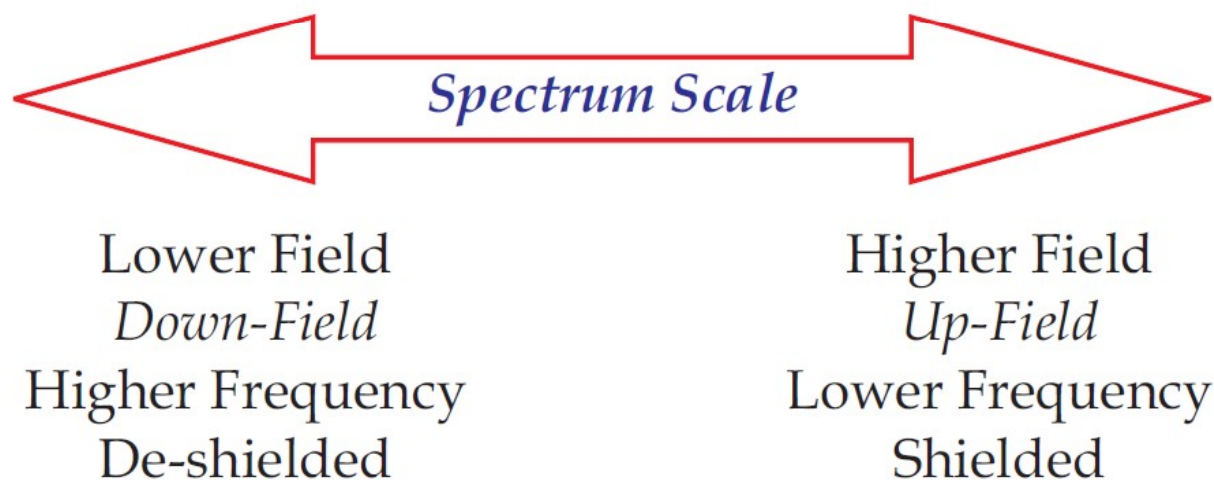


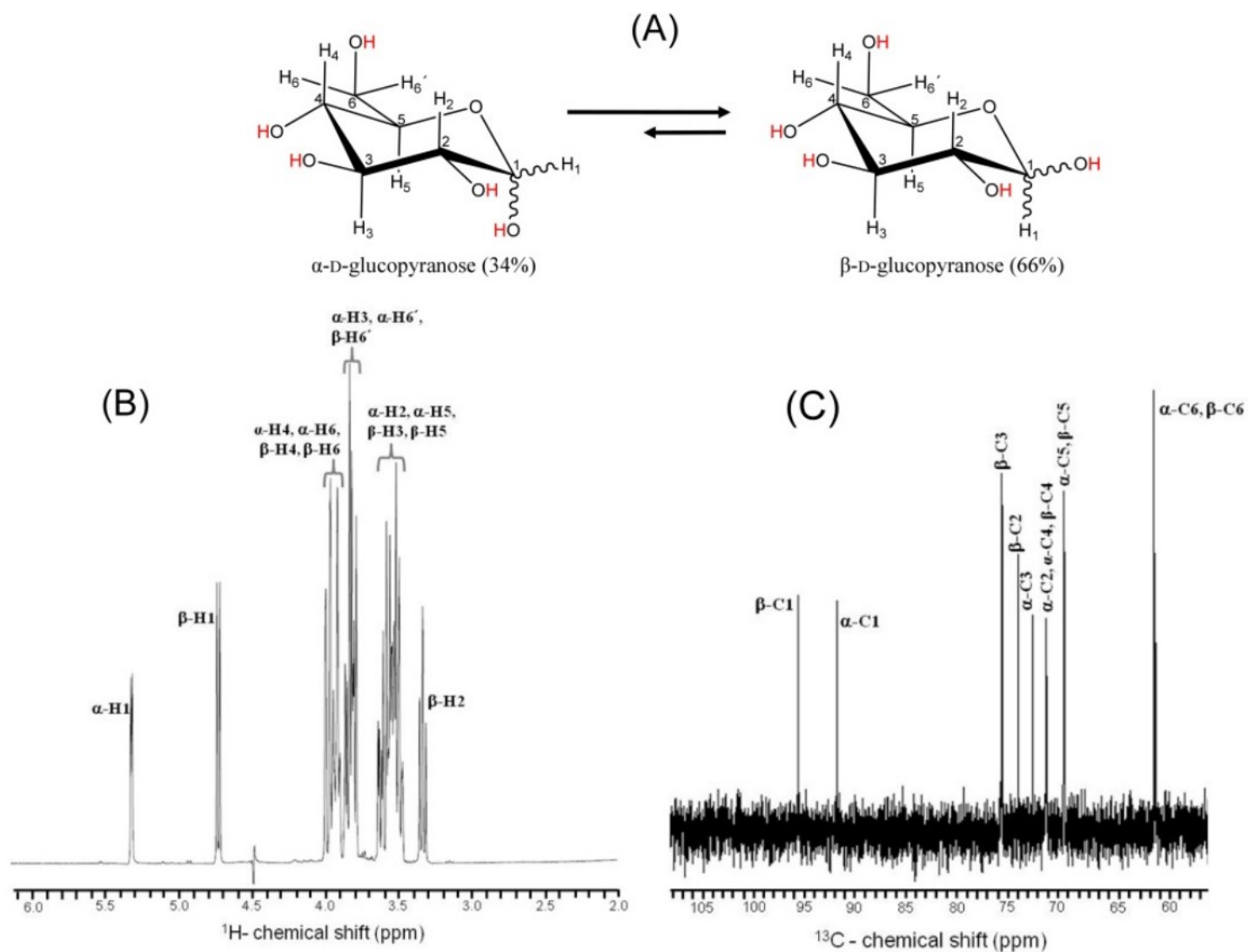
NMR Chemical Shift (δ)!

In a molecule, electrons act to *screen* or *shield* the nucleus from the static magnetic field. The result is a difference in the resonance frequency (ω_0) for atoms of the same type that are in different *bonding* environments. Changes in electron density surrounding the nucleus will dictate the chemical shift of different structures.

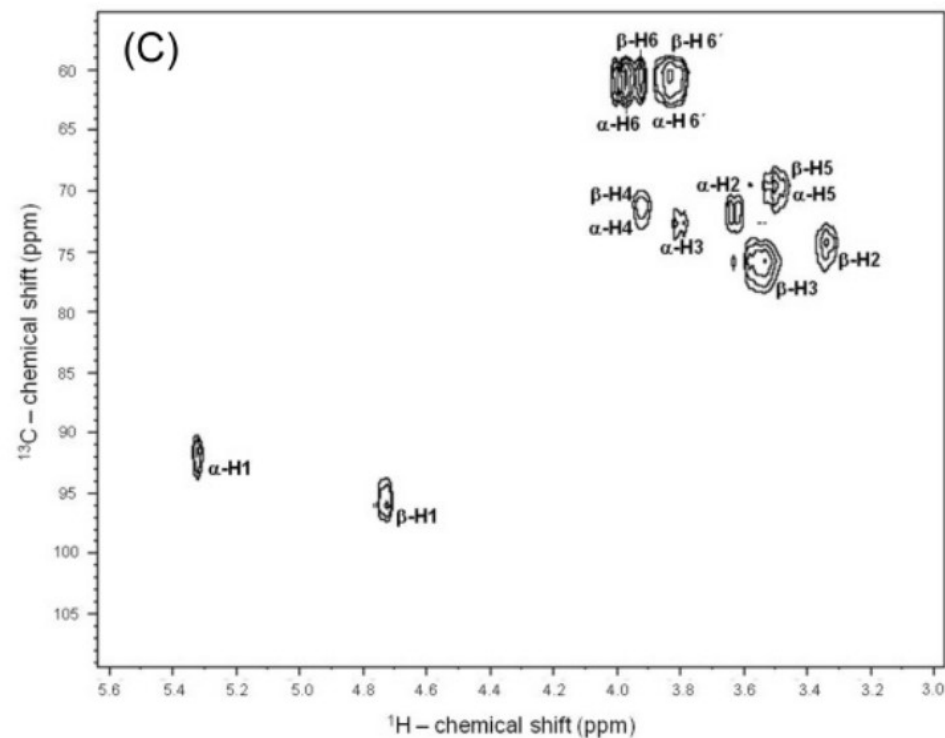
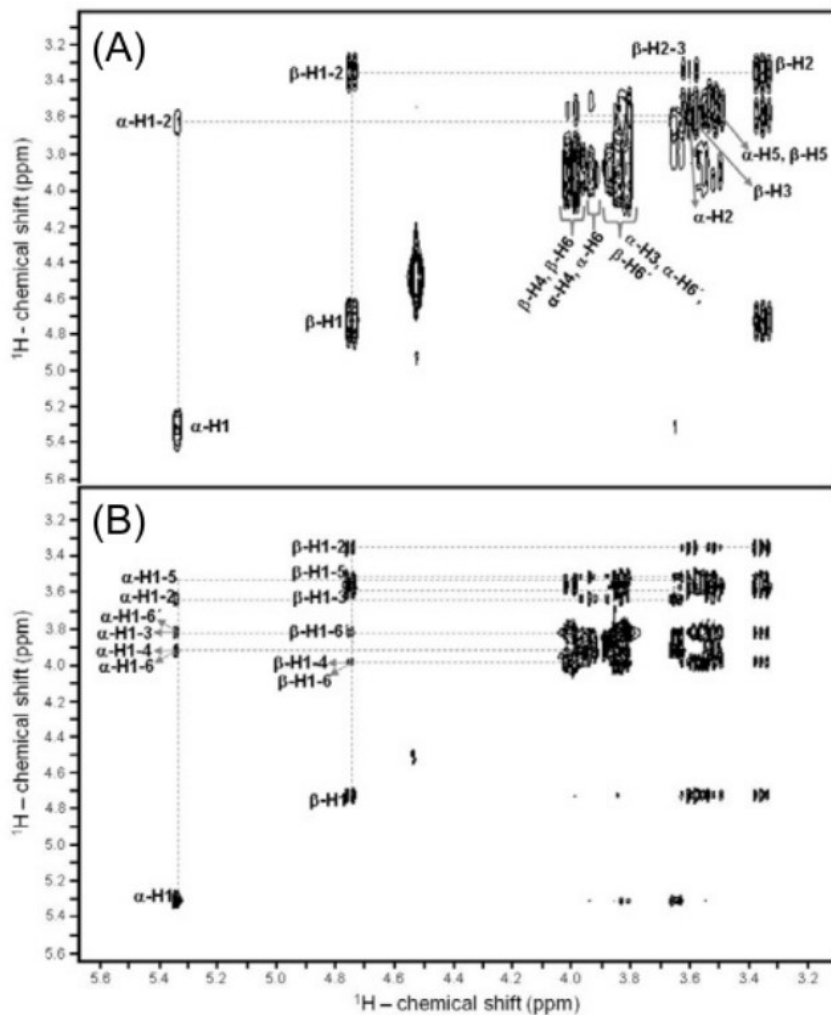


Standard convention places lower or negative chemical shift values at the right and higher or positive to the left.

^1H and ^{13}C chemical shift assignment on glucose in 100 % D_2O (1D NMR spectra)



^1H and ^{13}C chemical shift assignment on glucose in 100 % D_2O (2D NMR spectra)



$\alpha\text{-D-Glcp}$	$\beta\text{-D-Glcp}$
$\alpha\text{-H1}$ - 5.32	$\beta\text{-H1}$ - 4.74
$\alpha\text{-H2}$ - 3.63	$\beta\text{-H2}$ - 3.37
$\alpha\text{-H3}$ - 3.83	$\beta\text{-H3}$ - 3.60
$\alpha\text{-H4}$ - 3.92	$\beta\text{-H4}$ - 3.92
$\alpha\text{-H5}$ - 3.50	$\beta\text{-H5}$ - 3.5
H6/6' - 3.91/3.82	H6/6' - 3.91/3.82
$\alpha\text{-C1}$ - 91.4	$\beta\text{-C1}$ - 95.9
$\alpha\text{-C2}$ - 71.8	$\beta\text{-C2}$ - 74.1
$\alpha\text{-C3}$ - 72.4	$\beta\text{-C3}$ - 75.8
$\alpha\text{-C4}$ - 71.2	$\beta\text{-C4}$ - 71.2
$\alpha\text{-C5}$ - 69.8	$\beta\text{-C5}$ - 69.8
$\alpha\text{-C6}$ - 60.3	$\beta\text{-C6}$ - 60.3

Properties of Chemical Shift

$$\nu_i \text{ (Hz)} = \gamma B_0 (1 - \sigma_i) / 2\pi$$

- The Larmor frequencies of nuclei depend on the electronic structure of the molecule and the electronic environments of the nuclei, and reflect the chemical properties
- The adjustments to the resonance frequencies to account for electronic structure and electronic shielding of nuclei from the magnetic field are embodied in the shielding constant, σ
- The values of σ are small (10^{-6}), and reduce the effective field strength by parts per million (ppm) ($B_{\text{eff}} = B_0(1 - \sigma)$)

Measurements are made relative to a reference peak (TMS).

Offsets given in terms of δ in parts per million, ppm, + downfield.

$$\delta_i = (\sigma_{\text{ref}} - \sigma_i) \times 10^6$$

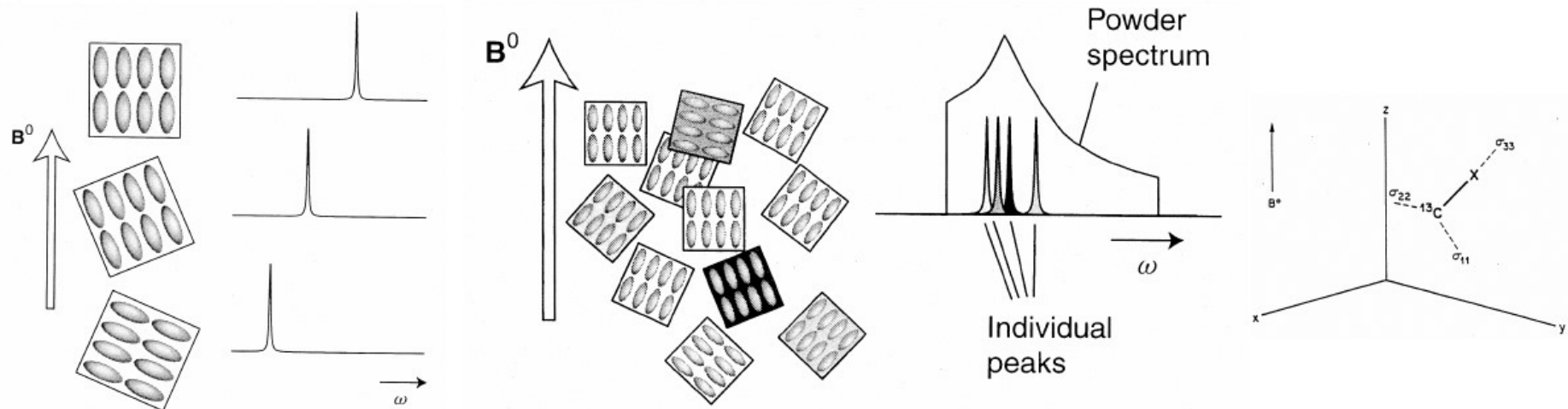
or

$$\delta_i = ((\nu_i - \nu_{\text{ref}}) / \nu_{\text{ref}}) \times 10^6$$

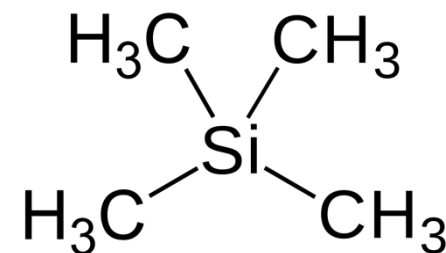
Ranges: ^1H , ^2H , 10 ppm; ^{13}C , ^{15}N , ^{31}P , 300 ppm; ^{19}F , 1000 ppm

Importance of Chemical Shifts and Their Origins

- Shieldings are tensor quantities: magnitudes depend on orientation to magnetic field (*chemical shift anisotropy*)
- In the solid state, different orientations give different shifts
- In solution (rapid molecular tumbling) an average value results
- However, in solution some orientation can be reintroduced in order to exploit available structural information
- Chemical shifts reflect chemical environment, so there is potentially lots of structural information in chemical shifts themselves if we can understand the relationship with structure



ppm and TMS



Chemical shifts of compounds are reported as the fractional frequency change from the resonance of a reference compound. The absolute frequency is high (MHz) but the differences we measure are quite small (Hz). We use a unit-less scale to reflect the difference in parts per million (ppm) from the reference:

$$\delta_s = 1,000,000 (\omega_s - \omega_r) / \omega_r$$

This convention makes Chemical Shifts independent from the strength of the applied magnetic field, so values measured on any instrument can be directly compared. Absolute frequencies of resonances depend on the magnetic field strength and are rarely reported.

Each type of nucleus has a generally accepted standard. For ¹H, ¹³C and ²⁹Si the standard is *tetramethylsilane* (TMS). It was chosen because it could be added to most organic samples and was relatively inert. It also has a very large up-field shift and falls away from most other resonances of organic compounds.

Factors that impact on Chemical Shifts

Since shielding is caused by electron density around the nucleus any factor that changes the electron density will have a major effect on the chemical shift.

Some of the more critical factors that dictate chemical shifts are:

- 1) Types of bonds present
- 2) Electronegativity of nearby (through bond) functional groups
- 3) Proximity (spacial) to sources of electron density

Bond types and influence on chemical shifts

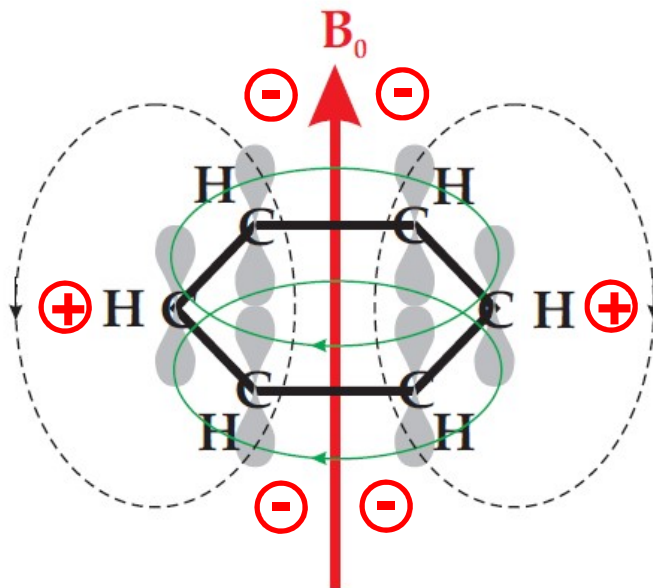
Different types of bonds shield the nuclei (^{13}C) and the attached protons differently. The presence of π bonds introduce electron motion that σ bonds cannot exhibit.

Bond types	^1H Chemical Shift (ppm)	^{13}C Chemical Shift (ppm)
$\text{H}_3\text{C}-\text{CH}_3$	0.86	7.3
$\text{H}_2\text{C}=\text{CH}_2$	5.28 _I	128.5
C_6H_6	7.26	128.5
$\text{HC}\equiv\text{CH}$	1.80	71.9

Ring current

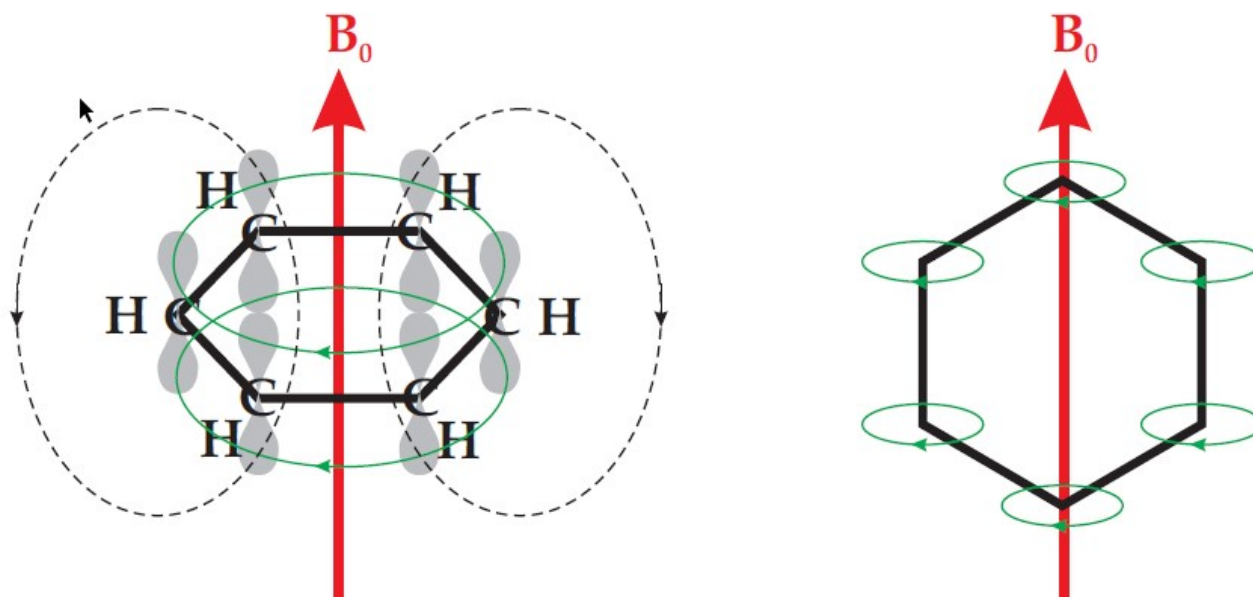
Circulation of electrons in a molecule contribute to shielding or deshielding of atoms in the molecule. The ring current in a benzene ring is an example of this phenomena.

The local field generated by electron motion can either act to add to the applied field (B_0) or subtract from it. This results in chemical shifts that depend on the position of the nucleus to the ring.



Chemical Shift Anisotropy

Orientation of a molecule with respect to the applied magnetic field dictates the types of electron circulation. This changes the shielding of the nuclei and therefore, changes the chemical shifts. These effects are very prominent in the solid-state but are averaged out for molecules that *isotropically* tumble (i.e., molecules in the liquid-state, in solution or in the gas phase).



Electronegativity

The ability of an atom or functional group to attract electrons.

More electronegative groups will deshield the adjacent ^{13}C and ^1H and cause a greater downfield chemical shift

	Functional Group Electronegativity*	^1H Chemical Shift ($-\text{CH}_3$) ppm	^{13}C Chemical Shift ($-\text{CH}_3$) ppm
$\text{CH}_3 - \text{OH}$	3.89	3.39	50.2
$\text{CH}_3 - \text{NH}_2$	3.40	2.47	28.3
$\text{CH}_3 - \text{SH}$	2.61	2.00	6.5
$\text{CH}_3 - \text{H}$	2.1	0.23	-2.3

* Pauling Scale

Electronegativity

The effect of electronegative groups extends across bonds to adjacent carbons and protons down a chain. Note that the remote trends are not as prominent and sometimes reversed.

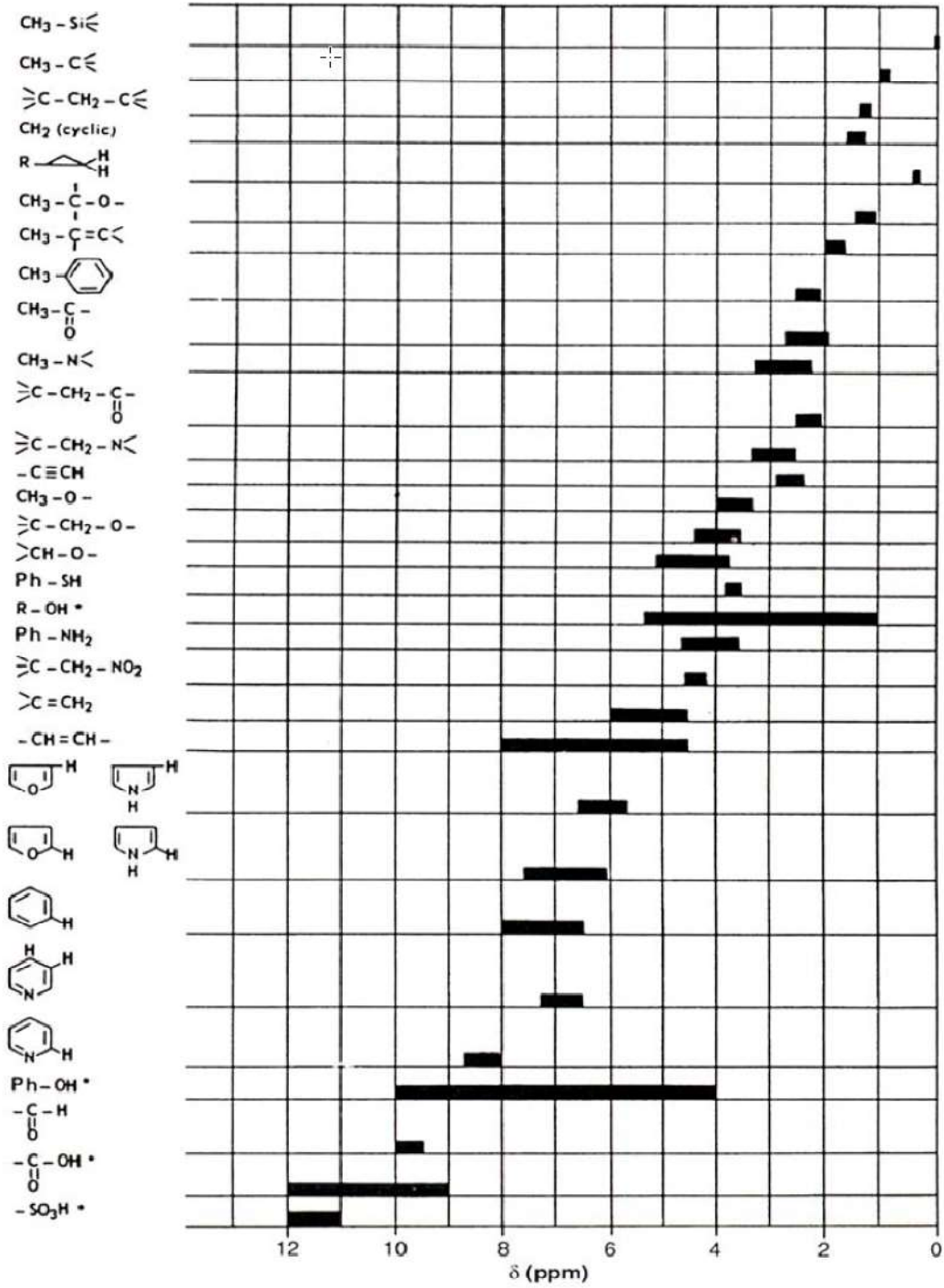
X-CH ₂ CH ₃	¹ H (ppm)		¹³ C (ppm)	
	CH ₂	CH ₃	CH ₂	CH ₃
X				
-OH	3.59	1.18	57.8	18.2
-NH ₂	2.74	1.10	36.9	19.0
-SH	2.44	1.31	19.1	19.7

X-CH ₂ CH ₂ CH ₃	¹ H (ppm)			¹³ C (ppm)		
	CH ₂	CH ₂	CH ₃	CH ₂	CH ₂	CH ₃
X						
-OH	3.49	1.53	0.93	64.2	25.9	10.3
-NH ₂	2.51	1.43	0.93	44.6	27.4	11.5
-SH	2.46	1.57	1.02	26.4	27.6	12.6

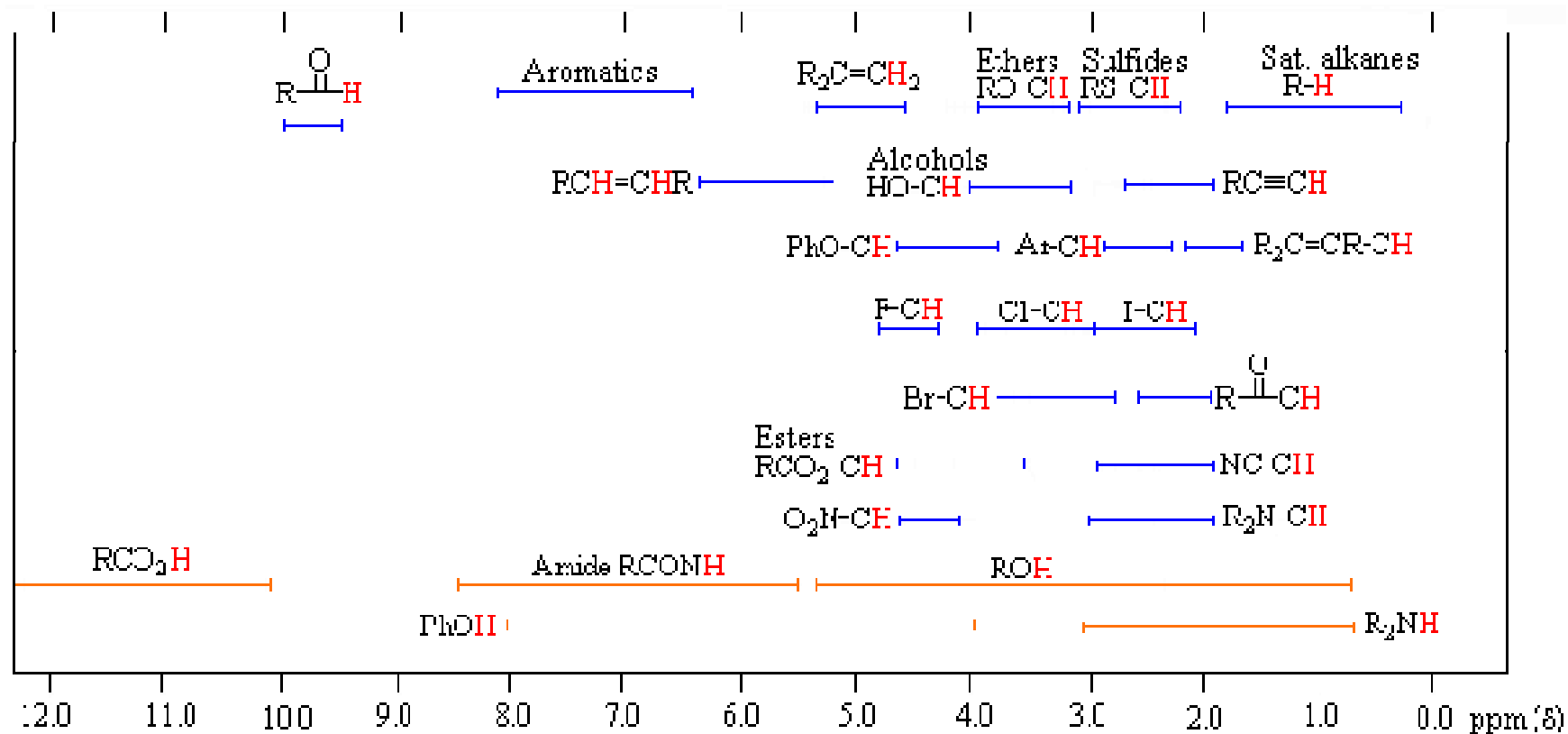
Other influential factors!

- ☹️ Some chemical shifts are temperature dependent
- ☹️ Some chemical shifts are solvent dependent
- ☹️ Some chemical shifts are concentration dependent
- ☹️ Labile protons (OH's, NH's etc.) are often exchange-averaged with free H₂O present in most NMR solvents.
- ☹️ Referencing is often done based on default instrument parameters or residual solvent resonances. This introduces error in the values measured or reported.

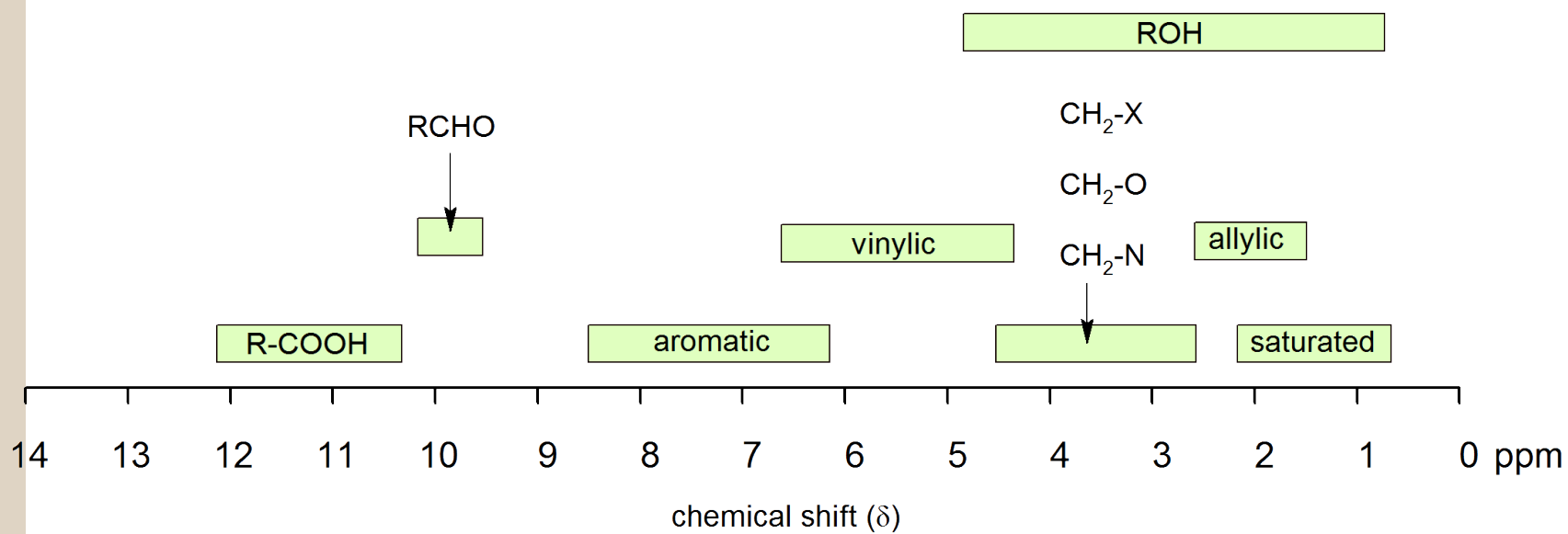
Reference ^1H chemical shifts



Reference ^1H chemical shifts



Reference ^1H chemical shifts



Reference ^{13}C chemical shifts

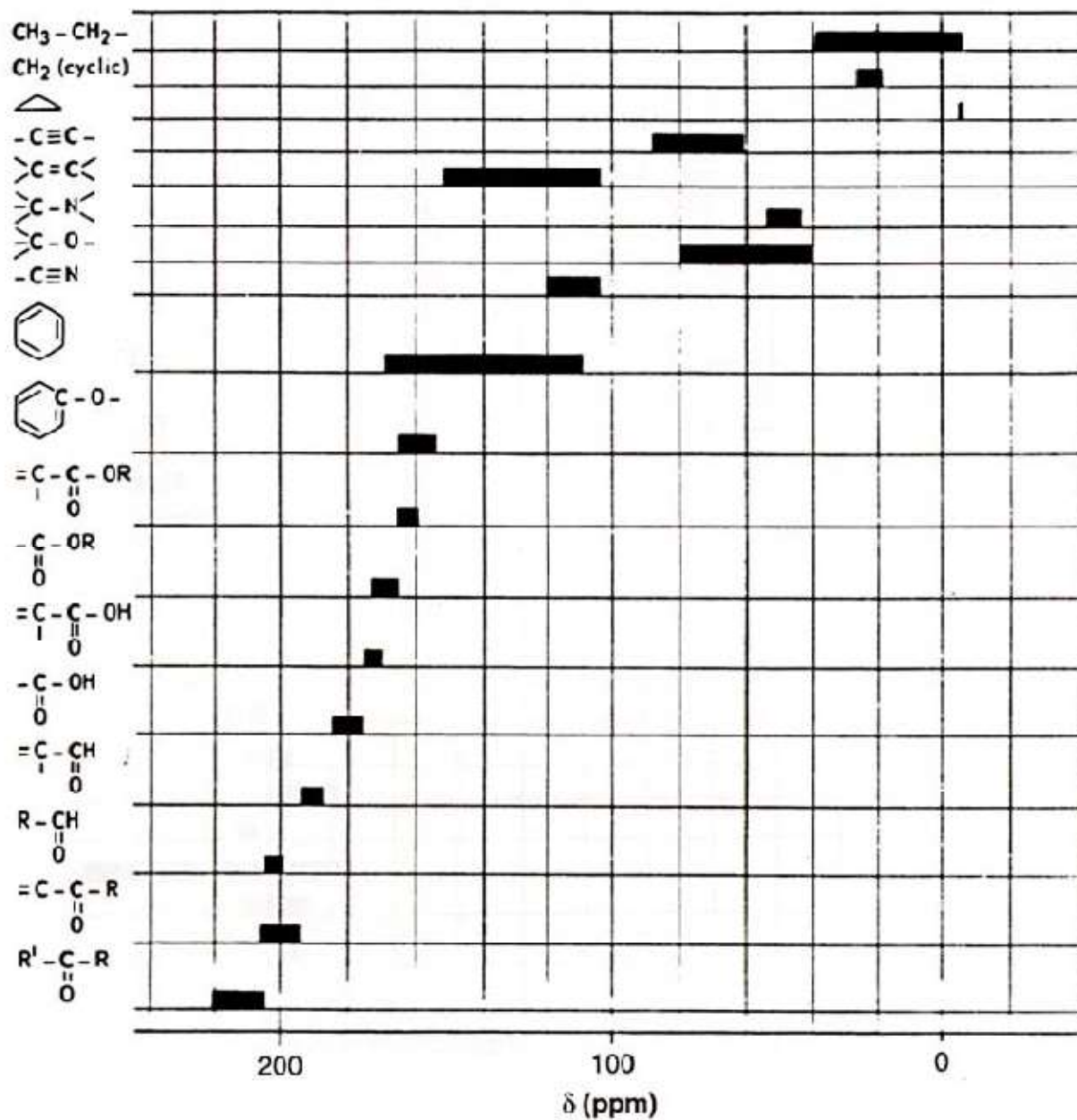
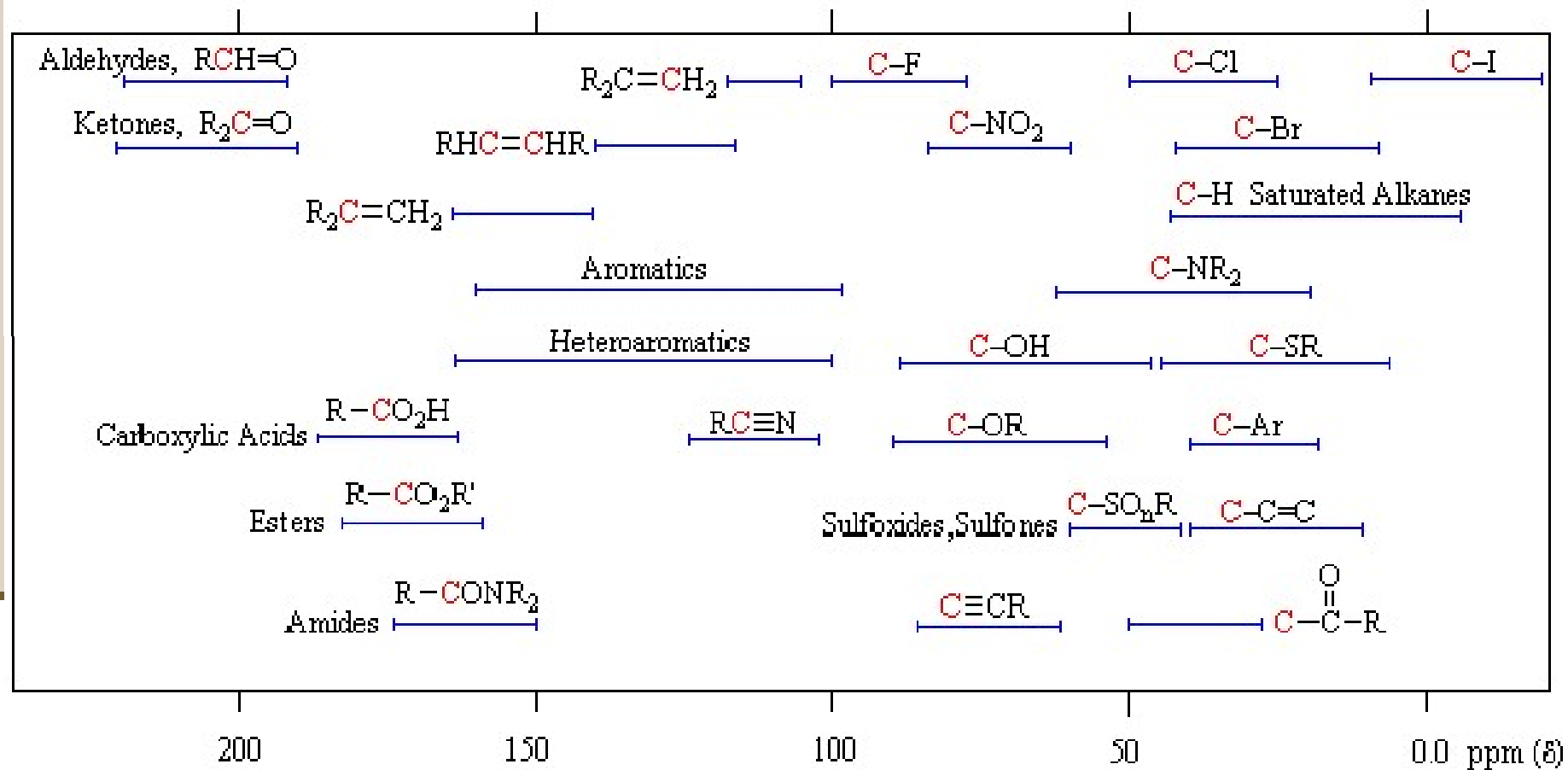


FIGURE 4.3 Approximate chemical shift ranges for ^{13}C (indicated in boldface) in various functional groups. Reference: ^{13}C in TMS (internal).

Reference ^{13}C chemical shifts



Reference ^{19}F and ^{15}N chemical shifts

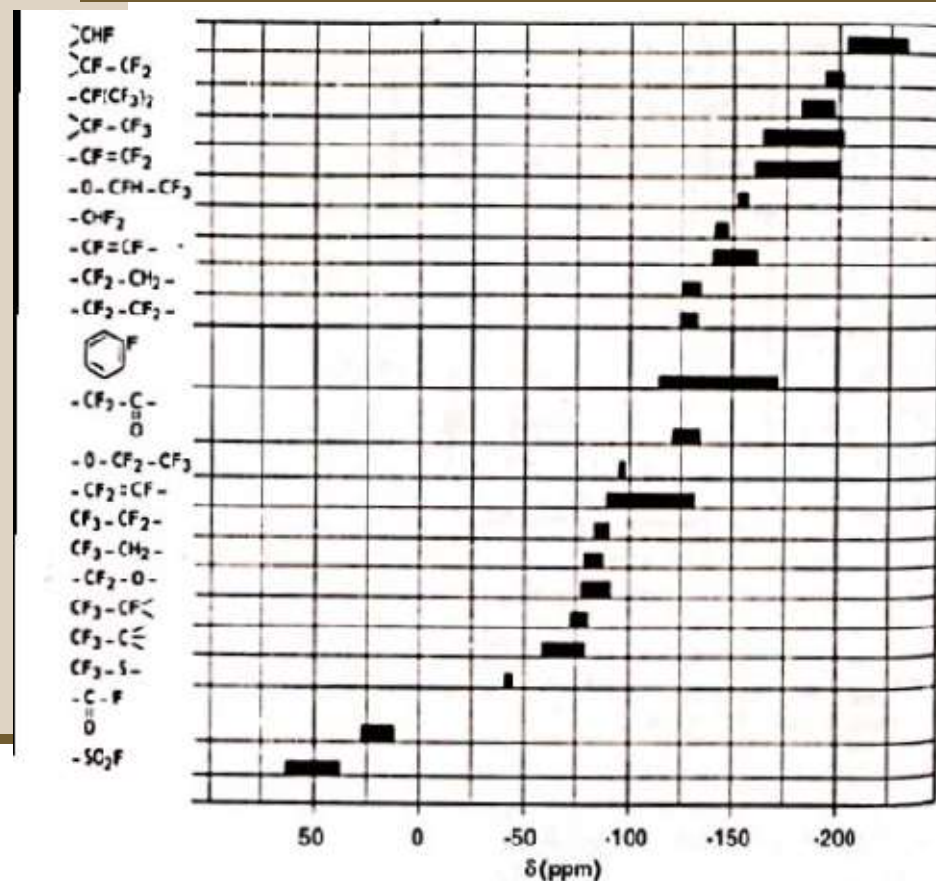


FIGURE 4.6 Approximate chemical shift ranges for ^{19}F in various functional groups. Reference: CCl_3F (external).

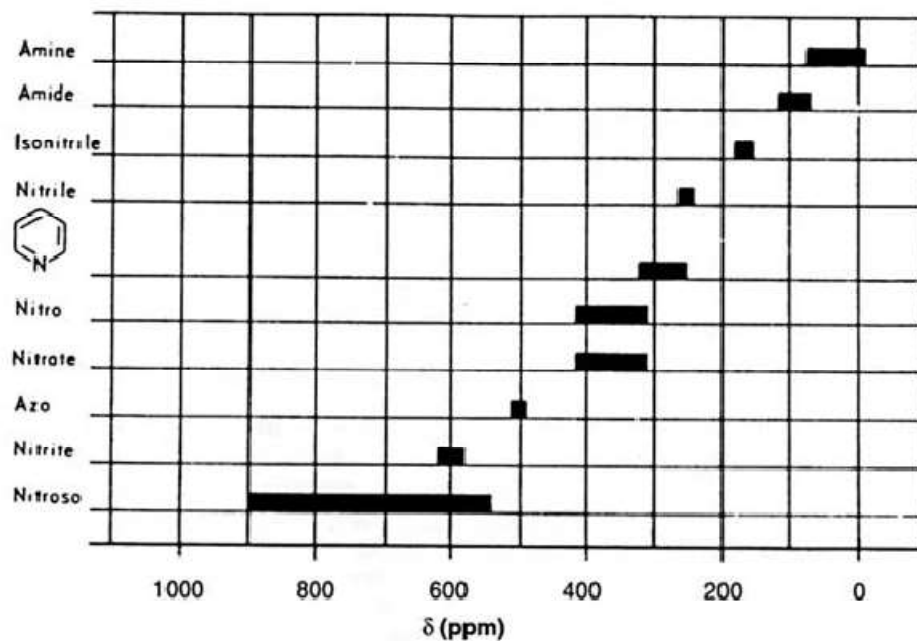


FIGURE 4.4 Approximate chemical shift ranges for ^{14}N and ^{15}N in various functional groups. Reference: Liquid NH_3 (external).

