B18OA1 ^{1}H NMR Spectroscopy

Characteristic ^{1}H NMR chemical shifts

A ^{1}H NMR (say "proton NMR" or "one H NMR") spectrum provides 4 key bits of information:

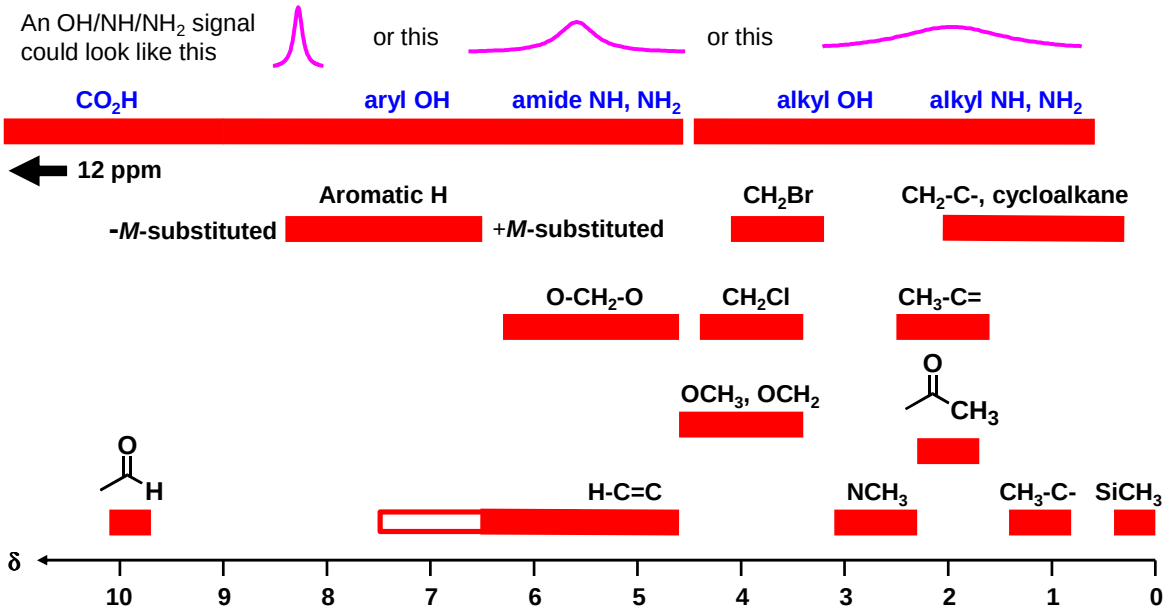
i) **Chemical shift** — tells you about adjacent atoms (Cl, O, N) or environments (C=C, C=O, aromatic ring),

ii) **Integration** — tells you the relative number of protons that share the same environment,

iii) **Multiplicity** — tells you about the number of adjacent protons, and

iv) **Coupling constant** — tells you about the angle and distance between coupling protons.

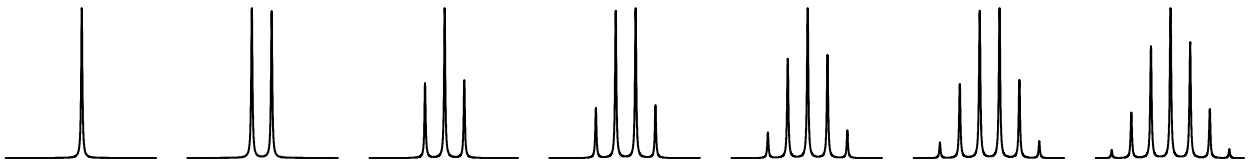
Chemical shifts are measured in δ or ppm (which mean basically the same thing).



Characteristic multiplicities and signal shapes

To a first approximation, protons just couple to protons on the next C. If there are *n* protons on neighbouring carbon(s), coupling splits the signal into *n* + 1 lines. The splitting of a signal is called *multiplicity*. The simplest multiplicities are **singlets** (*n* = 0, that is no protons nearby), **doublets** (*n* = 1 or just 1 proton nearby), **triplets** (*n* = 2), **quartets** (*n* = 3), **quintets** (*n* = 4), **sextets** (*n* = 5) and **septets** (*n* = 6). The theoretical intensity of the individual lines can be derived from Pascal's triangle.

***n* = 0**	**1**
***n* = 1**	**1 1**
***n* = 2**	**1 2 1**
***n* = 3**	**1 3 3 1**
***n* = 4**	**1 4 6 4 1**
***n* = 5**	**1 5 10 10 5 1**
***n* = 6**	**1 6 15 20 15 6 1**



Singlet (s) Doublet (d) Triplet (t) Quartet (q) Quintet (qui) Sextet Septet

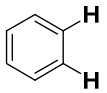
Note that you will see the symmetrical distribution of intensities predicted by Pascal's triangle *only when* the signals coupling to each other *all share the same coupling constant*. Pascal's triangle will no longer be valid when couplings are different, spin systems move closer together and become higher order, or a molecule has a (pro)chiral centre.

When a proton signal shows no recognisable symmetry or multiplicity pattern at all, we refer to it as a **multiplet**.

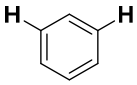
Coupling constants (***J***) are measured in **Hz**. A typical coupling constant between alkyl protons on adjacent carbons is about 6 – 8 Hz. The magnitude of the spin-spin coupling between protons in general decreases as the number of bonds between the coupled nuclei increases. Protons that are more than 3 bonds apart

tend to show very small or no coupling at all. An exception arises when the protons are rigidly fixed in a W or zig-zag arrangement. These so-called long-range couplings are seen in aromatic and rigid non-aromatic rings, as well as (conjugated) alkene systems.

Some typical coupling constants: H_3C-CH_2R $^3J_{vicinal}$ 6 - 8 Hz



$^3J_{ortho}$ 8 Hz



$^4J_{meta}$ 1.5 Hz

$^3J_{trans}$ 12 - 18 Hz

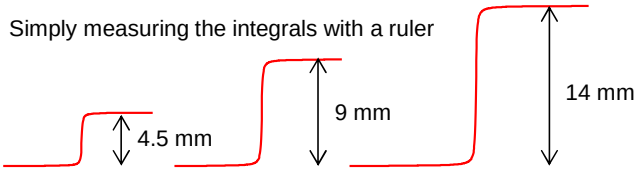
$^3J_{cis}$ 7 - 12 Hz

$^2J_{geminal}$ 1 - 3 Hz

Doublets, triplets, quartets etc. are the simplest multiplicities. However, protons frequently couple to more than one type of signal groups, with different coupling constants. Such successive splitting will lead to more complex multiplicities, for example, doublets of doublets, doublets of triplets or triplets of quartets, to name just a few possibilities.

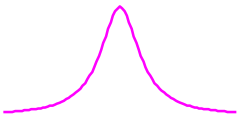
Integration: ^{1}H NMR spectra are routinely integrated. The integral of a signal is proportional to the number of protons contributing to it. Units are irrelevant: use the electronic integral, or simply measure the integral height in mm, then calculate the number of protons 1H, 2H, 3H … Integrals have to be taken with a pinch of salt and can be off by 10%, or more in case of exchangeable OH/NH signals. It is important that the sum total of your integrals equals the number of hydrogens in your compound.

Simply measuring the integrals with a ruler



gives an integral ratio of 1H : 2H : 3H (or 2H : 4H : 6H ...)

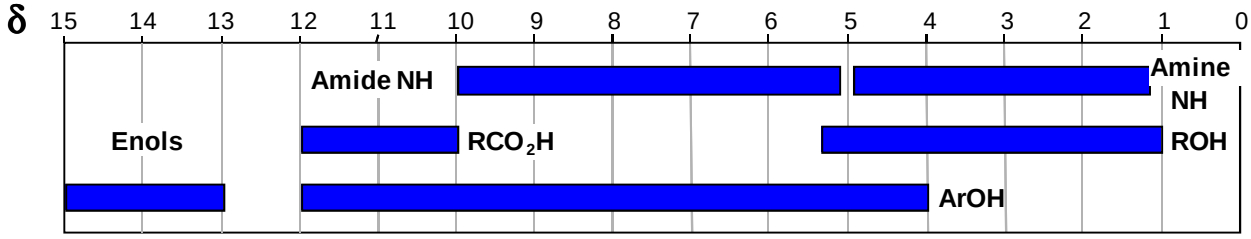
OH and NH signals



A **broad** singlet (br s)

Signals of OH and NH groups usually don't show any coupling to other protons at all. In the ^{1}H NMR spectrum you will recognise them as **broad singlets**.

The OH chemical shift can vary over a wide range depending on whether you are dealing with an aliphatic alcohol, a phenol, a carboxylic acid or an enol. Similar variations are seen for the NH chemical shift of aliphatic amines, aromatic amines and amides. Their signals are usually somewhat broadened, as well as influenced by sample concentration, water content and the choice of solvent.



An OH or NH signal is D_2O exchangeable, and this provides one of the best ways of identification. So, if you add a drop of D_2O to a solution of your sample in $CDCl_3$ and shake it, the signals of exchangeable OH and NH protons will no longer be seen when you record the ^{1}H NMR spectrum again because they are converted into OD or ND groups.

$$R\text{-}OH + D_2O \longrightarrow R\text{-}OD + HDO$$

Some pecularities of OH and NH signals:

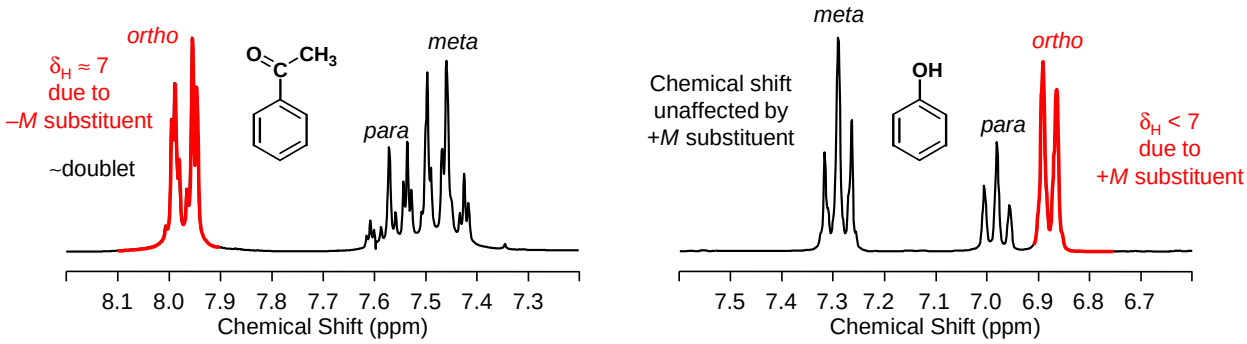
- OH and NH signals are often broad.
- Their chemical shifts depend on solvent, concentration, temperature, water content.
- Their integration often appears too small.
- Exchange with *e.g.* water (H_2O) wipes out all coupling.
- OH and NH signals vanish upon exchange with D_2O; this test detects OH and NH signals.

Signal shapes of some common aromatic coupling systems

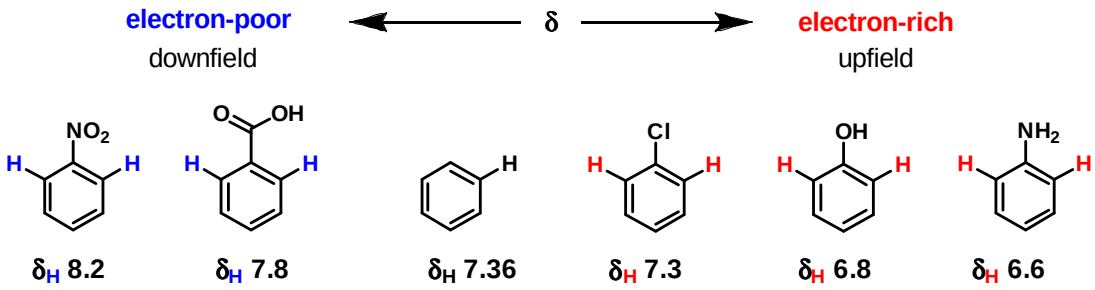
The coupling system of a monosubstituted benzene is non-first-order, that is, it is best described as multiplet. However, benzene itself and benzenes with identical substituents in 1,4- or 1,3,5-position will show true singlets because of their molecular symmetry.

Unsplit spectra (showing approximate ~singlets) are sometimes produced by monosubstituted benzene derivatives if the substituent has no strong electron-withdrawing or electron-donating effect (*e.g.* toluene).

A single substituent that is either electron-withdrawing (for example, a nitro or carbonyl group) or electron-donating (e.g. OCH_3, OH and NH_2), usually causes the *ortho* protons to move to higher or lower δ values with respect to the *meta* or *para* protons. We then observe a 2-proton complex multiplet that is separated from a 3-proton complex multiplet. Note that the *ortho* proton signal resembles roughly a doublet (after all, it couples to only one H on the nearest neighbouring carbon) — unlike *meta* and *para* signals which are both ~triplets. The smaller splittings, which are almost always seen, are due to long-range (*meta*) couplings and/or higher order effects.

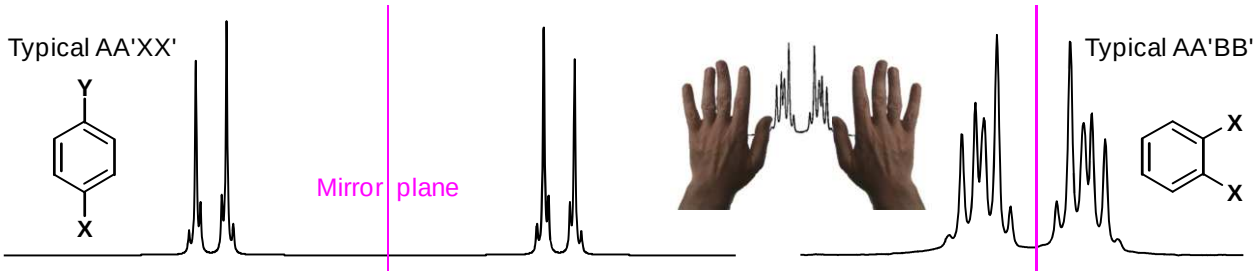


^{1}H NMR chemical shifts are quite sensitive towards the electronic environment. While the aromatic protons of an alkyl-substituted benzene will have almost the same chemical shift as benzene itself (δ_H 7.36 in $CDCl_3$), this changes if there is a strongly electron-donating or electron-withdrawing substituent on the benzene ring.



The *ortho* protons (and less so the *para* protons) will be affected the most, and move upfield (= to lower ppm values) in the case of an electron-donating substituent or downfield (= to higher ppm values) if they are next to an electron-withdrawing substituent. This can provide useful information on the type of substituent, as well as help with the assignment of proton signals in substituted benzenes.

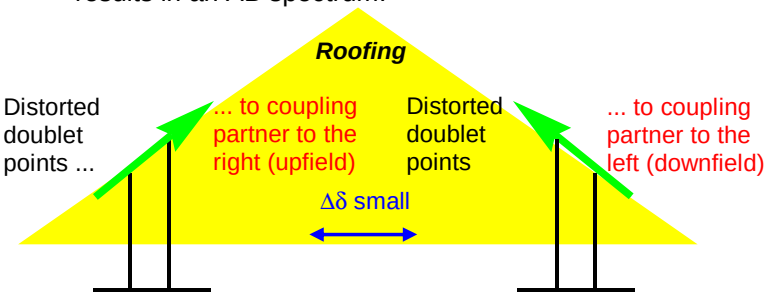
An unsymmetrical *para*-disubstitution leads to a symmetrical pair of signals which look almost like a pair of doublets. There are, however, a number of tiny extra lines within each “doublet” which you see if you take a closer look at an expansion. Although you will be allowed to call it a “doublet” at this stage, strictly speaking, the multiplicity is a higher-order AA’XX’ (pronounced “A A dash X X dash”) or AA’BB’ system, the letters of the alphabet indicating whether the chemical shifts are far from each other or not.



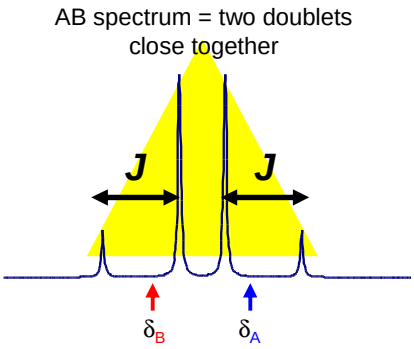
Similarly, identical *ortho* substituents also make the molecule symmetrical but the resulting multiplicity becomes more complex due to the three large *ortho* couplings. The ^{1}H NMR signal pattern shows a characteristic symmetry about the mid-point of the 12 – 24 line multiplet (it often looks very much like a pair of hands). The resulting multiplicity is a non-first-order AA’BB’ spin system, with even more complexity than seen in the case of *para*-disubstituted aromatic systems due to there being now three *ortho* couplings.

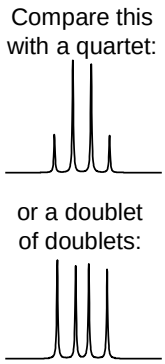
Roofing and AB spectra

When the difference in the chemical shift between two coupled groups of signals becomes smaller, the intensity distribution in the lines of the two groups of signals can differ considerably from the theoretical intensities predicted by Pascal's triangle. The intensity of the lines nearest to the signal of the neighbouring group becomes larger, while the intensity of the other lines turn out smaller. This is called **roofing**. In the extreme case where the difference in chemical shift in Hertz has about the size of the coupling constant, this results in an AB spectrum.



Tip: If a signal shows roofing, look for the coupling partner on the side where the lines are higher.

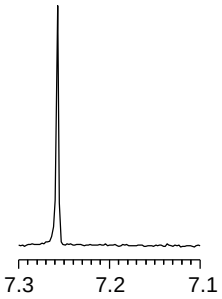
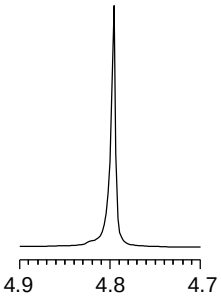
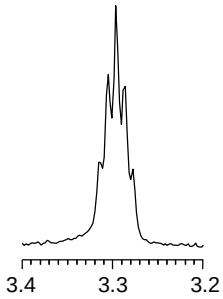
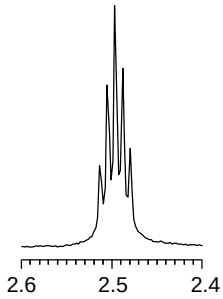




NB: These are TWO doublets and belong to TWO protons which both have *the same* coupling constant, whereas a "doublet of doublets" has *TWO coupling constants* because there are TWO coupling partners.

NMR solvents

Deuterated solvents give rise to residual signals in the ^{1}H NMR spectrum. You should familiarise yourself with the chemical shifts and multiplicities of the more common NMR solvents so that you don't mistake them for signals belonging to the sample. In addition, "extra signals" often come from traces of water (moisture) and acetone (from cleaning NMR tubes). By convention, solvent signals due to deuterated solvent are not quoted when NMR data are tabulated.

	$CDCl_3$ (Deuterochloroform)	D_2O (Deuterium oxide)	CD_3OD (Deuterated methanol)	$(CD_3)_2SO$ or d_6-DMSO (Deuterated DMSO)
Residual solvent δ_H	7.26	4.80	3.30	2.50
				
H_2O	1.56*	4.80	4.87	3.33
Acetone	2.17	2.22	2.15	2.09

* Exchange, particularly with acidic protons, can shift this signal downfield.

NB: Whereas the residual solvent signal in $CDCl_3$ is due to undeuterated chloroform ($CHCl_3$), the major impurity in d_6-DMSO is d_5-DMSO and coupling of the single proton in the CD_2H methyl group to the two deuteriums (with a nuclear spin of 1) gives $2n + 1 = 2 \times 2 + 1 = 5$ lines or a quintet in the ^{1}H NMR spectrum.

Real-life NMR spectra often show signals due to impurities, such as residual extraction or recrystallisation solvents. Here is a useful paper: H. E. Gottlieb, V. Kotlyar, A. Nudelman, "NMR Chemical Shifts of Common Laboratory Solvents as Trace Impurities", *J. Org. Chem*. **1997**, *62*, 7512 – 7515. Access it through VISION.

For more on NMR spectroscopy, see online video tutorials on Vision. Online videos