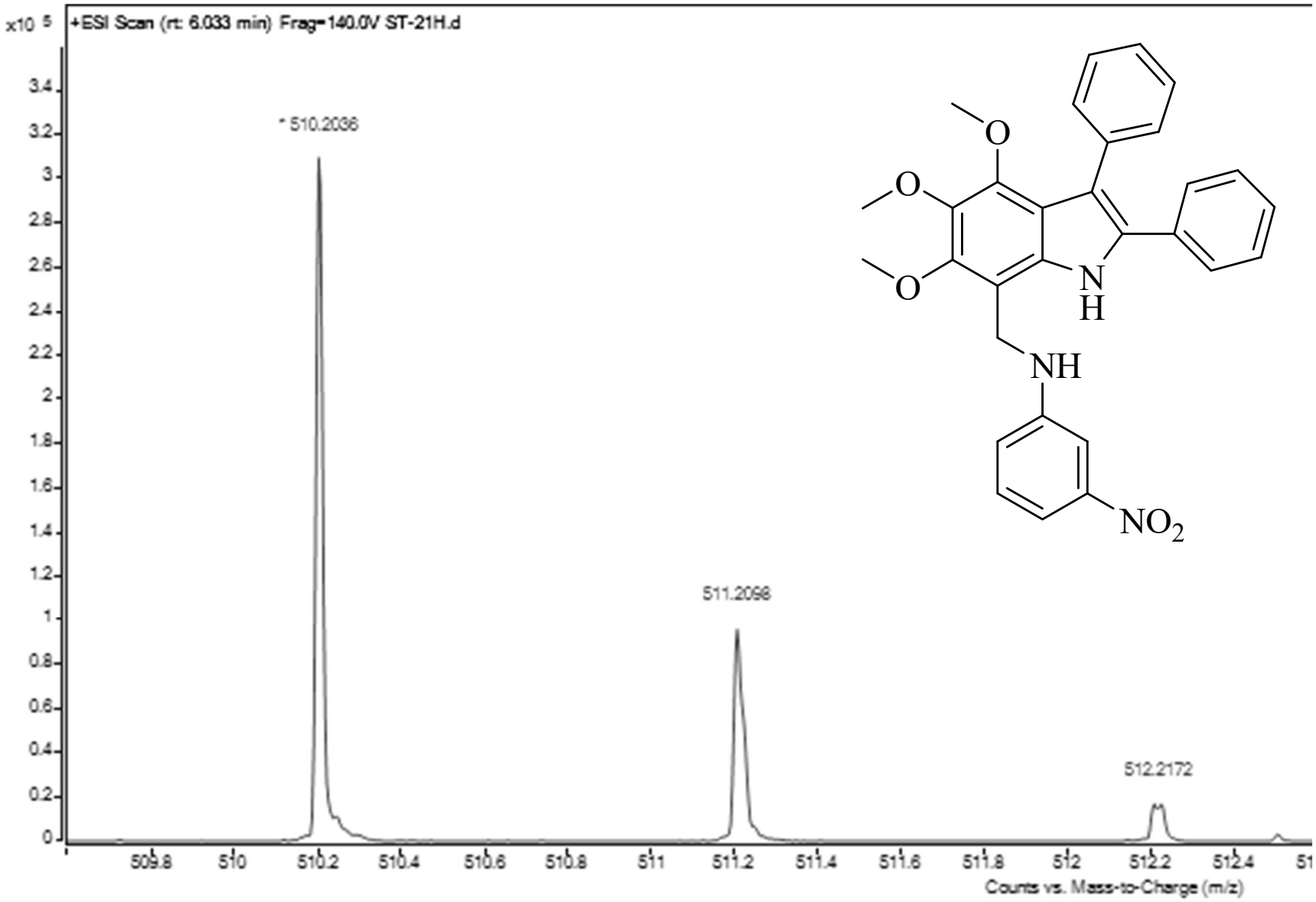
Calculating Number of Cs

m/z = 418.2002 amu [M+H] (100%)
m/z = 419.2036 amu [M+H] (29%)

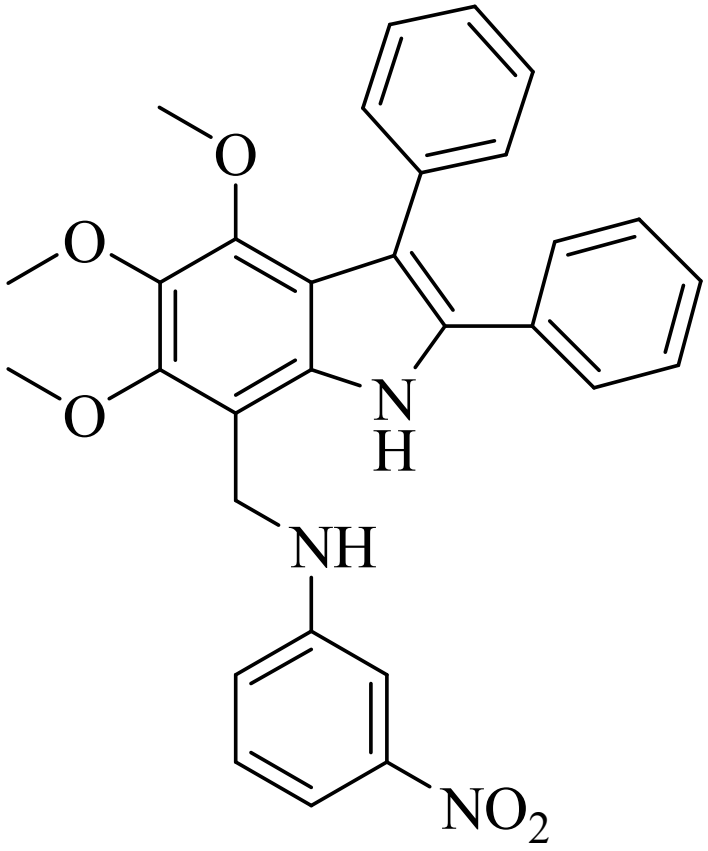
$$\text{Number of Cs} = \frac{\%\ \text{of Shadow ion}}{1.1\%\ (\text{Natural abundance of } {}^{13}\text{C})}$$

$$\text{Number of Cs} = \frac{29}{1.1} = 26.4$$

Calculating Number of Cs



Calculating Number of Cs



m/z = 509.20 amu

Mol. Formula = $C_{30}H_{27}N_3O_5$

31% [M] ⟶ 100% (x 3.23)

10% [M+1] ⟶ 32.3 %

$$\text{Number of Cs} = \frac{32.3}{1.1} = 29.4$$