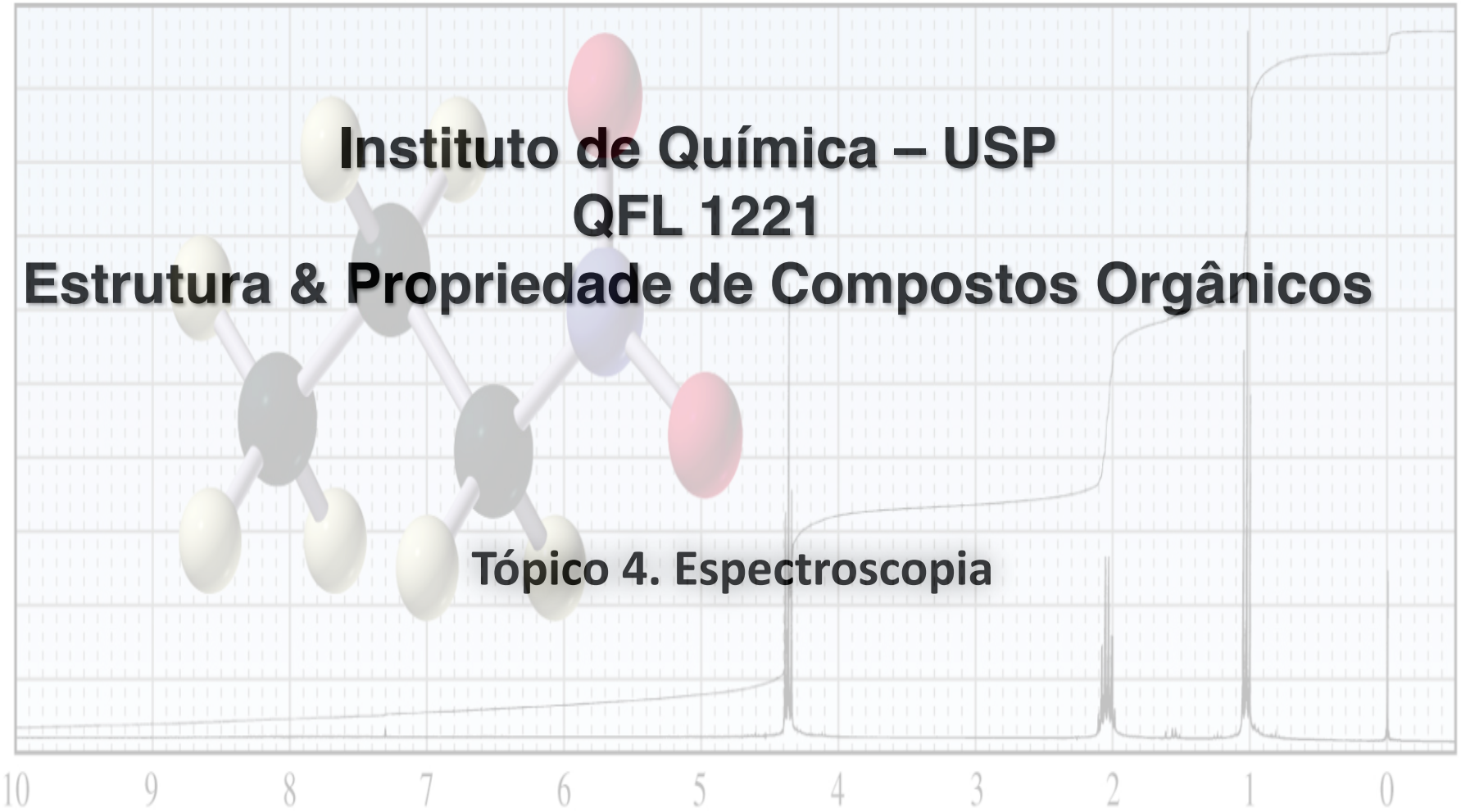


Instituto de Química – USP
QFL 1221
Estrutura & Propriedade de Compostos Orgânicos

Tópico 4. Espectroscopia

Literatura Recomendada

- **Clayden, Greeves, Warren, Wothers:** cap. 3, 1ª ou 2ª ed.

Cap. 11 ed. 1 ou 13 ed. 2: RMN
Cap. 15 ed. 1 ou 18 ed. 2: Revisão de métodos espectroscópicos

Espectroscopia

MS: massa molecular e composição de átomos

RMN: esqueleto carbônico

IV: grupos funcionais

What is spectroscopy?

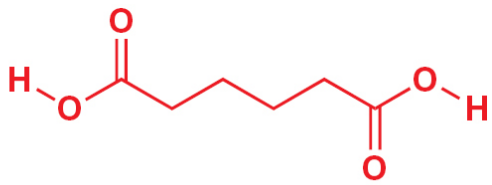
Rays or waves interact with molecules:
- X-rays are scattered
- Radio waves make nuclei resonate
- Infrared waves are absorbed

Spectroscopy:
- measures these interactions
- plots charts of absorption
- relates interactions with structure

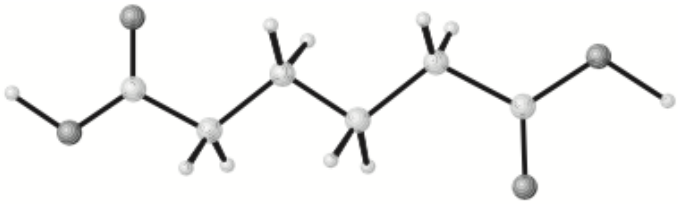
X-rays give bond lengths and angles. **Nuclear magnetic resonance** tells us about the carbon skeleton of the molecule. **Infrared spectroscopy** tells us about the types of bond in a molecule.

Raio-X: estrutura mais realista

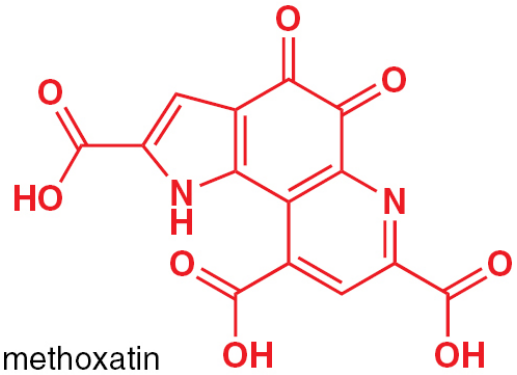
hexanedioic acid



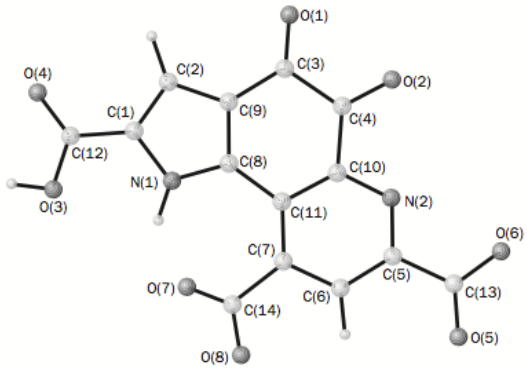
shape of hexanedioic acid



data for structure taken from Cambridge Crystallographic Data Centre



methoxatin



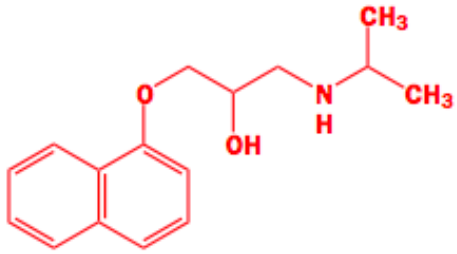
Espectroscopia | Utilidade

Raio-X: tem limitações

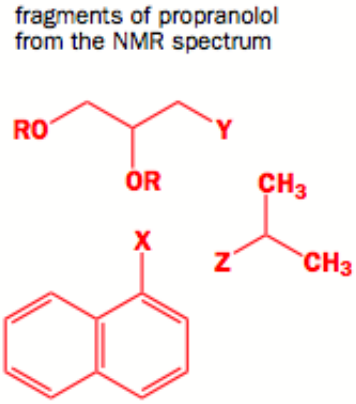
- ✓ Aplicável para sólidos cristalinos
- ✓ Não é uma análise de rotina e demanda tempo e pessoal especializado

Análises espectroscópicas são utilizadas para:

- ✓ Descobrir a estrutura de um produto desconhecido de uma reação química
- ✓ Descobrir um composto desconhecido da Natureza
- ✓ Detectar contaminantes em comida
- ✓ Checar de forma rotineira a pureza de remédios sintéticos



propranolol $C_{16}H_{21}NO_2$



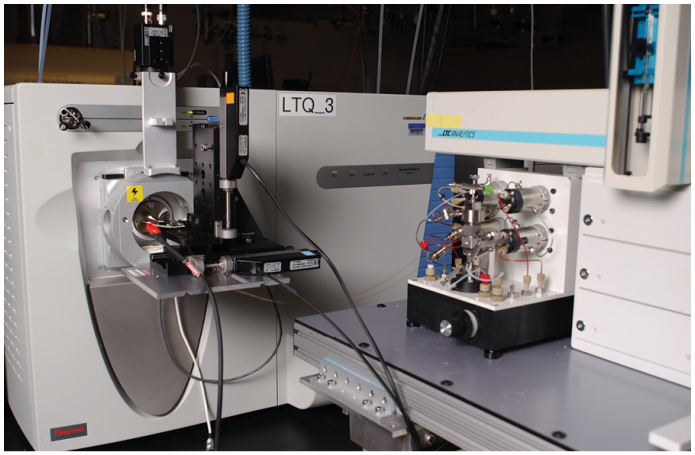
Espectroscopia | Técnica

O que cada uma das técnicas oferece?

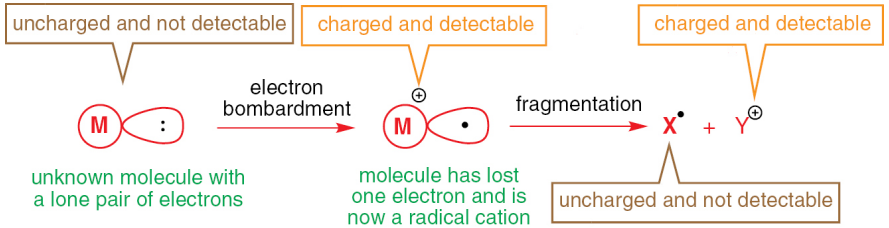
What each spectroscopic method tells us

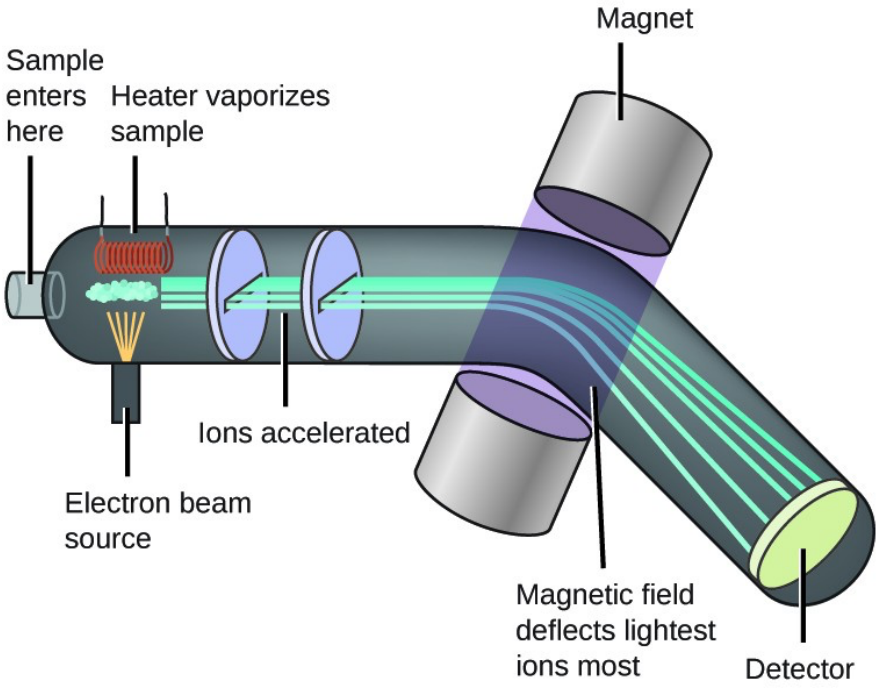
Method and what it does	What it tells us	Type of data provided
Mass spectrum weighs the molecule	molecular weight (relative molecular mass) and composition	259; $C_{16}H_{21}NO_2$
^{13}C NMR reveals all different carbon nuclei	carbon skeleton	no C=O group; ten carbons in aromatic rings; two carbons next to O; three other saturated C atoms
Infrared reveals chemical bonds	functional groups	no C=O group; one OH; one NH

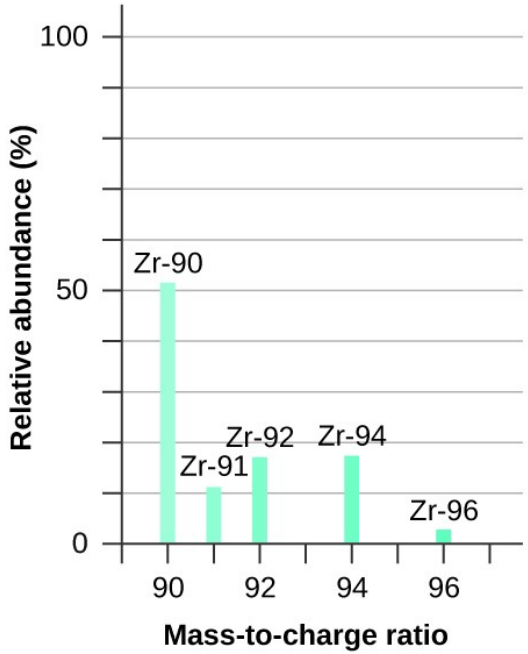
Espectrometria de Massas (MS)



MS/EI: espectrometria de massas por impacto de elétrons

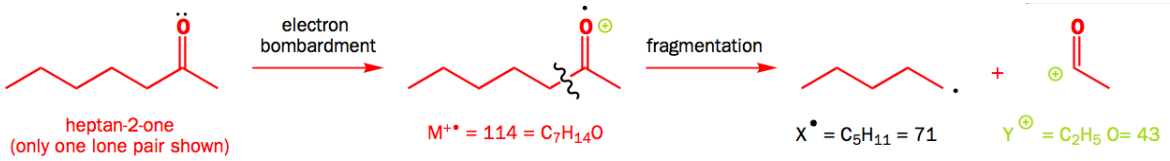


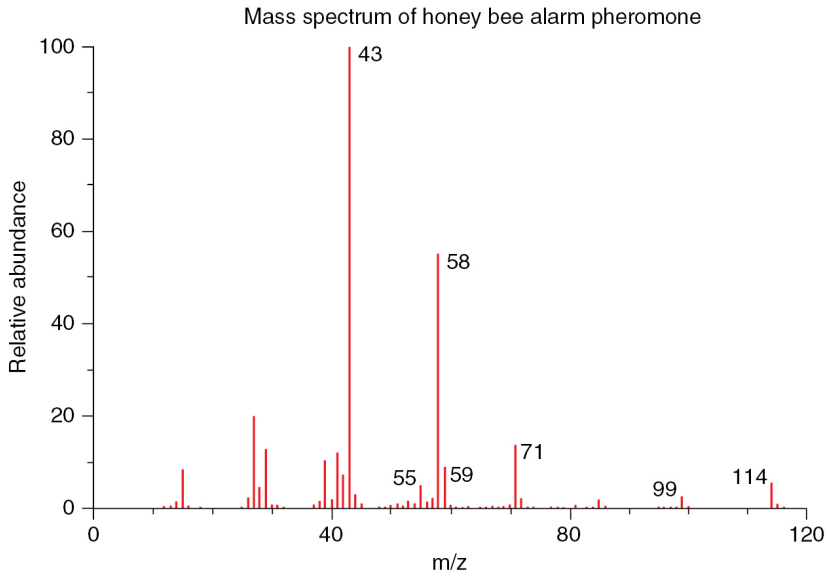




Espectrometria de Massas (MS)

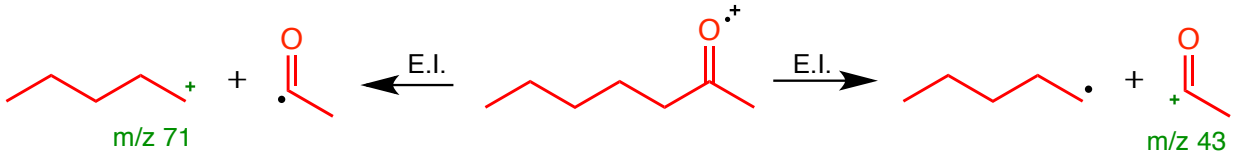
MS/EI: espectrometria de massas por impacto de elétrons





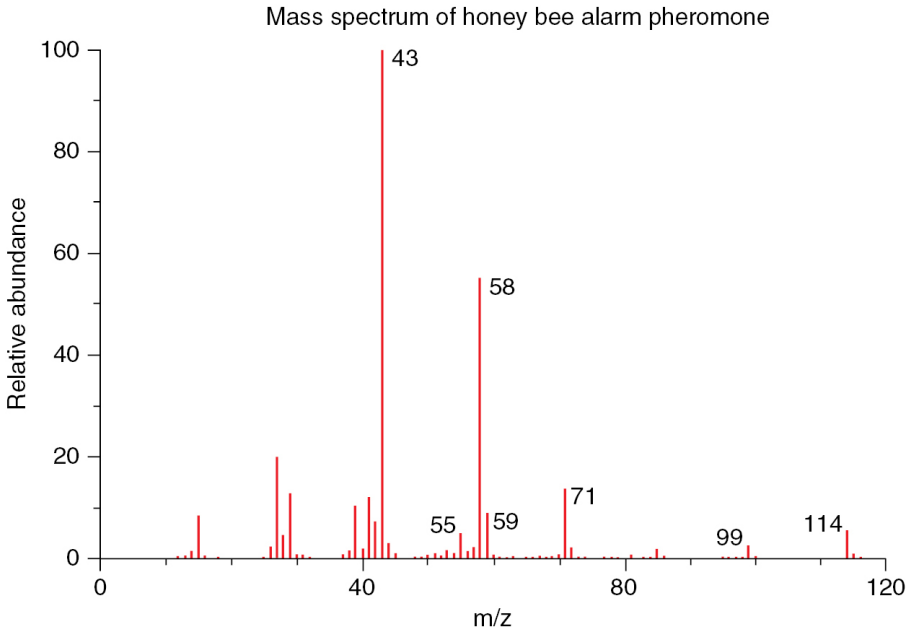
MS/EI da heptan-2-ona

a fragmentação pode ser de duas formas

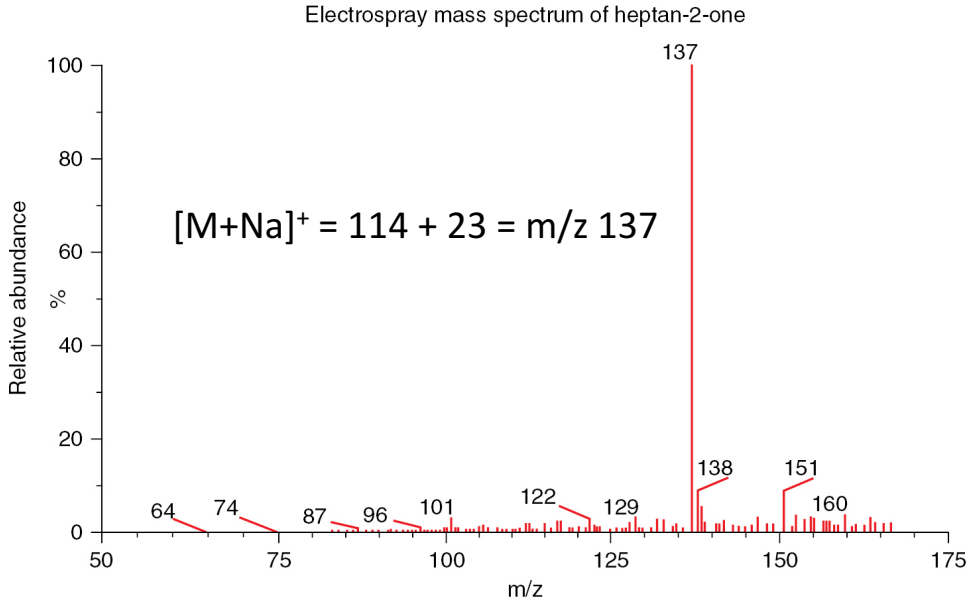


Espectrometria de Massas (MS)

MS/ES: espectrometria de massas por spray de elétrons – ionização mais branda



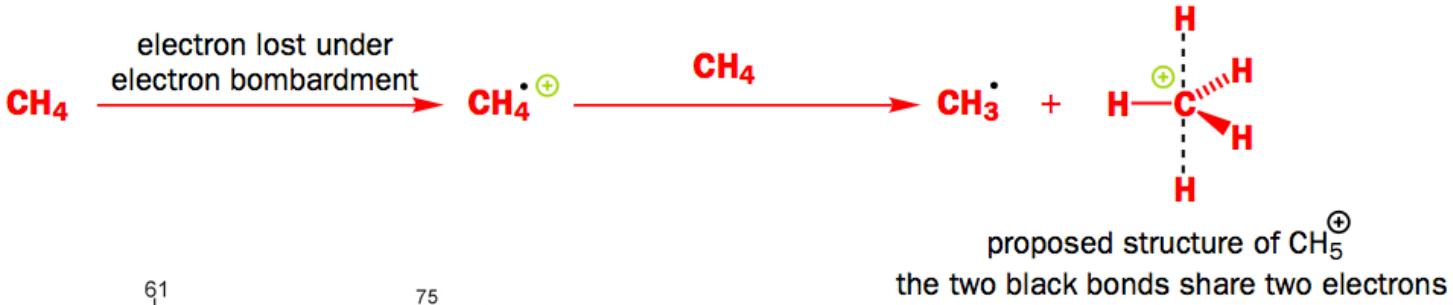
MS/EI da heptan-2-ona

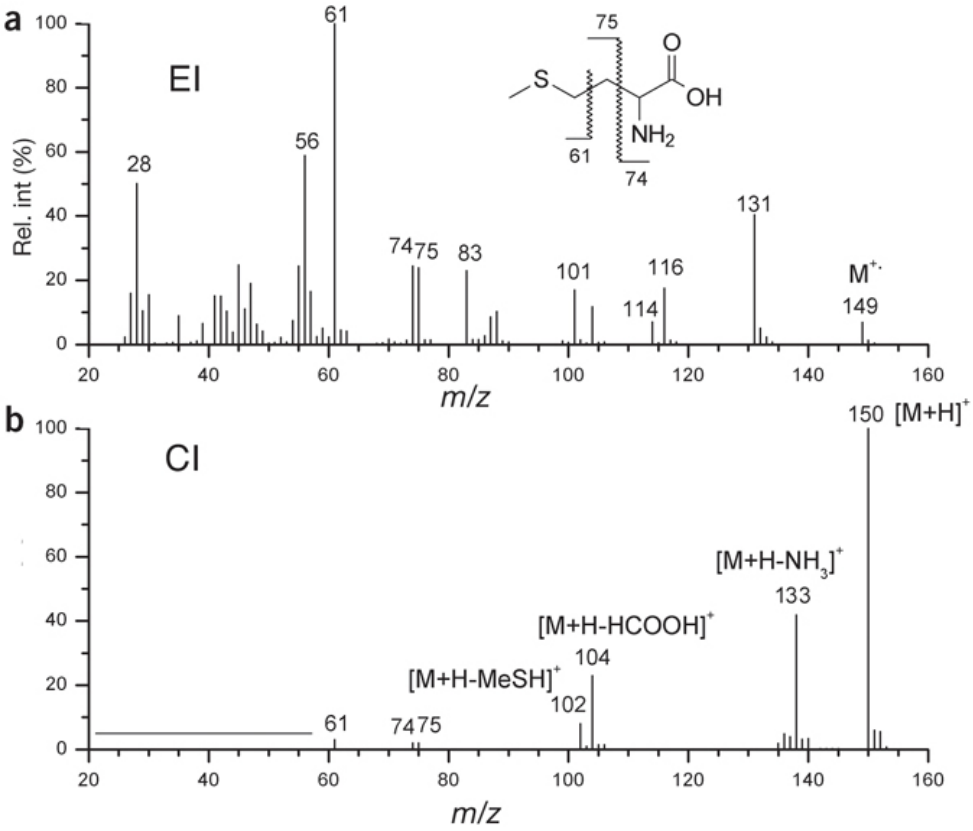


MS/ES da heptan-2-ona

Espectrometria de Massas (MS)

MS/CI: espectrometria de massas por ionização química



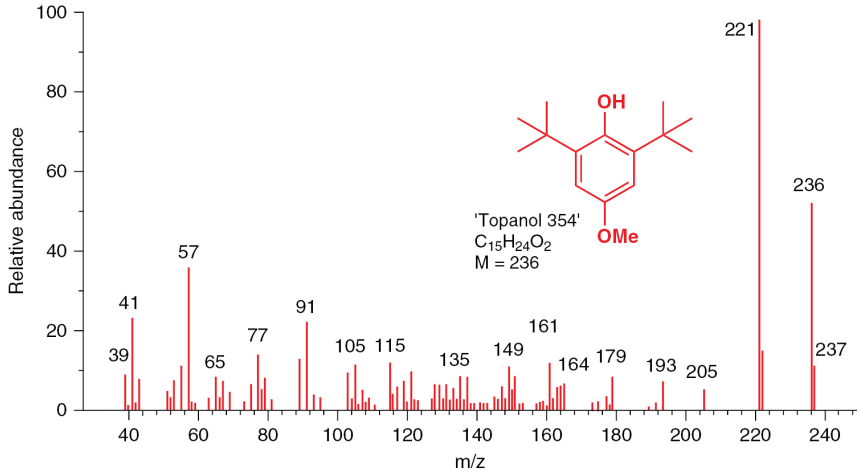


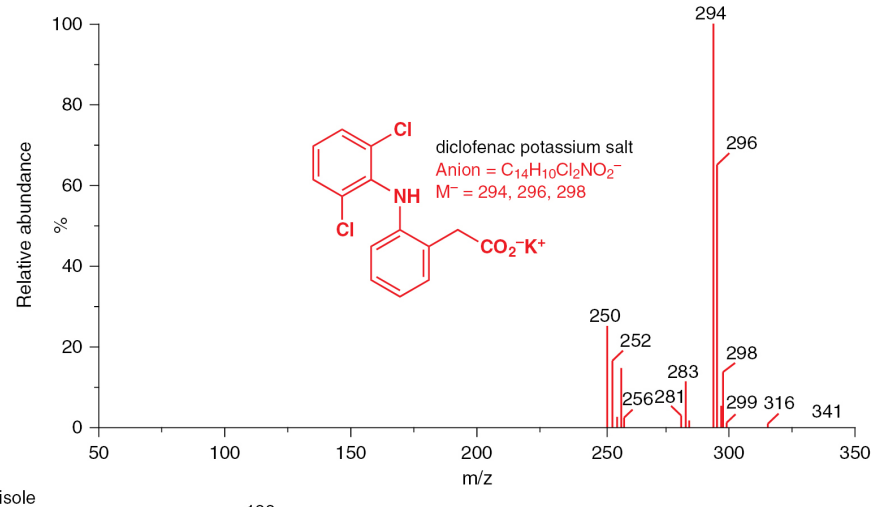
CH_5^+ : é um ácido muito forte que protona qualquer outra molécula em fase gasosa. O íon molecular M^+ é detectado como $[M+H]^+$.

Espectrometria de Massas (MS)

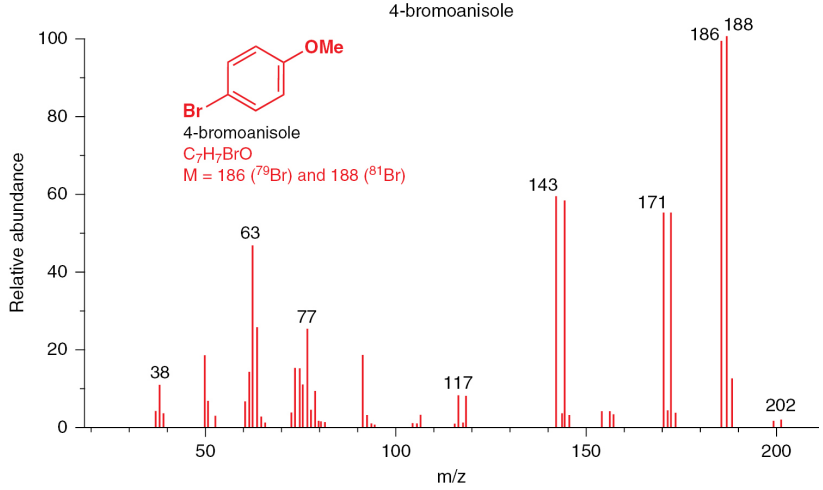
Isótopos

Element	Carbon	Chlorine	Bromine
isotopes	^{12}C, ^{13}C	^{35}Cl, ^{37}Cl	^{79}Br, ^{81}Br
rough ratio	1.1% ^{13}C (90:1)	3:1	1:1



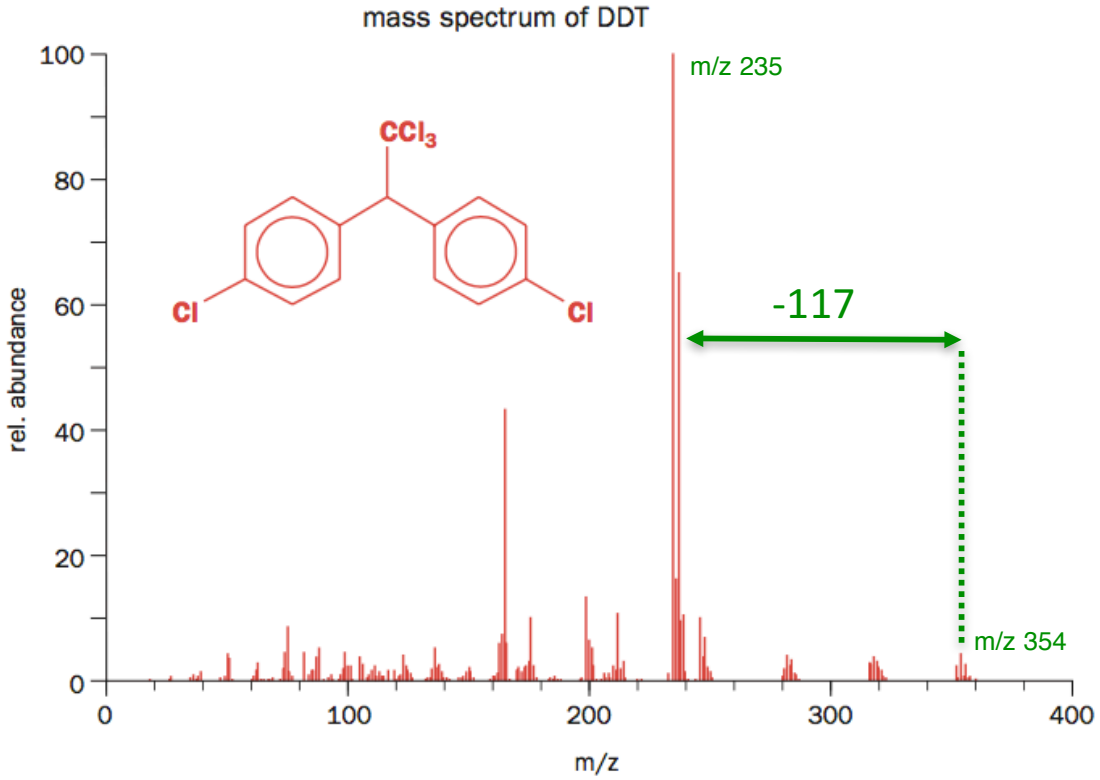


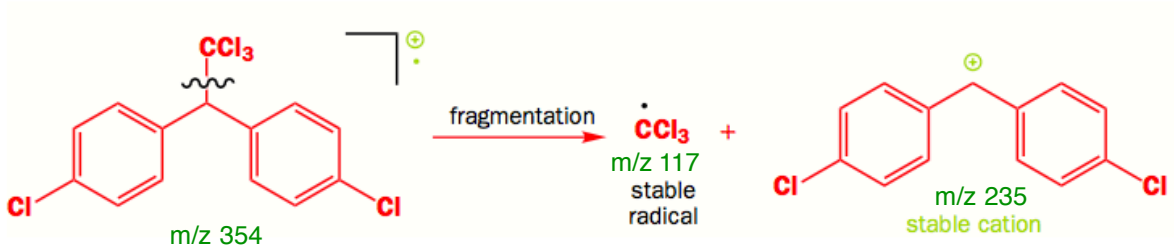
4-bromoanisole



Espectrometria de Massas (MS)

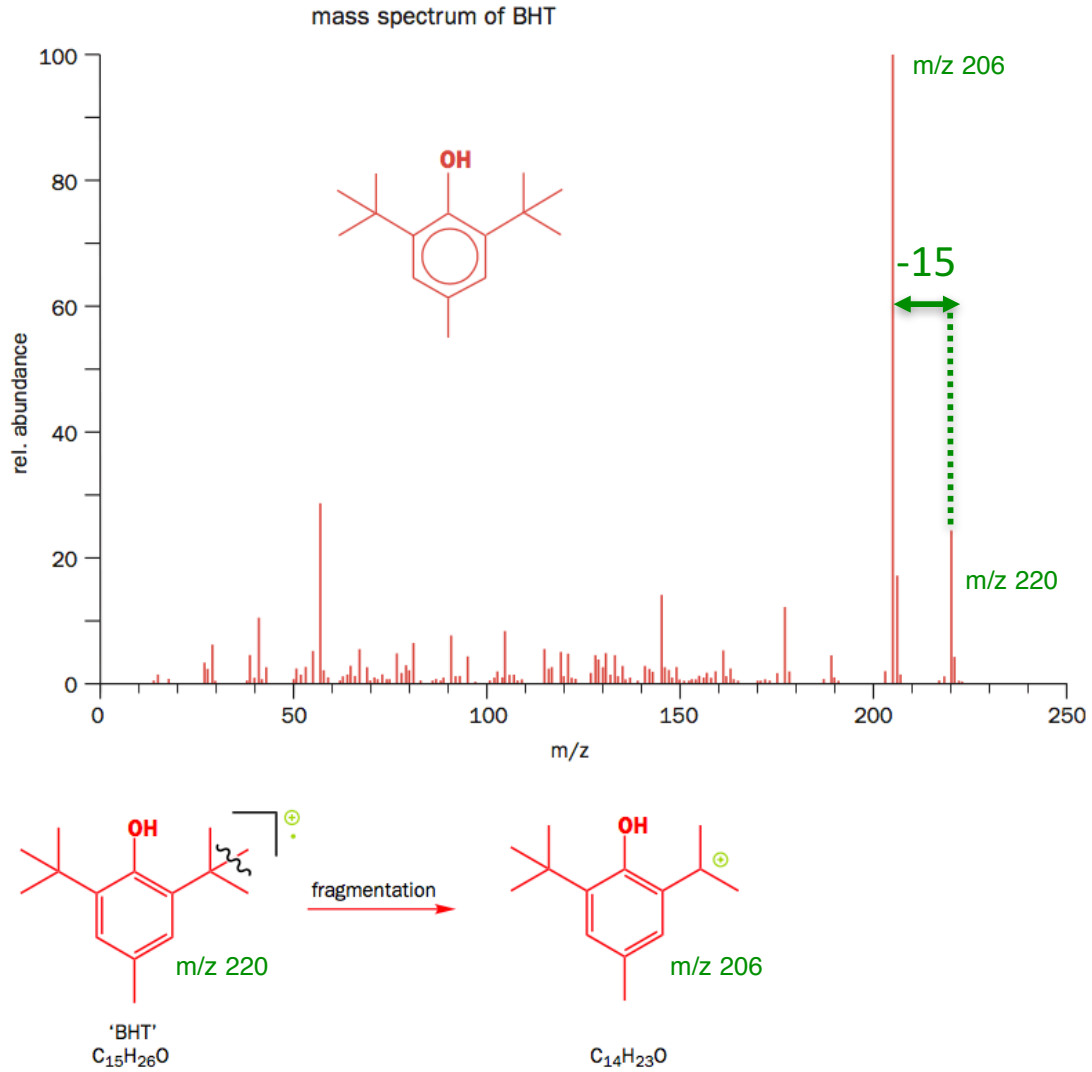
Espectro de Massas do DDT





Espectrometria de Massas (MS)

Espectro de Massas do BHT



Espectrometria de Massas (MS)

A composição de átomos pode ser determinada por HRMS (MS de alta resolução)

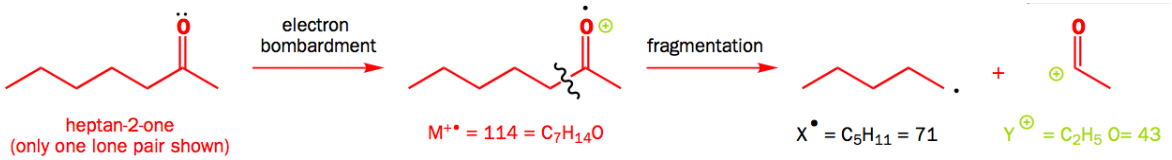


Table 3.3 Exact masses of common elements

Element	Isotope	Atomic weight	Exact mass
hydrogen	^{1}H	1	1.00783
carbon	^{12}C	12	12.00000
carbon	^{13}C	13	13.00335
nitrogen	^{14}N	14	14.00307
oxygen	^{16}O	16	15.99492
fluorine	^{19}F	19	18.99840
phosphorus	^{31}P	31	30.97376
sulfur	^{32}S	32	31.97207
chlorine	^{35}Cl	35	34.96886
chlorine	^{37}Cl	37	36.96590
bromine	^{79}Br	79	78.91835
bromine	^{81}Br	81	80.91635

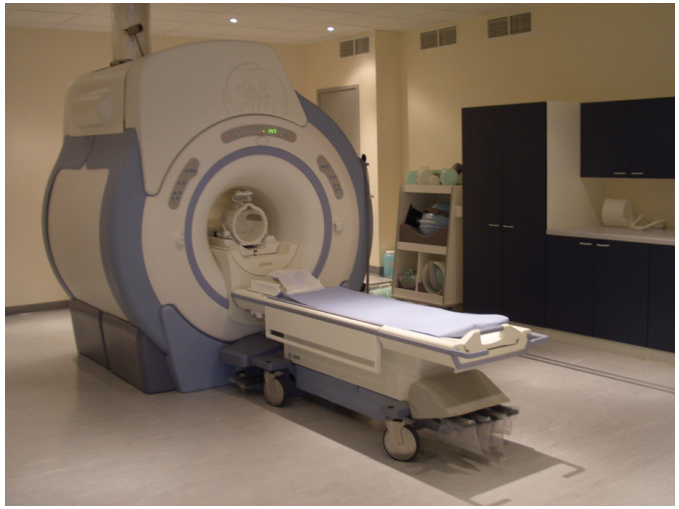
Chemical Formula: $C_7H_{14}O$
Exact Mass: 114,104
Molecular Weight: 114,188
m/z: 114.104 (100.0%), 115.108 (7.6%)

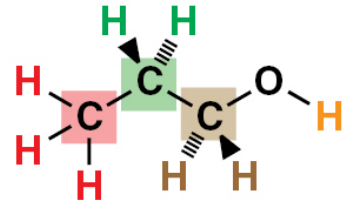
Table 3.4 Exact mass determination for the bee alarm pheromone

Composition	Calculated M^+	Observed M^+	Error in p.p.m.
$C_6H_{10}O_2$	114.068075	114.1039	358
$C_6H_{14}N_2$	114.115693	114.1039	118
$C_7H_{14}O$	**114.104457**	**114.1039**	5
C_8H_{18}	114.140844	114.1039	369

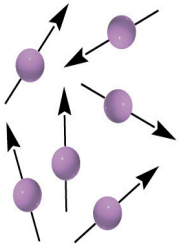
Ressonância Magnética Nuclear (RMN)

Princípio da RMN

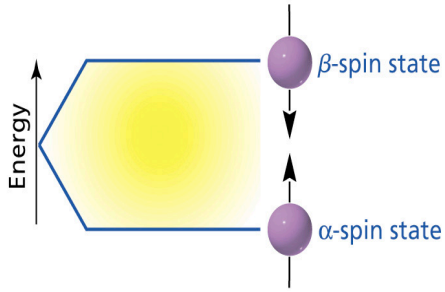




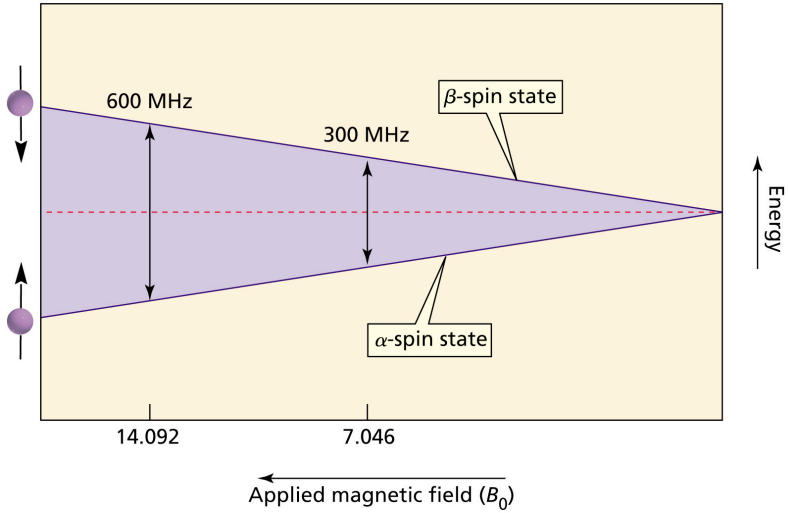
^{1}H NMR distinguishes the coloured hydrogens
^{13}C NMR distinguishes the boxed carbons



no applied magnetic field

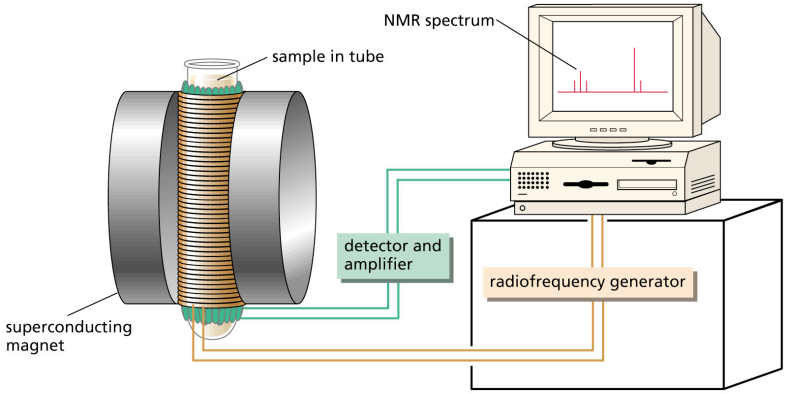


magnetic field is applied

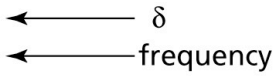


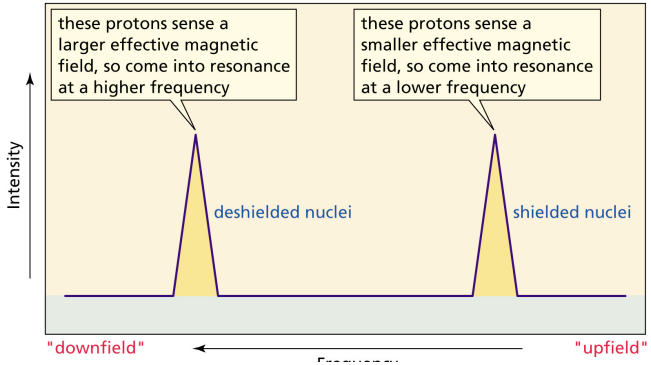
Ressonância Magnética Nuclear (RMN)

Princípio da RMN



protons in electron-poor environments	protons in electron-dense environments
deshielded protons	shielded protons
downfield	upfield
high frequency	low frequency
large δ values	small δ values





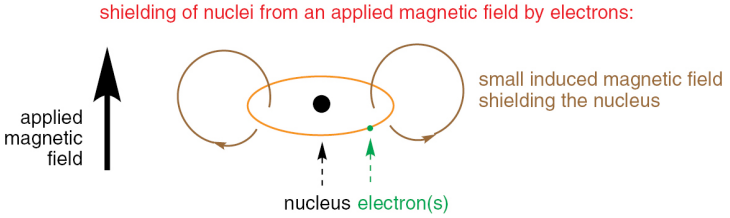
Ressonância Magnética Nuclear (RMN)

Princípio da RMN

absorção ΔE

Estado de spin-α ⇌ Estado de spin-β

liberação ΔE

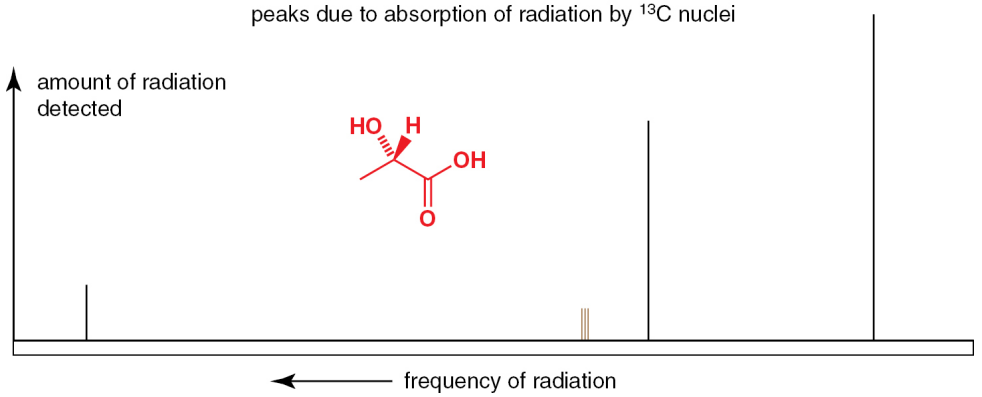


- Changes in the **distribution of electrons** around a nucleus affect:
  - the *local magnetic field* that the nucleus experiences
  - the *frequency* at which the nucleus resonates
  - the *chemistry* of the molecule at that atom

  This variation in frequency is known as the **chemical shift**. Its symbol is δ.

Sinal detectado pelo RMN

Alguns núcleos orientam-se na mesma direção do campo magnético
outros na direção contrária



Ressonância Magnética Nuclear (RMN)

RMN ^{13}C

- O número de sinais reflete o número de diferentes tipos de carbono

- A intensidade do sinal de ^{13}C é, em geral, 6400 vezes menor do que a intensidade de um sinal de ^{1}H

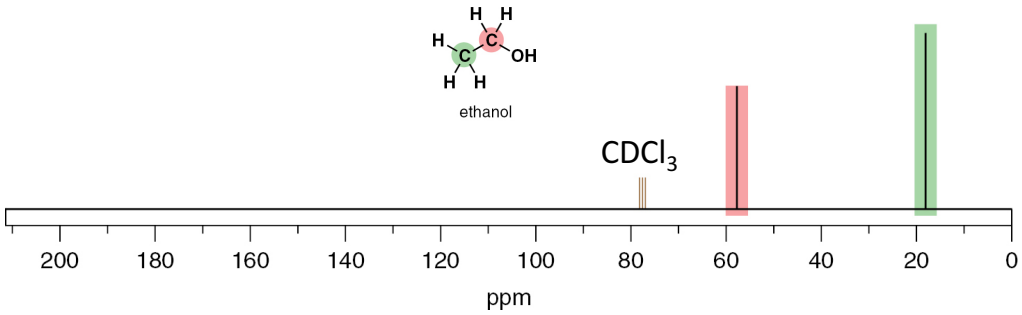
- Os deslocamentos químicos varia acima de 220 ppm, enquanto o de próton, somente 10 ppm

- Os núcleos mais comuns são ^{1}H e ^{13}C, mas outros núcleos, como ^{2}H, ^{6}Li, ^{10}B, ^{11}B, ^{14}N, ^{15}N, ^{17}O, ^{19}F, ^{23}Na, ^{29}Si, ^{31}P, ^{35}Cl, ^{113}Cd, ^{129}Xe e ^{195}Pt são também estudados por RMN em campo alto

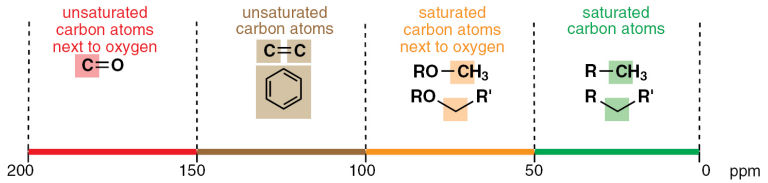
Ressonância Magnética Nuclear (RMN)

Espectros de RMN ^{13}C e Escala

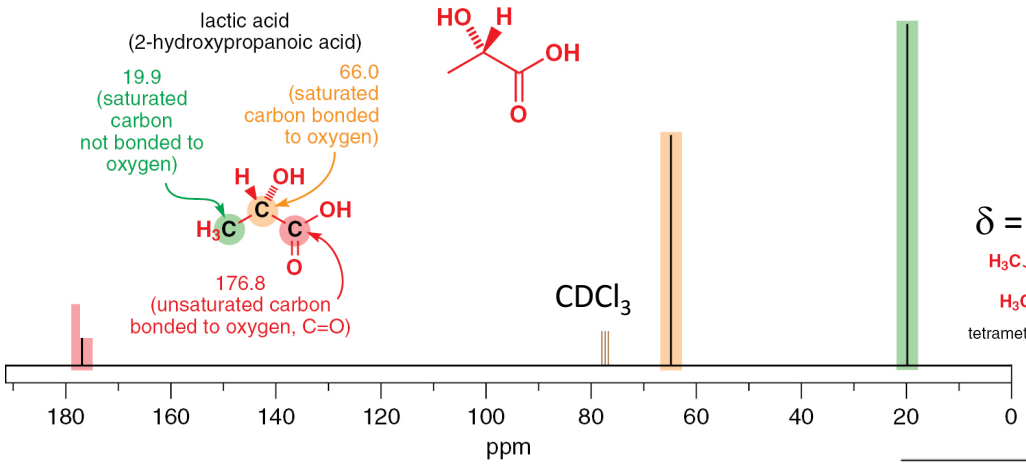
^{13}C NMR spectrum of ethanol

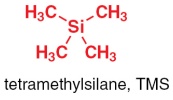


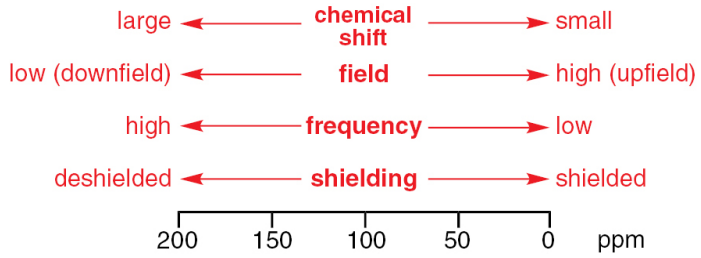
$$\delta = \frac{\text{frequency (Hz)} - \text{frequency TMS (Hz)}}{\text{frequency TMS (MHz)}}$$



^{13}C NMR spectrum of lactic acid







Regions of the ^{13}C NMR spectrum (scale in p.p.m.)

Unsaturated carbon atoms next to oxygen (C=O)	Unsaturated carbon atoms (C=C and aromatic carbons)	Saturated carbon atoms next to oxygen (CH_3O, CH_2O, etc.)	Saturated carbon atoms (CH_3, CH_2, CH)
δ = 200–150	δ = 150–100	δ = 100–50	δ = 50–0

Ressonância Magnética Nuclear (RMN)

Deslocamento Químico RMN ^{13}C

Table 14.4 Approximate Values of Chemical Shifts for ^{13}C NMR

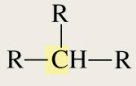
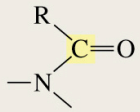
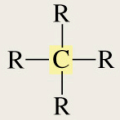
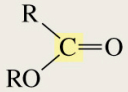
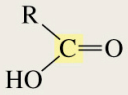
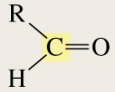
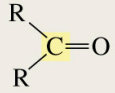
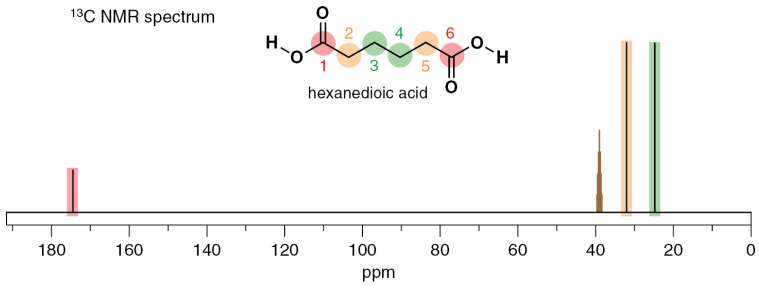
Type of carbon	Approximate chemical shift (ppm)	Type of carbon	Approximate chemical shift (ppm)
$(CH_3)_4Si$	0	C—I	0–40
R—CH_3	8–35	C—Br	25–65
R—CH_2—R	15–50	C—Cl C—N C—O	35–80 40–60 50–80
	20–60		165–175
	30–40		165–175
≡C	65–85		175–185
=C	100–150		190–200
	110–170		205–220

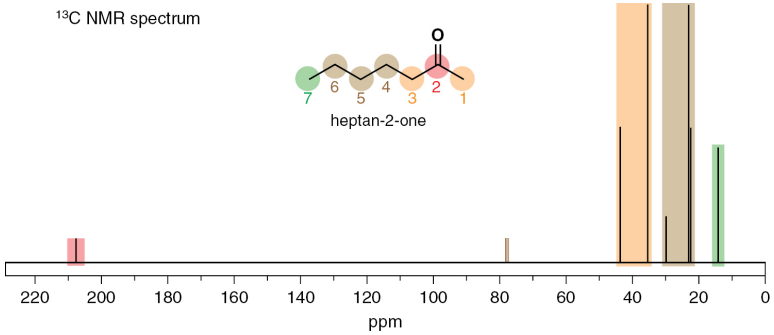
Table 3.5 Effect of electronegativity on chemical shift

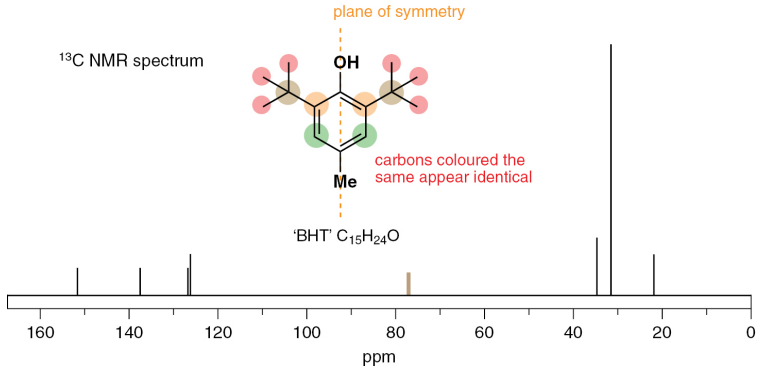
Electronic effect	Electronegativity of atom bonded to carbon	Compound	$\delta(CH_3)$	$\delta(CH_3) - 8.4$
donation	1.0	CH_3–Li	–14	–22.4
↑	2.2	CH_3–H	–2.3	–10.7
weak	1.8	CH_3–$SiMe_3$	0.0	–8.4
no effect	2.5	CH_3–CH_3	8.4	0
weak	3.1	CH_3–NH_2	26.9	18.5
↓	—	CH_3–COR	~30	~22
↓	3.5	CH_3–OH	50.2	41.8
withdrawal	4.1	CH_3–F	75.2	66.8

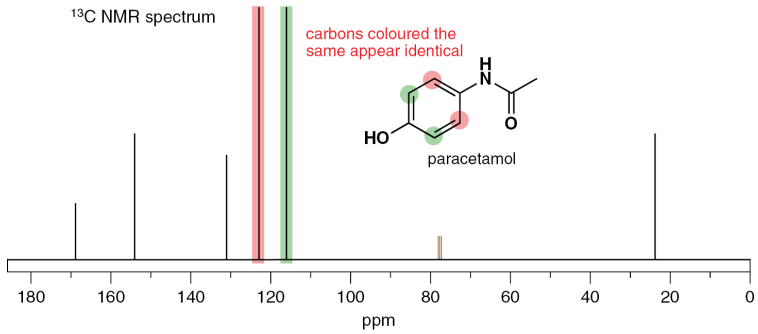
Ressonância Magnética Nuclear (RMN)

Espectros de RMN ^{13}C



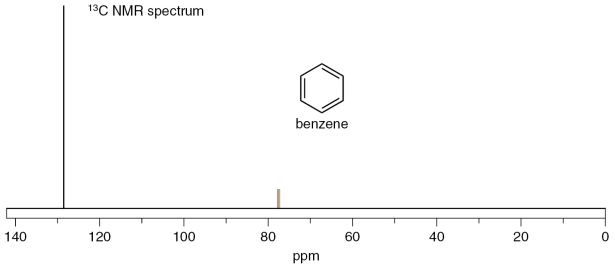


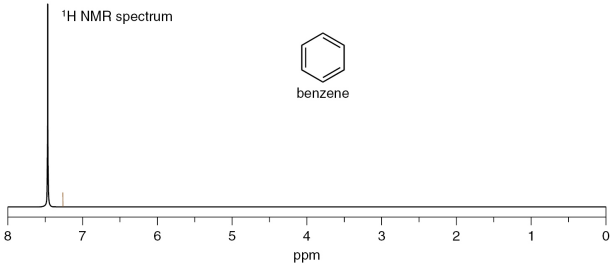


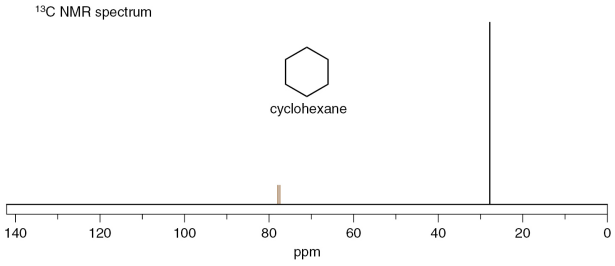


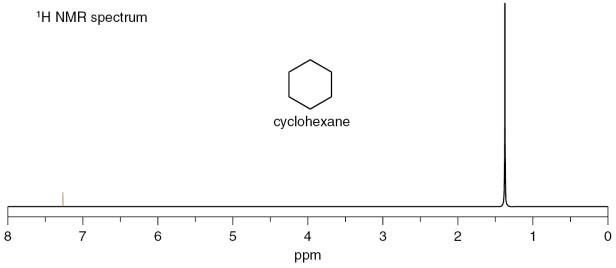
Ressonância Magnética Nuclear (RMN)

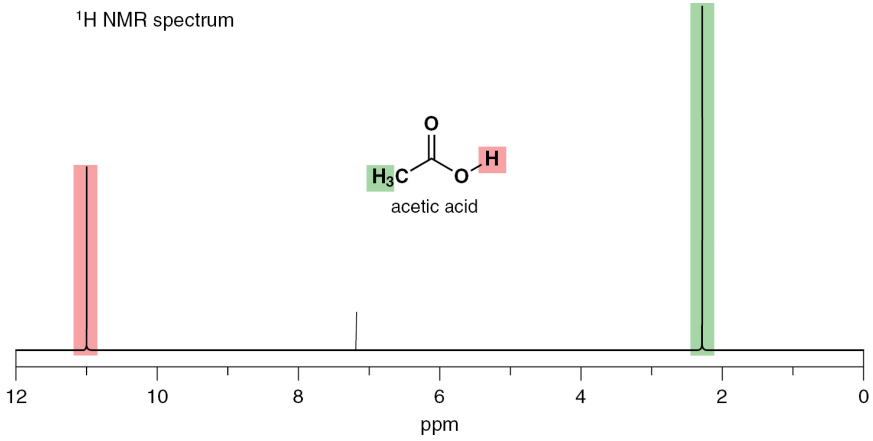
Espectros de RMN ^{13}C e ^{1}H

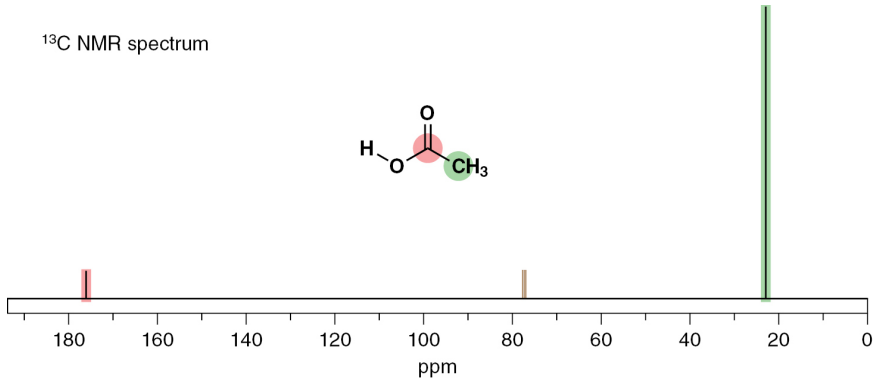






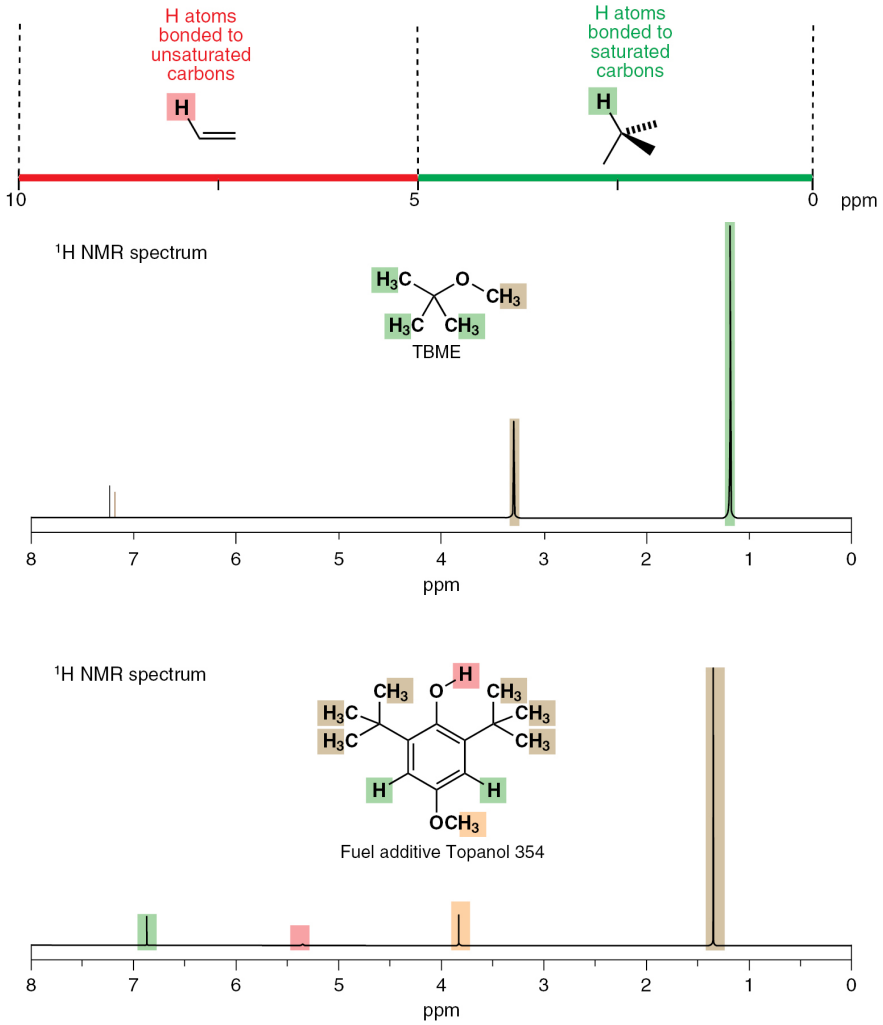






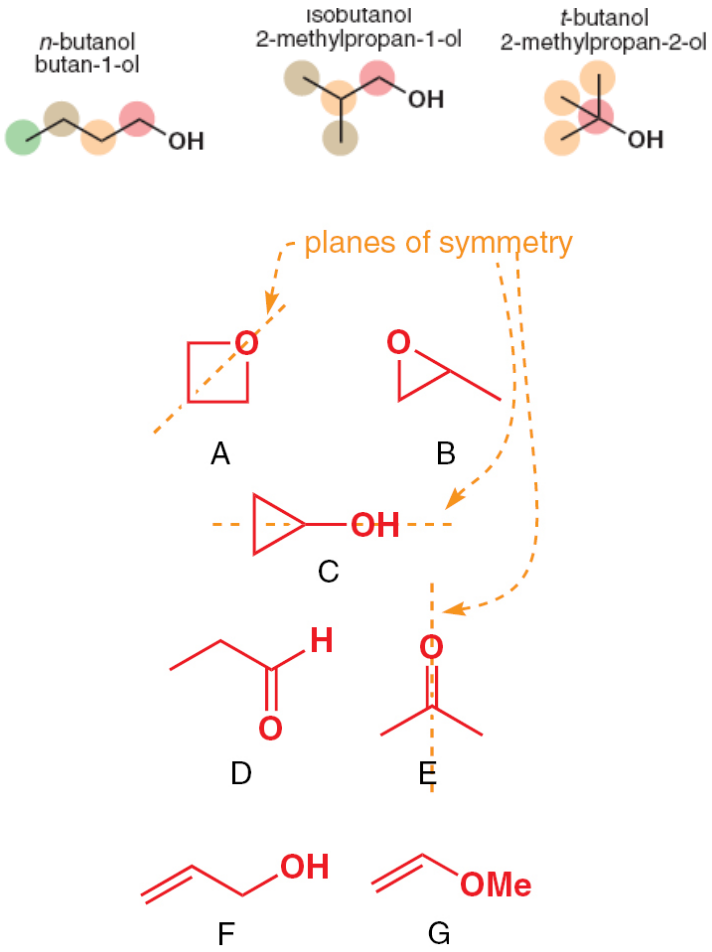
Ressonância Magnética Nuclear (RMN)

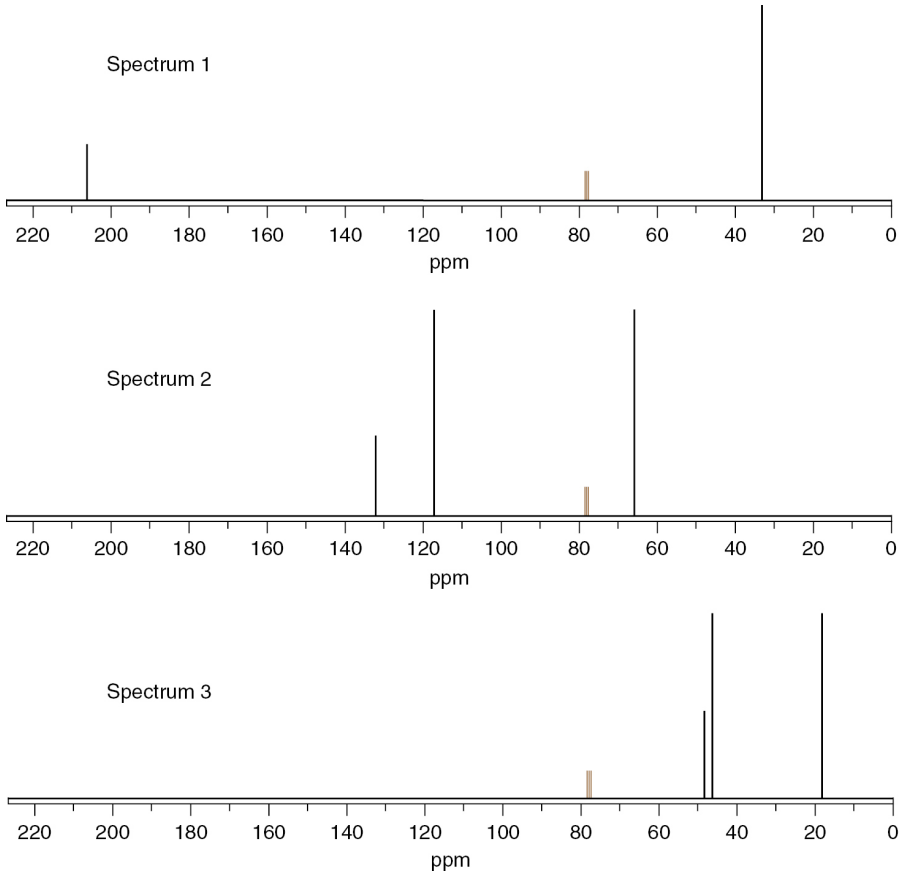
Espectros de RMN ^{1}H



Ressonância Magnética Nuclear (RMN)

RMN é uma técnica poderosa para elucidar a estrutura de moléculas

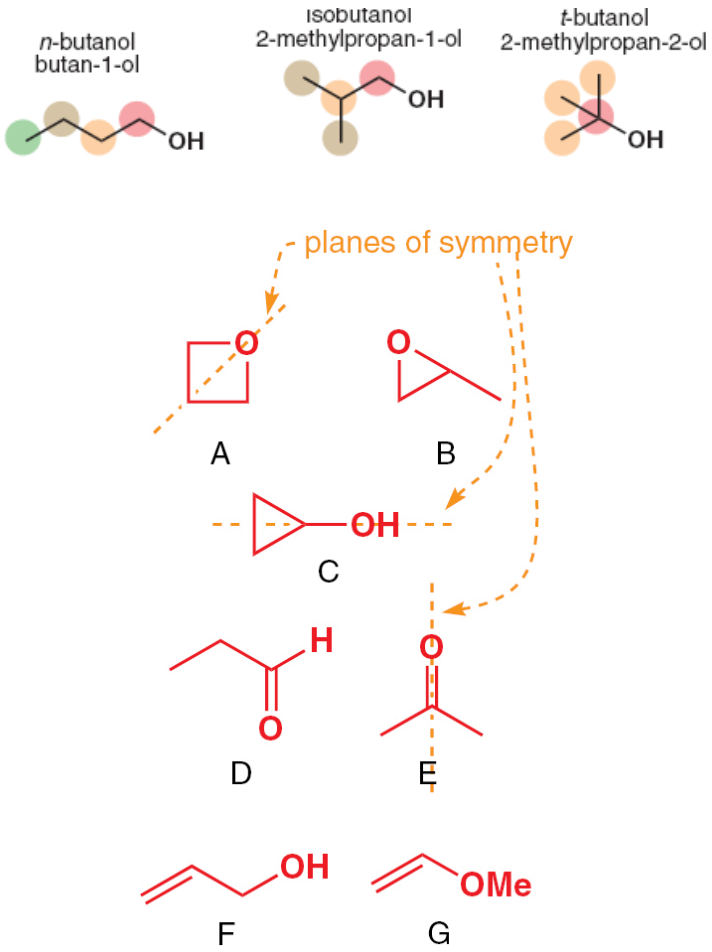


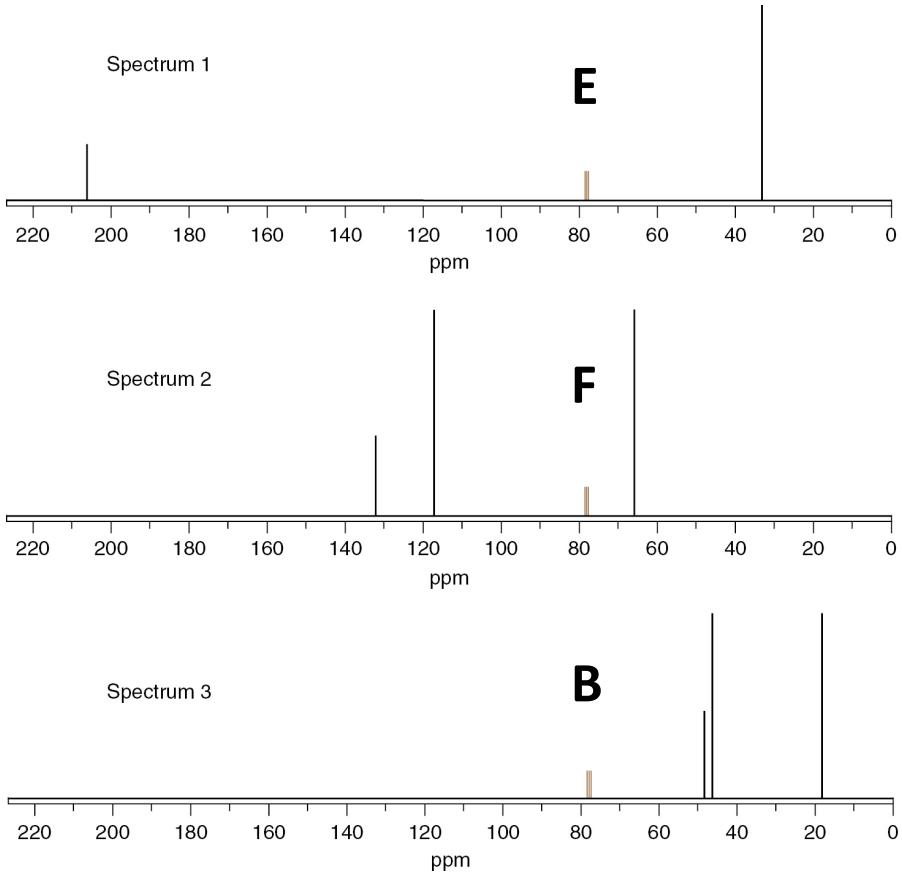


Você é capaz de indicar qual espectro corresponde a qual molécula de A a G?

Ressonância Magnética Nuclear (RMN)

RMN é uma técnica poderosa para elucidar a estrutura de moléculas

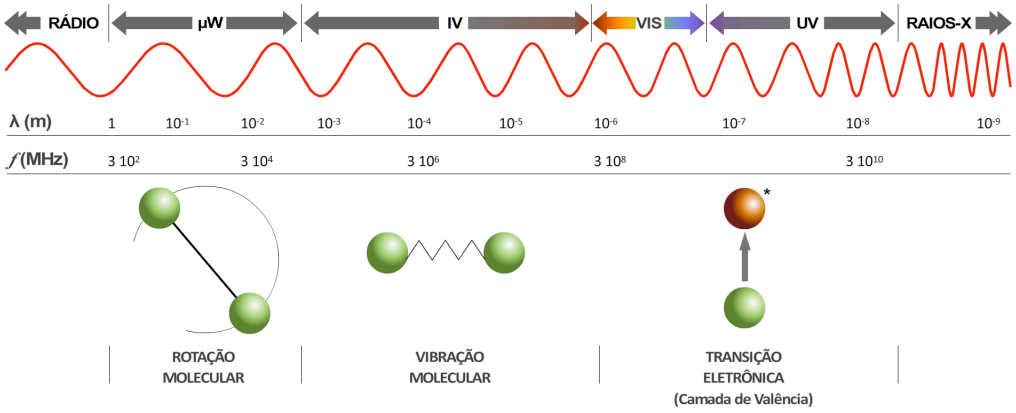


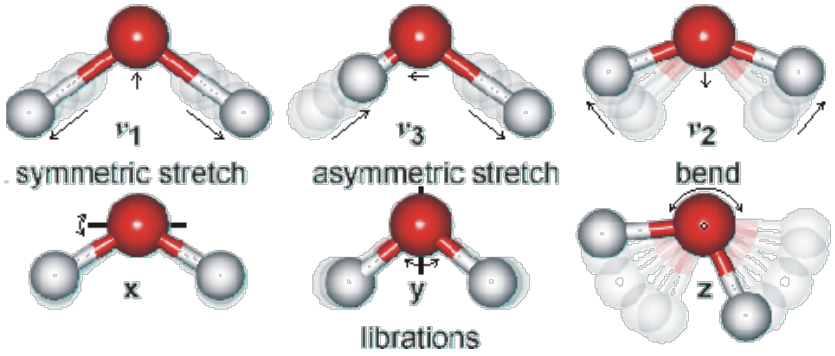


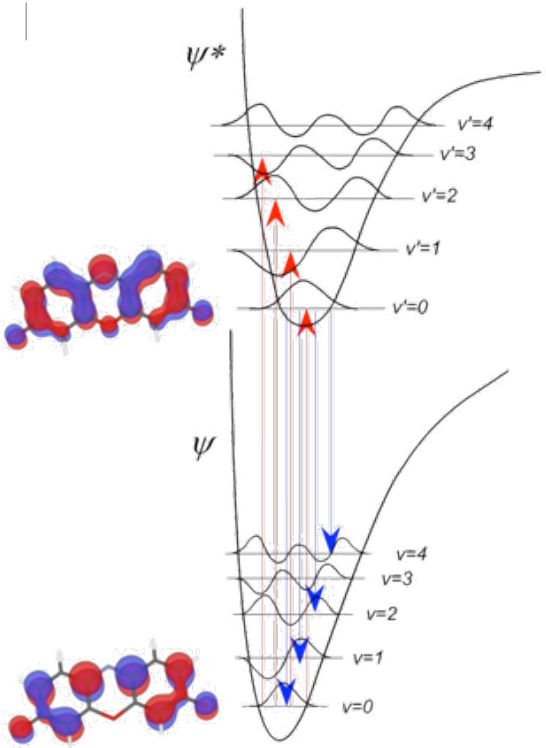
Você é capaz de indicar qual espectro corresponde a qual molécula de A a G?

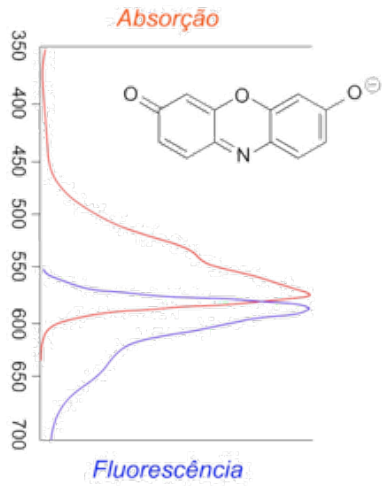
Infravermelho (IV)

Princípio da espectroscopia no IV



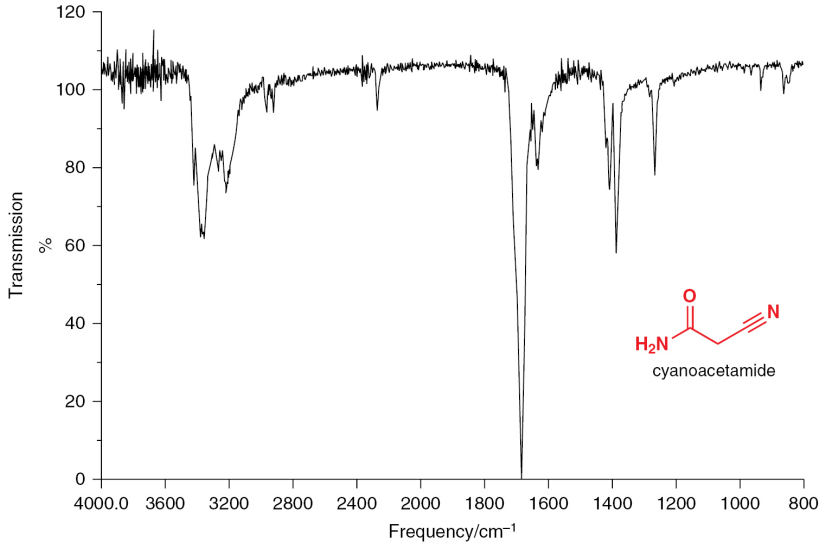


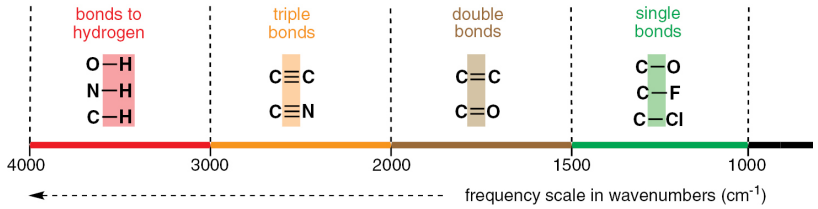




Infravermelho (IV)

Espectro de IV: a técnica permite a identificação de grupos funcionais





Values chiefly affected by mass of atoms: (lighter atom, higher frequency)

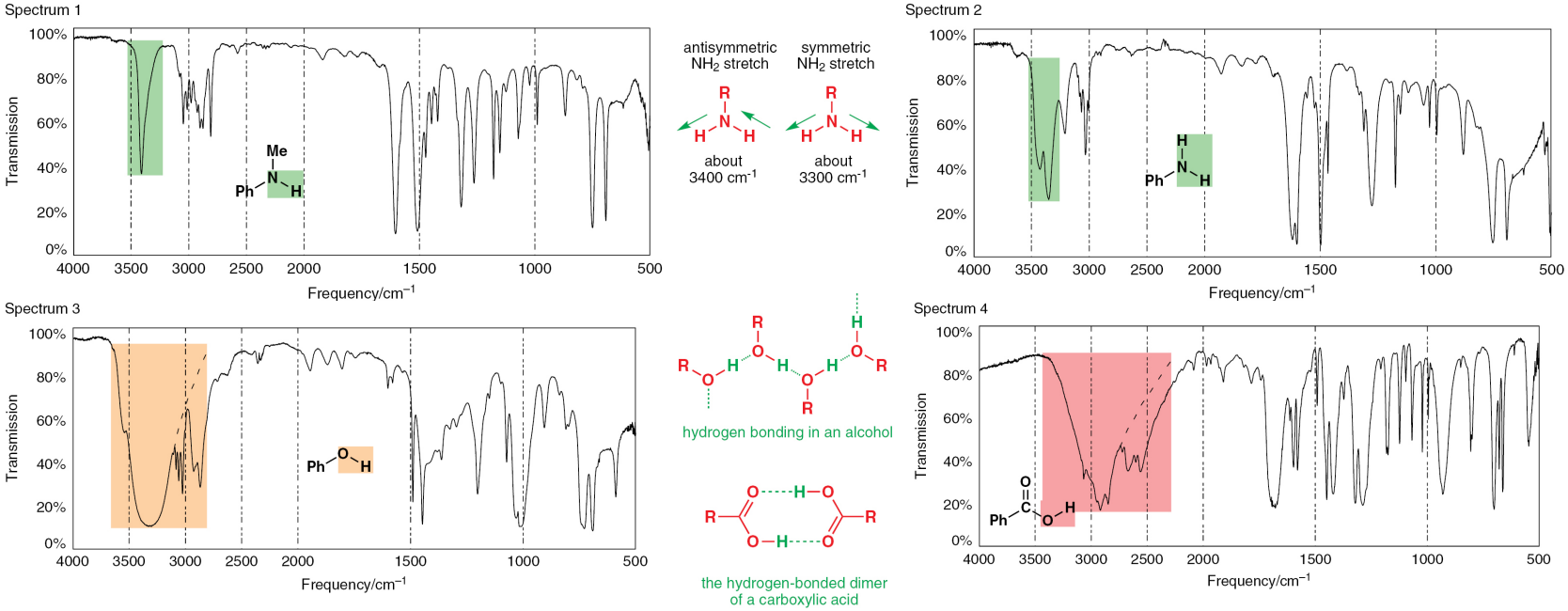
C–H	C–D	C–O	C–Cl
3000 cm^{-1}	2200 cm^{-1}	1100 cm^{-1}	700 cm^{-1}

Values chiefly affected by bond strength (stronger bond, higher frequency)

C≡O	C=O	C–O
2143 cm^{-1}	1715 cm^{-1}	1100 cm^{-1}

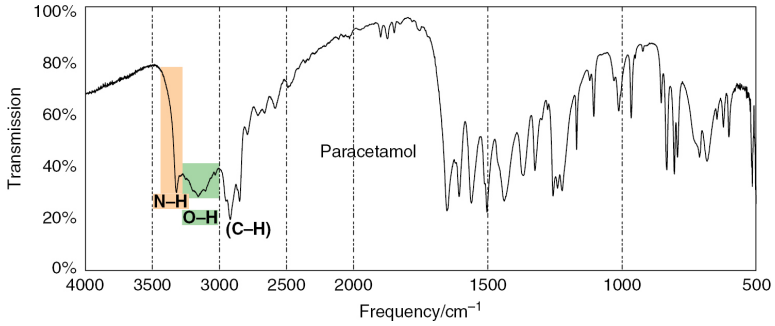
Infravermelho (IV)

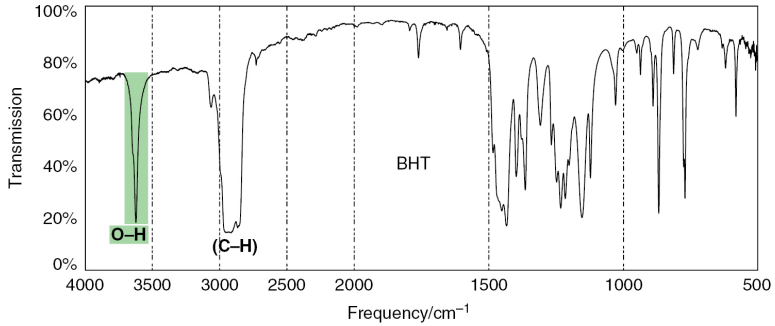
Espectro de IV: ligação de hidrogênio

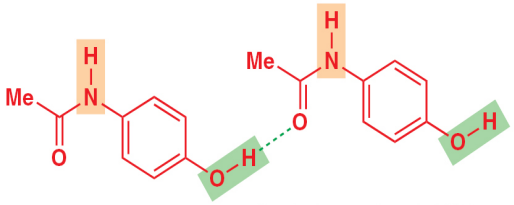


Infravermelho (IV)

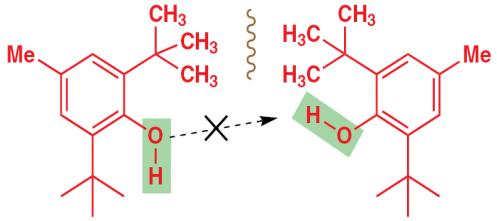
Espectro de IV: ligação de hidrogênio e C-H



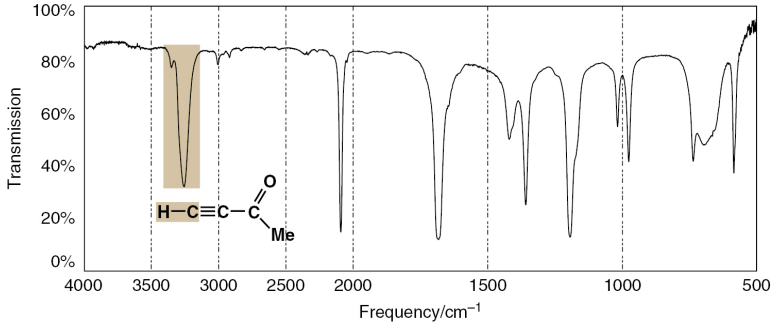




the hydrogen-bonded OH group in paracetamol

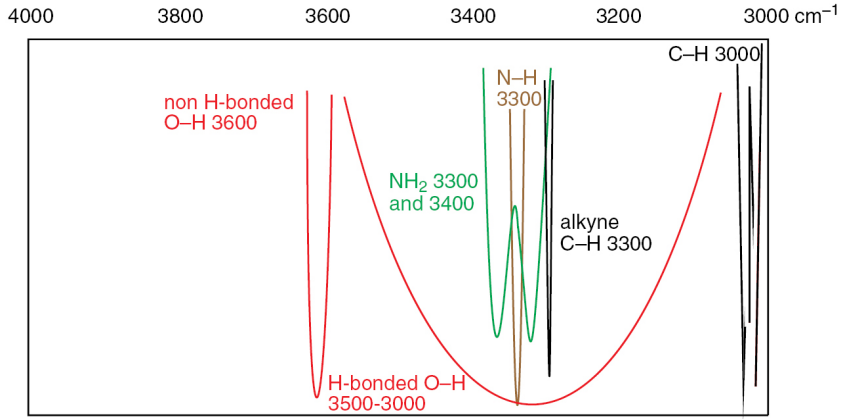


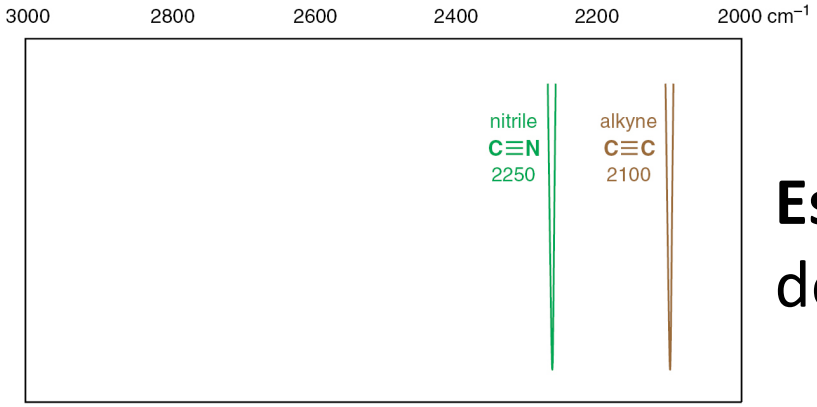
in BHT hydrogen bonding is prevented by large *t*-butyl groups



Infravermelho (IV)

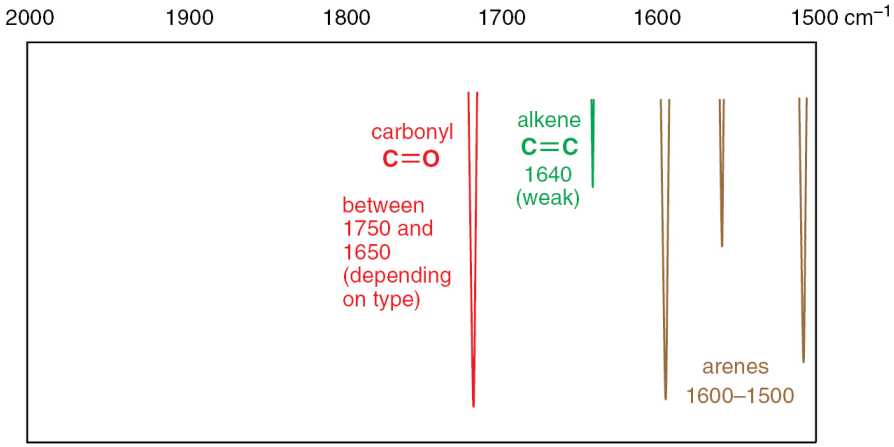
Espectro de IV: padrão típico de bandas O-H e C-H



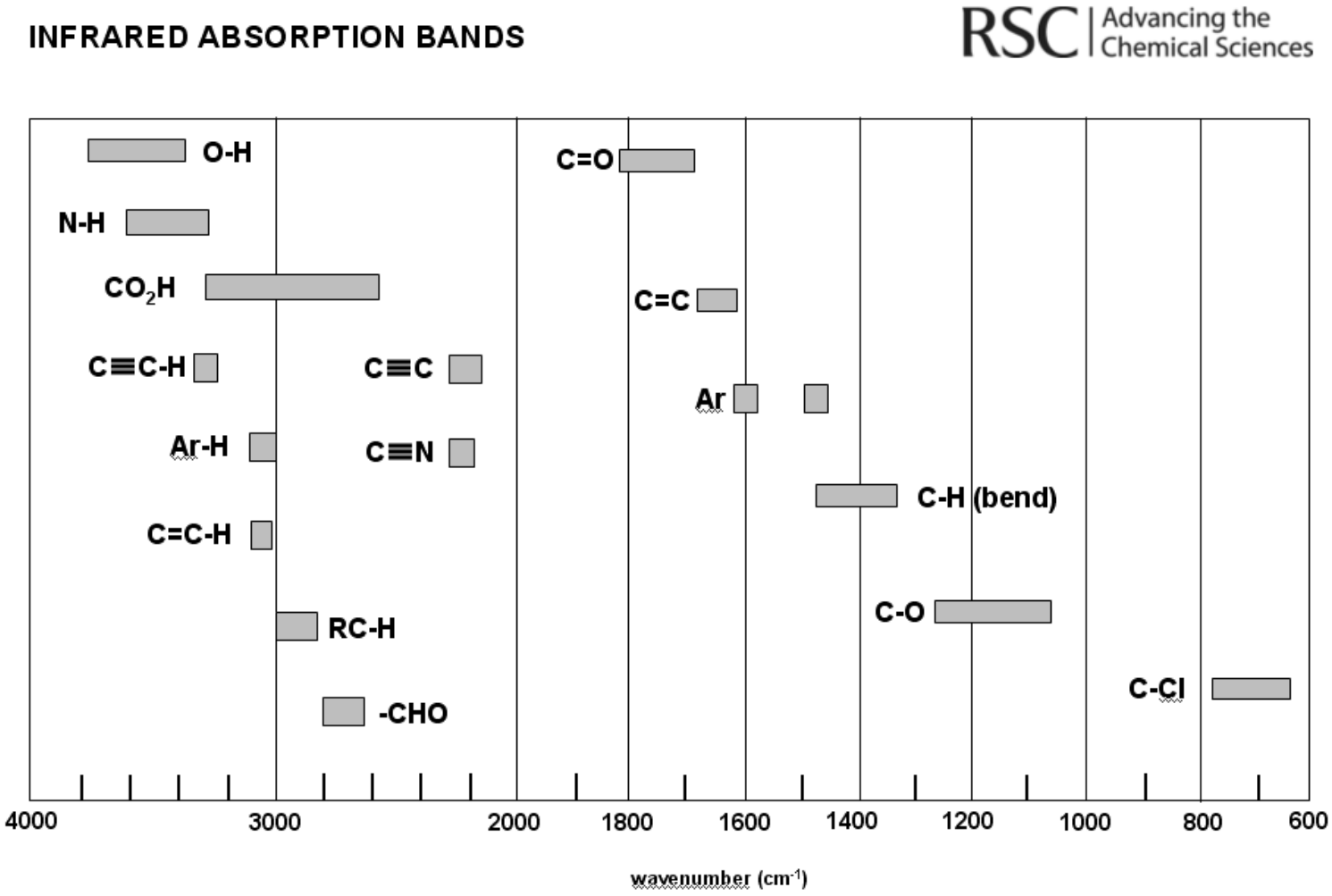


Espectro de IV: região de 3000-2000 cm^{-1}

Espectro de IV: região de dubla ligação



Infravermelho (IV)

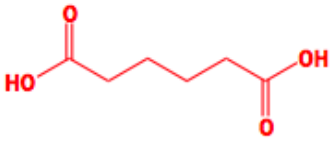


Infravermelho (IV)

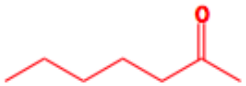
Características da banda de IV

Absorptions in IR spectra

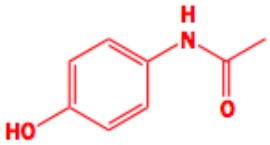
Position of band depends on →	reduced mass of atoms	**light** atoms give **high** frequency
	bond strength	**strong** bonds give **high** frequency
Strength of band depends on →	change in dipole moment	**large** dipole moment gives **strong** absorption
Width of band depends on →	hydrogen bonding	**strong H** bond gives **wide** peak



hexanedioic acid
1720 cm^{-1}



heptan-2-one
1710 cm^{-1}



paracetamol
1667 cm^{-1}

Table 3.7 Single bonds

Pair of atoms	Reduced mass	Bond strength
C–C	6.0	350 kJ mol^{-1}
C–N	6.5	305 kJ mol^{-1}
C–O	6.9	360 kJ mol^{-1}

Infravermelho (IV)

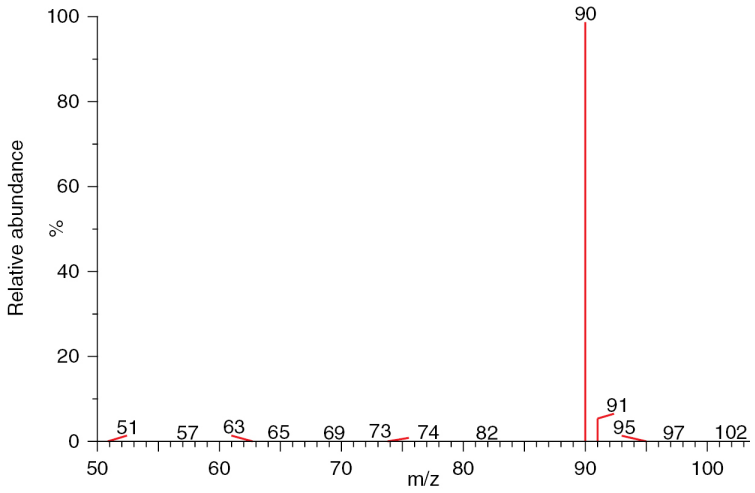
Região abaixo de 1500 cm^{-1} confere a identidade da substância (fingerprint)

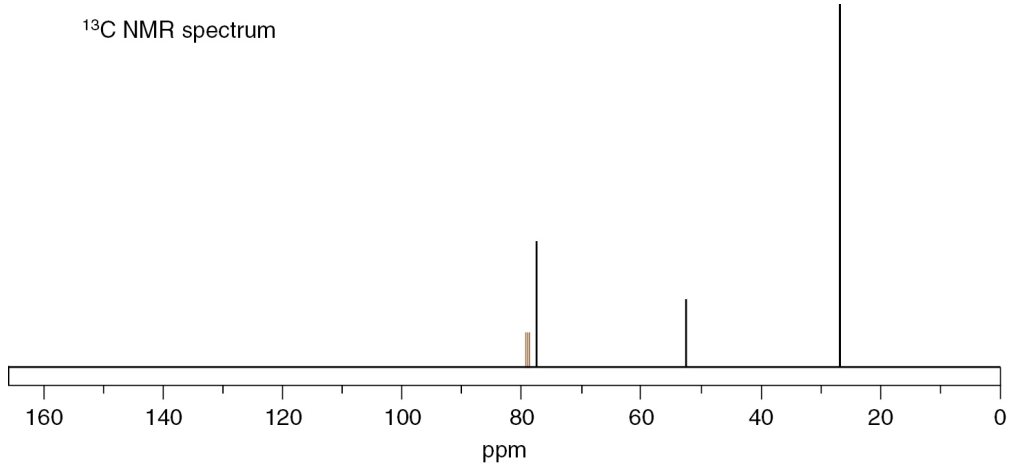
Table 3.9 Useful absorptions in the fingerprint region

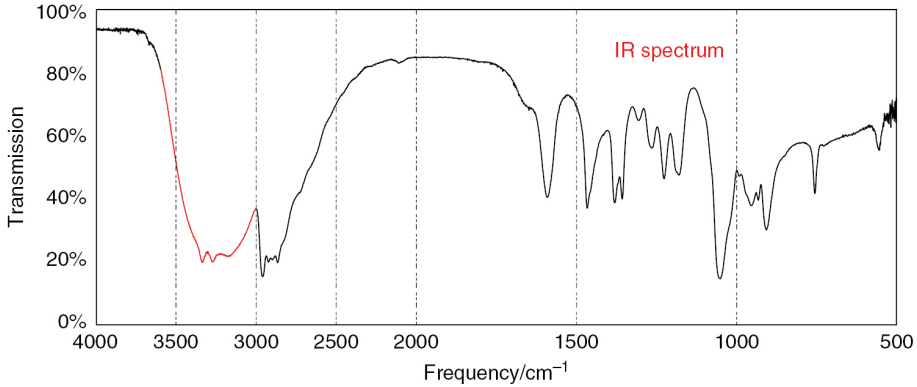
Frequency, cm^{-1}	Strength	Group	Comments
1440–1470	medium	CH_2	deformation (present in nujol)
~1380	medium	CH_3	deformation (present in nujol)
~1350	strong	NO_2	symmetrical N=O stretch
1250–1300	strong	P=O	double bond stretch
1310–1350	strong	SO_2	antisymmetrical S=O stretch
1120–1160	strong	SO_2	symmetrical S=O stretch
~1100	strong	C–O	single bond stretch
950–1000	strong	C=CH	*trans* alkene (out-of-plane deformation)
~690 *and* ~750	strong	Ar–H	five adjacent Ar–H (out-of-plane)
~750	strong	Ar–H	four adjacent Ar–H (out-of-plane)
~700	strong	C–Cl	single bond stretch

Identificação de Molécula

MS, RMN e IV combinadas tornam a identificação de uma molécula possível



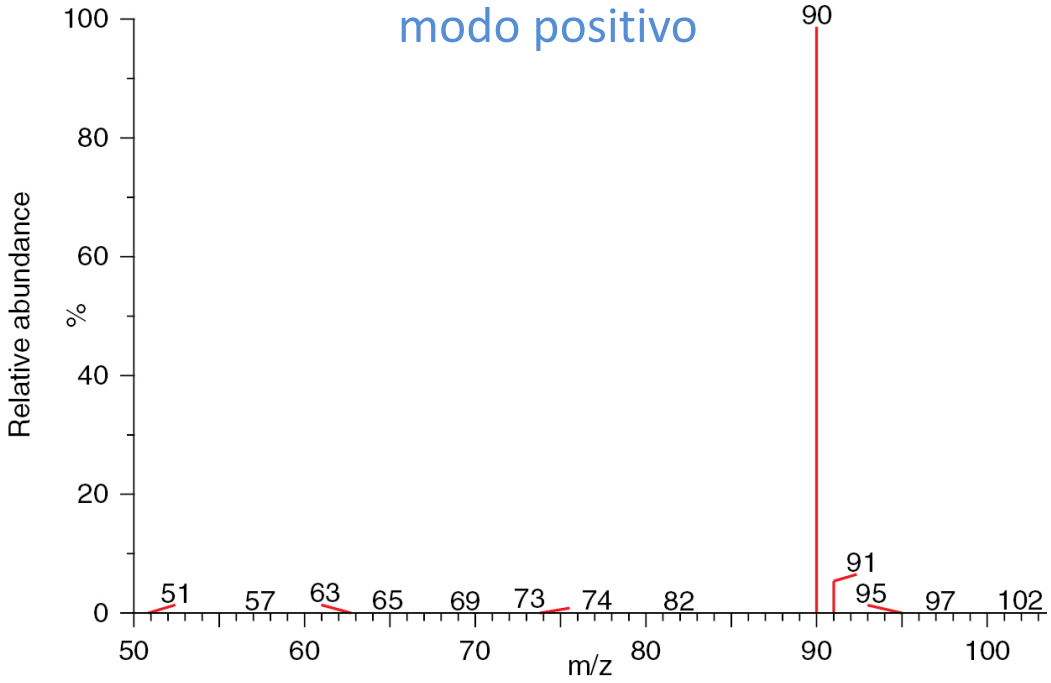




Identificação de Molécula

MS, RMN e IV combinadas tornam a identificação de uma molécula possível

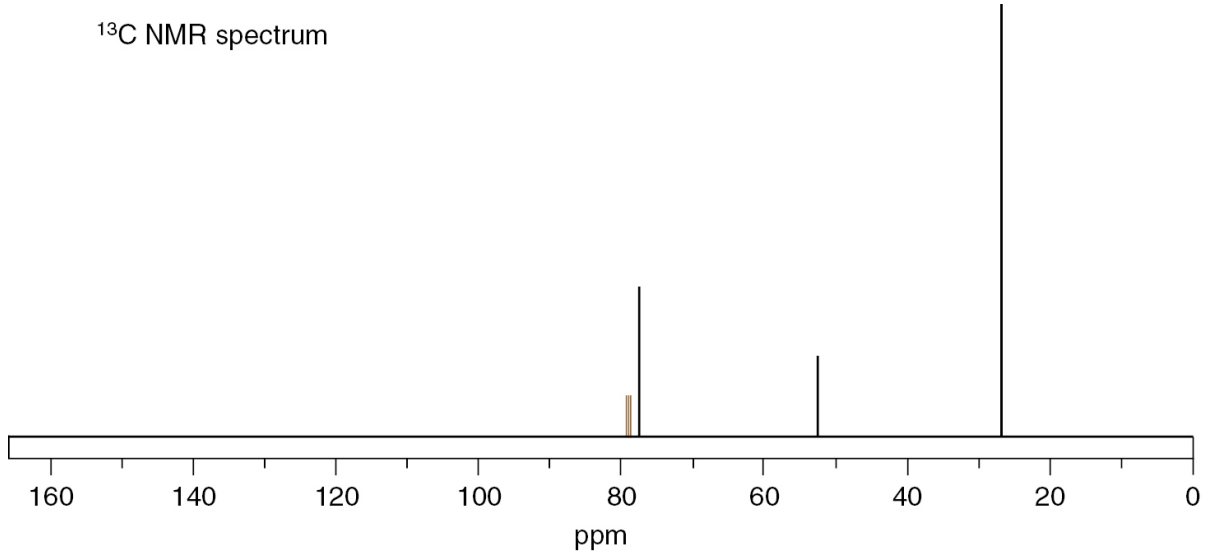
HRMS/ESI$^+$: espectrometria de massas de alta resolução com ionização por elétron spray em modo positivo



1. HRMS/ESI$^+$: m/z $[M\text{-}H]^+$ 90,091 | -1,007 = m/z $[M^+]$ 89,084 = **$C_4H_{11}NO$**

Identificação de Molécula

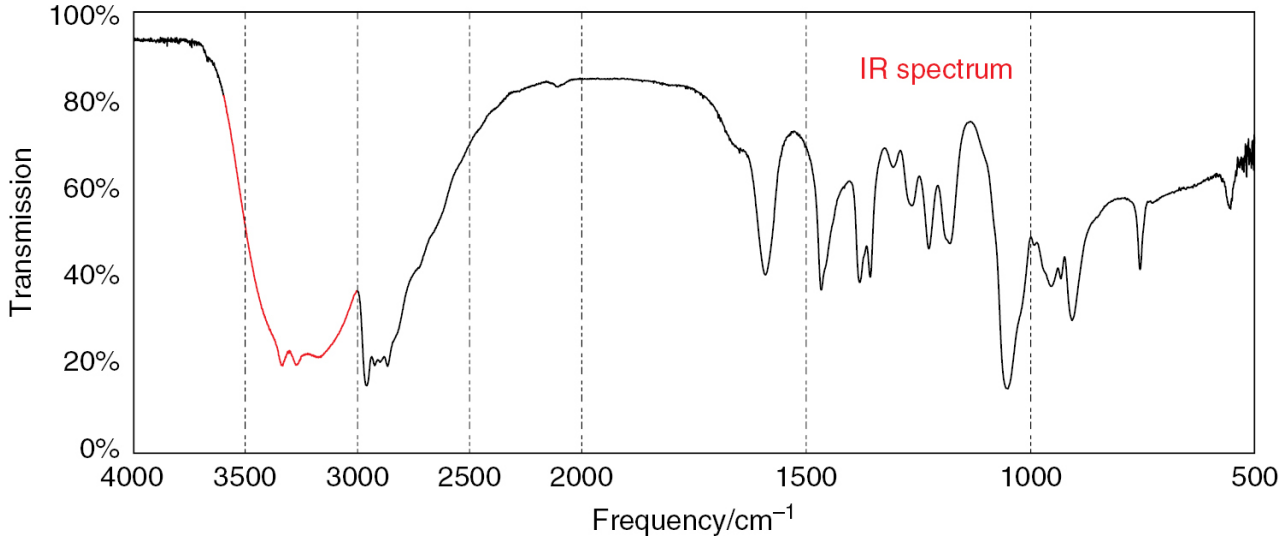
MS, RMN e IV combinadas tornam a identificação de uma molécula possível



2. Três sinais de carbono. Como a molécula tem 4 (**$C_4H_{11}NO$**), dois são simétricos, provavelmente o pico em 25 ppm (2 x CH_3?)

Identificação de Molécula

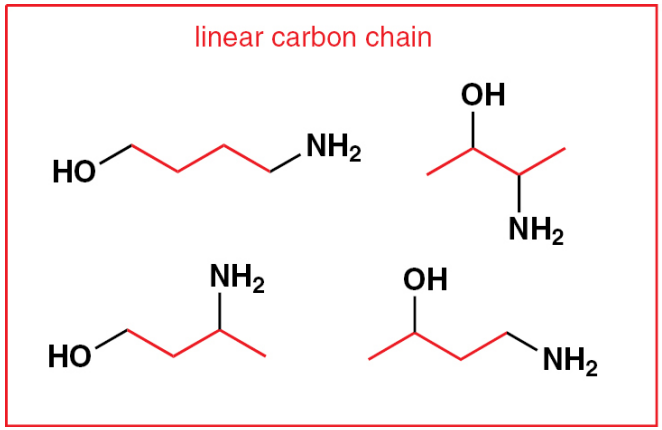
MS, RMN e IV combinadas tornam a identificação de uma molécula possível

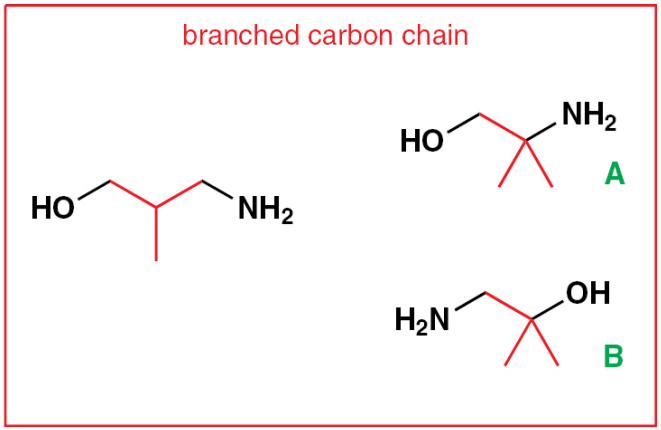


3. Banda larga em *ca.* 3400 cm^{-1}, indicando OH e com dois picos salientes, indicando NH_2: C-OH e C-NH_2 na molécula.

Identificação de Molécula

MS, RMN e IV combinadas tornam a identificação de uma molécula possível





1. HRMS/ESI$^+$: m/z $[M-H]^+$ 90,091 | -1,007 = m/z $[M^+]$ 89,084 = **$C_4H_{11}NO$**

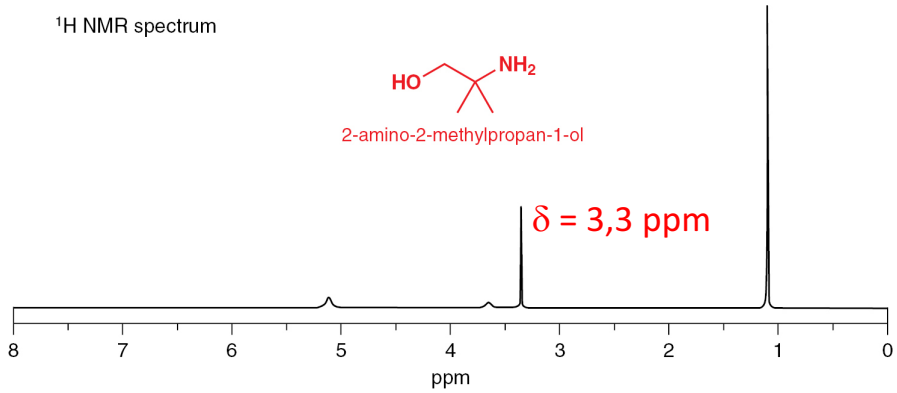
2. Três sinais de carbono. Como a molécula tem 4 (**$C_4H_{11}NO$**), dois são simétricos, provavelmente o pico em 25 ppm (2 x CH_3?)

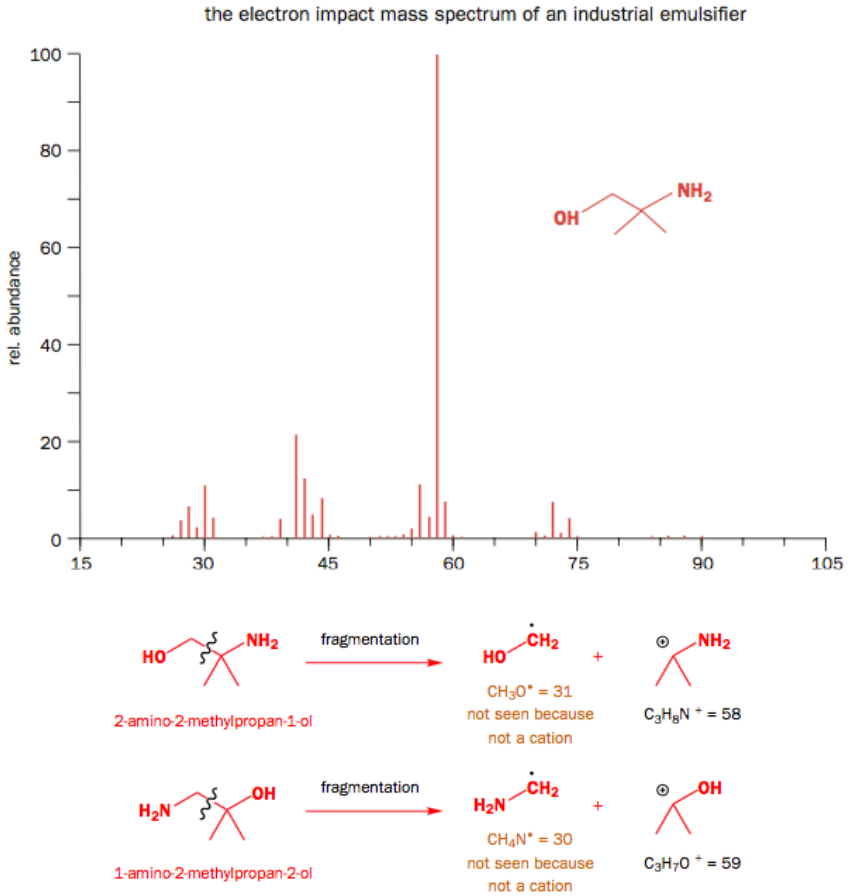
3. Banda larga em *ca.* 3400 cm^{-1}, indicando OH e com dois picos salientes, indicando NH_2: C-OH e C-NH_2 na molécula.

Como decidir entre A e B?

Identificação de Molécula

MS, RMN e IV combinadas tornam a identificação de uma molécula possível



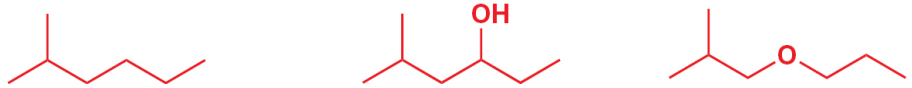


Espectro de RMN ^{1}H (δ = 3,3 ppm) indica que é a estrutura A, pois o próton está muito desblindado

Identificação de Molécula

Equivalente de dupla ligação e anel (DBE) ajuda a elucidar estrutura

saturated hydrocarbon C_7H_{16} saturated alcohol $C_7H_{16}O$ saturated ether $C_7H_{16}O$

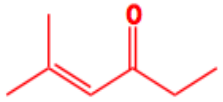


All have $(2n + 2)$ H atoms

Moléculas saturadas tem 2n + 2 átomos de hidrogênio

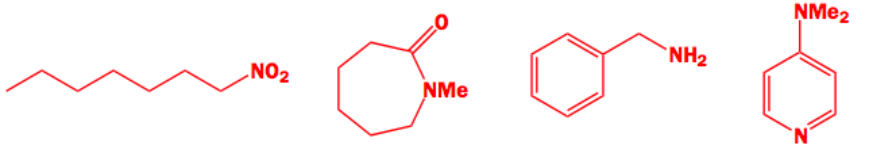
Como calcular?

1	Maximum number of H atoms for 7 Cs	$2n + 2 = 16$
2	Subtract the actual number of H atoms (12)	$16 - 12 = 4$
3	Divide by 2 to give the DBEs	$4/2 = 2$



$C_7H_{12}O$ = two DBE

Entretanto, moléculas contendo **N** são diferentes. Cada N adiciona um H ”extra”, pois o N pode fazer três ligações



$C_7H_{15}NO_2$ = one DBE $C_7H_{13}NO$ = two DBE C_7H_9NO= four DBE $C_7H_{10}N_2$ = four DBE

N,N-dimetil piridina (DMP)

DMP

1	Maximum number of H atoms for 7 Cs	$2n + 2 = 16$
2	Subtract the actual number of H atoms (10)	$16 - 10 = 6$
3	Add number of nitrogens	$6 + 2 = 8$
4	Divide by 2 to give the DBEs	$8/2 = 4$

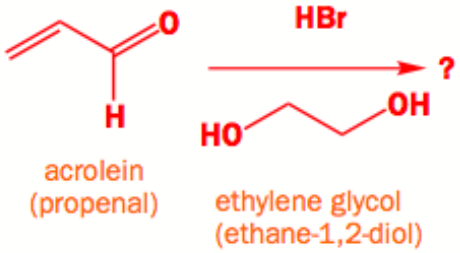
3 duplas e 1 anel = 4

Working out the DBEs for an unknown compound

1. Calculate the expected number of Hs in the saturated structure
   (a) For C_n there would be: $2n + 2$ Hs if C, H, O only
   (b) For C_nN_m there would be $2n + 2 + m$ Hs
2. Subtract the actual number of Hs and divide by 2. This gives the DBEs
3. If there are other atoms (Cl, B, P, etc.) it is best to draw a trial structure
4. If there are few Hs, e.g. less than the number of Cs, suspect a benzene ring
5. A benzene ring has *four* DBEs (three for the double bonds and one for the ring)
6. A nitro group has *one* DBE only

Identificação de Molécula

Mais um exemplo

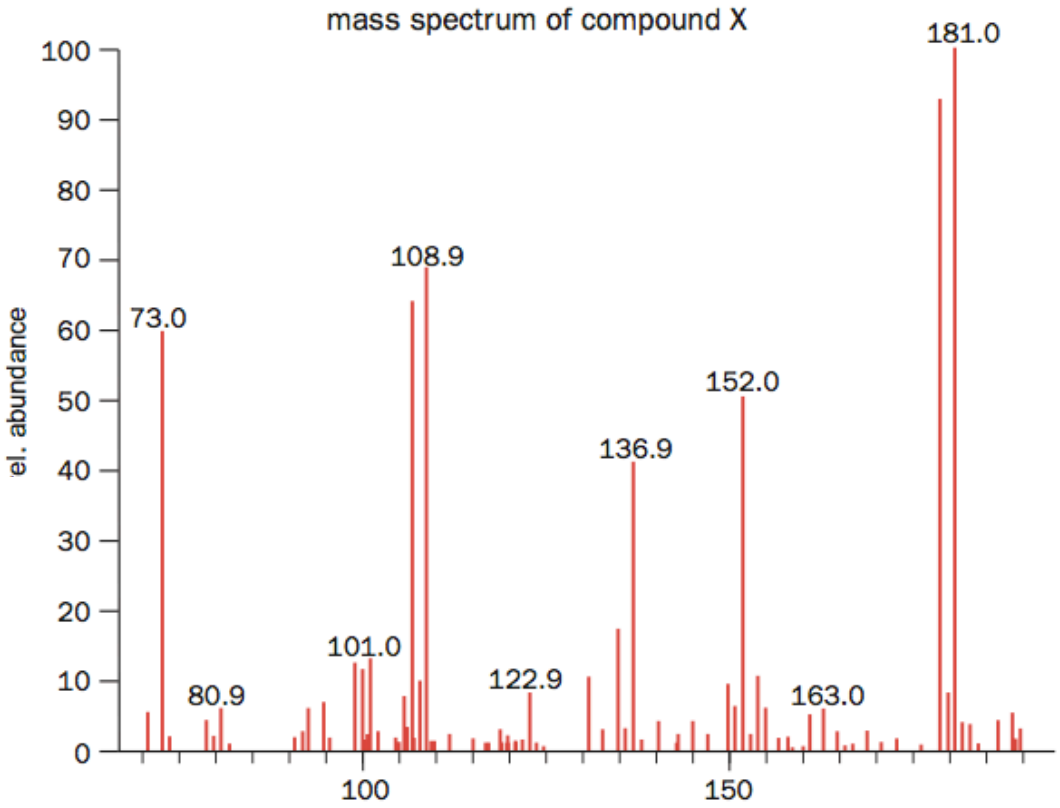


1. **MS/EI:** $[M]^+$ = m/z 181/179: molécula tem 1 bromo,

2. **HRMS:** m/z 179,979, $C_5H_9BrO_2$

3. **DBE:** 1

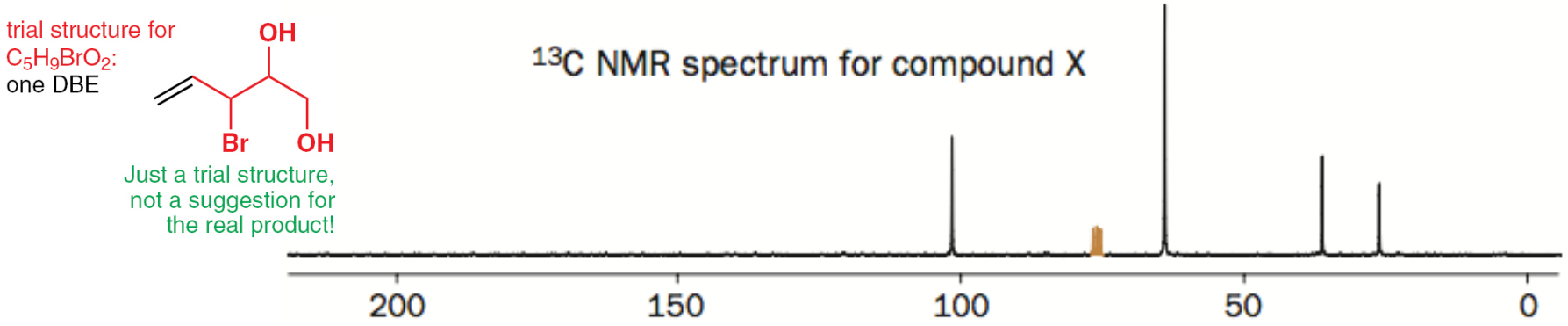
1	Maximum number of H atoms f	2n + 2 = 12
2	Subtract the actual number of H	12 – 10 (9H+1Br) = 2
3	Add number of nitrogens	2 + 0 = 2
4	Divide by 2 to give the DBEs	2/2 = 1



C_3H_4O + $C_2H_6O_2$ + HBr = $C_5H_{11}BrO_3$ = $C_5H_9BrO_2$ + H_2O

Identificação de Molécula

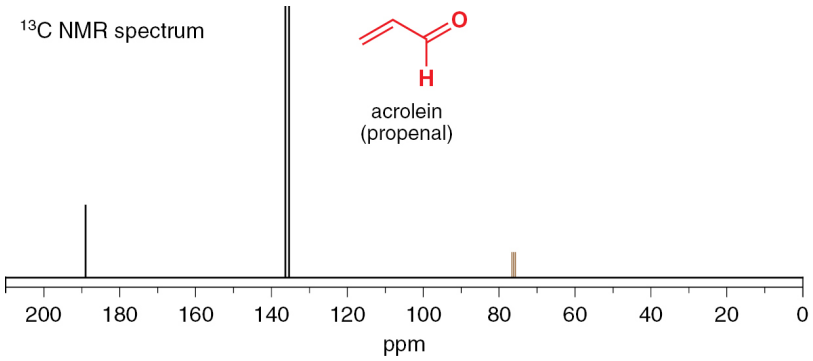
Mais um exemplo



4. **RMN ^{13}C:** 4 carbonos, sendo 2 simétricos e saturados (δ < 50 ppm), 1 perto do oxigênio (δ ~ 65 ppm) e 1 próximo da região de insaturados (δ > 100 ppm),

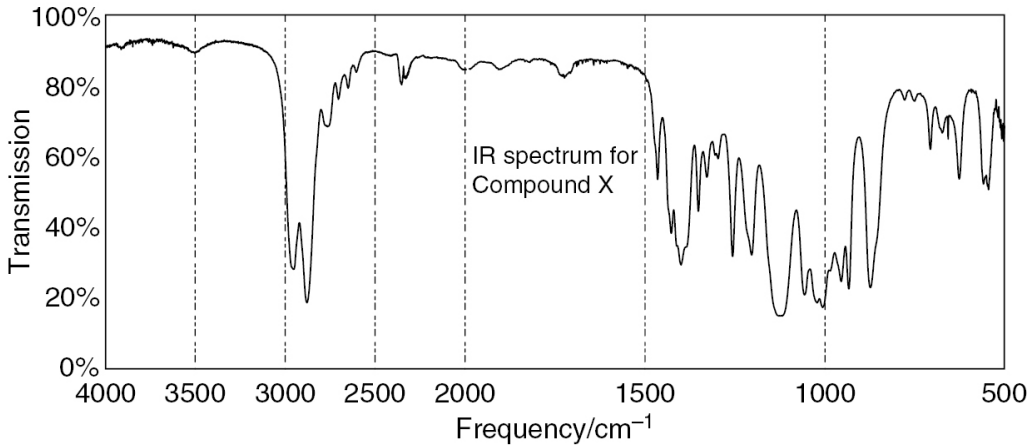
5. Não há duplas, pois não é possível uma dupla com um único carbono: só há um sinal acima de 100 ppm

6. Como não há duplas, deve ser um composto cíclico



Identificação de Molécula

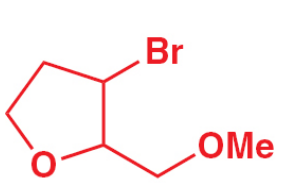
Mais um exemplo



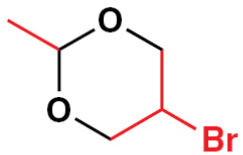
7. **IV:** não há grupos funcionais, nenhum OH, carbonila ou alceno

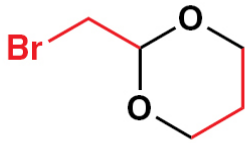
8. Deve ser um éter, ou melhor, duas ligações do tipo éter, pois há dois oxigênio

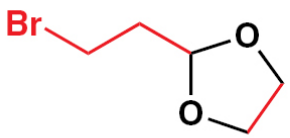
9. De fato, há uma banda em 1128 cm^{-1}, de estiramento C-O

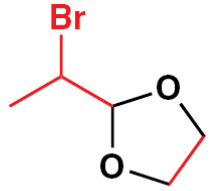


não há C simétrico

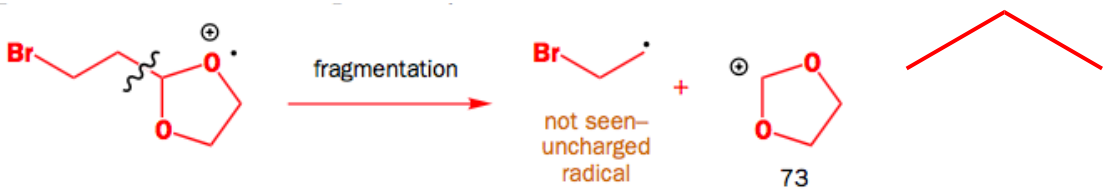






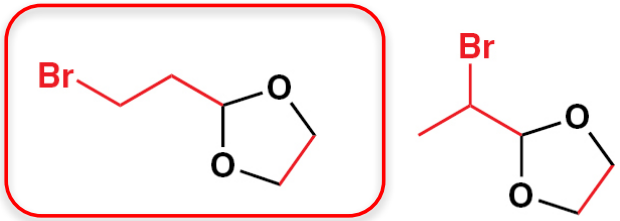


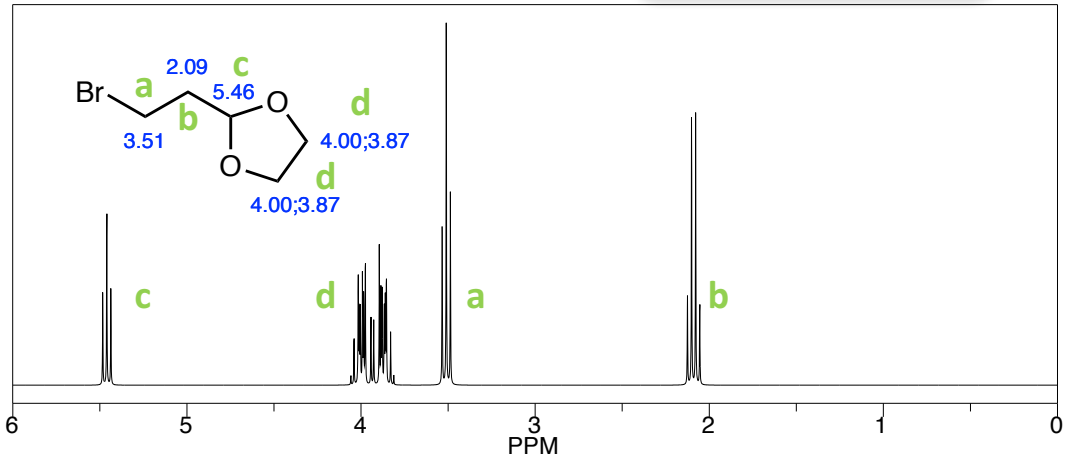
Nestas o esqueleto de C original é preservado



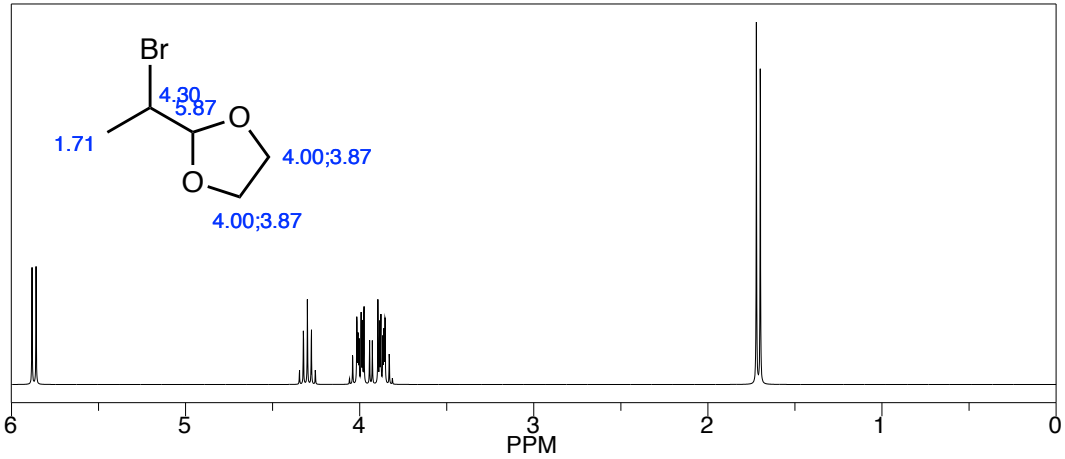
Identificação de Molécula

O espectro de RMN ^{1}H decide





Este é o espectro de RMN ^{1}H do produto



Ressonância Magnética Nuclear (RMN)

Mais adiante no curso, na disciplina de Química Orgânica Experimental, você aprenderá um pouco mais sobre RMN ^{1}H e **acoplamento.**