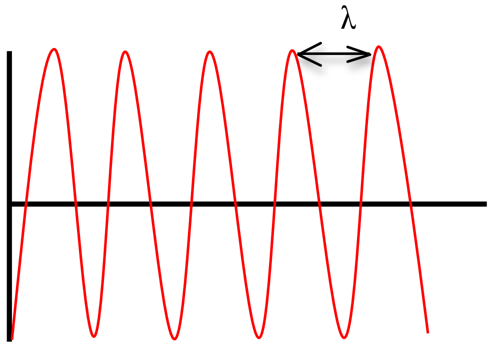
Chem 263 Sept. 6, 2016

Nuclear Magnetic Resonance (NMR) Spectroscopy

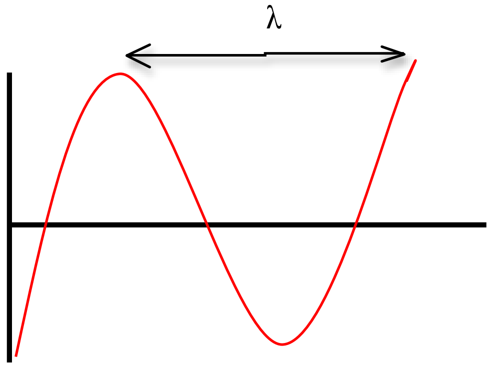
Light and Energy

$E = hv = hc / \lambda$

Where:
E = energy
v = frequency
c = speed of light = 3×10^{8} meter/second
h = Planck’s constant = 6.6×10^{-34} Joule•second
λ = wavelength

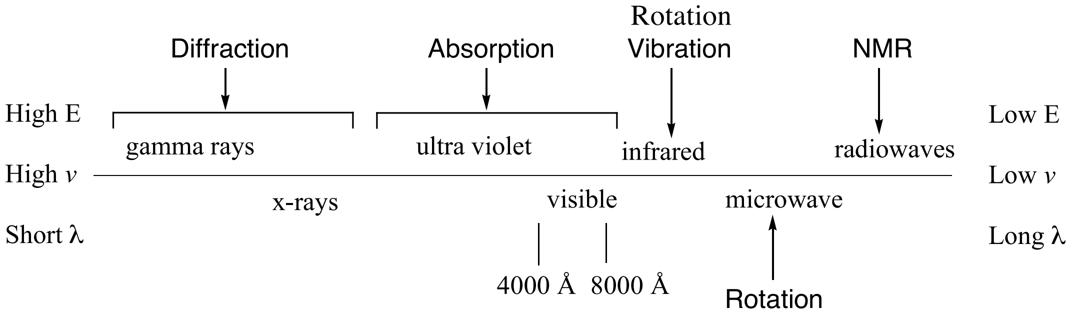


Short Wavelength, High Energy, High Frequency



Long Wavelength, Low Energy, Low Frequency

Electromagnetic Spectrum



Nuclear Magnetic Resonance (NMR)

If an atom has an odd number of protons and/or an odd number of neutrons, there is a nuclear magnetic moment (aka **nuclear spin**).

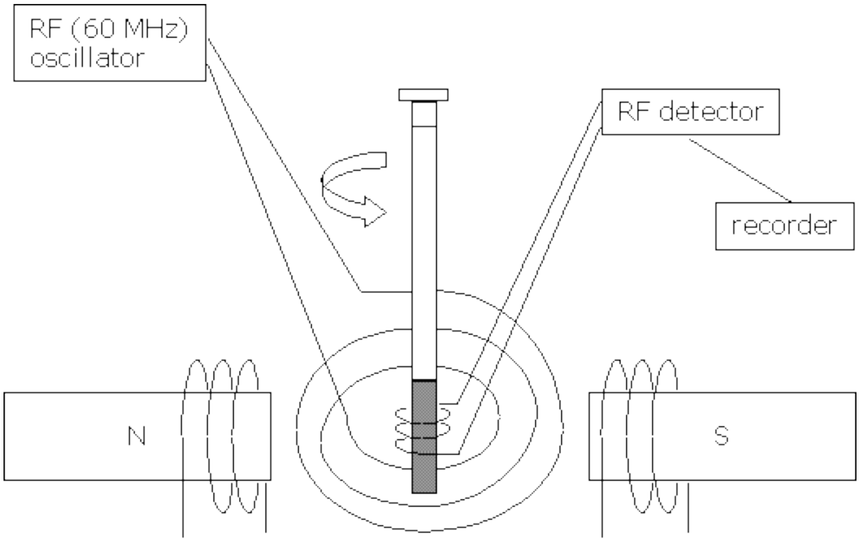
Examples:

- ^{1}H has atomic number 1 (therefore 1 proton), no neutrons, and nuclear spin ½; can be detected by NMR
- ^{2}H (deuterium) has atomic number 1, number of neutrons 1, and nuclear spin 1
- ^{3}H (tritium) has atomic number 1, number of neutrons 2, and nuclear spin ½
- ^{12}C has atomic number 6 (6 protons), number of neutrons 6, and no nuclear spin
- ^{13}C (only 1% of all carbon) has atomic number 6, number of neutrons 7, and a nuclear spin of ½ (and can be detected by NMR)
- ^{14}C has atomic number 6, number of neutrons 8, no nuclear spin, radioactive and used for "carbon dating"

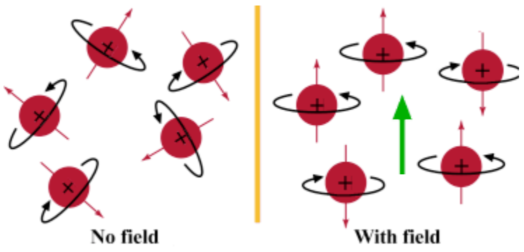
MRI (Magnetic Resonance Imaging): Based on the principles of NMR and developed by Paul Lauterbur

NMR Continued (focusing on ^{1}H NMR)

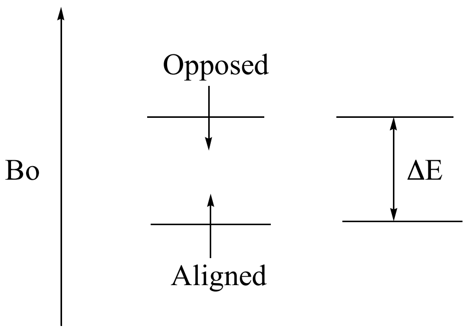
An NMR experiment requires a magnet (e.g.14 Tesla), and a radio frequency transmitter. A tube containing the sample is placed inside the magnet – Below is a crude drawing of the setup.
(http://www.chemistry.ccsu.edu/glagovich/teaching/316/nmr/instrumentation.html)



When no magnetic field is present, there is no net orientation to the nuclei.
If you apply a magnetic field (B_O) to an isolated ^{1}H nucleus, there are two possible energy states: one with the nuclear spin **aligned** with the field and the other with it **opposed**.



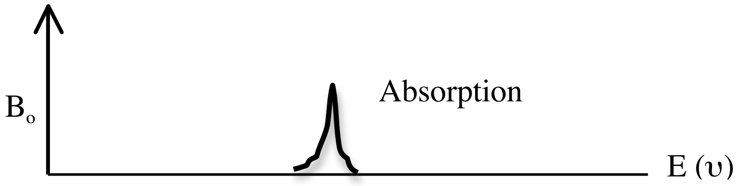
http://www.chem.ucalgary.ca/courses/351/Carey5th/Ch13/ch13-nmr-1.html



Arrow = spins

Note: $\Delta E = h\nu$ (ν is in the radio frequency range)
$= hc/\lambda$ (c is 3.0×10^8 m/s)

Absorption from the lower energy state to the higher one becomes possible, which allows a spectrum to be observed:

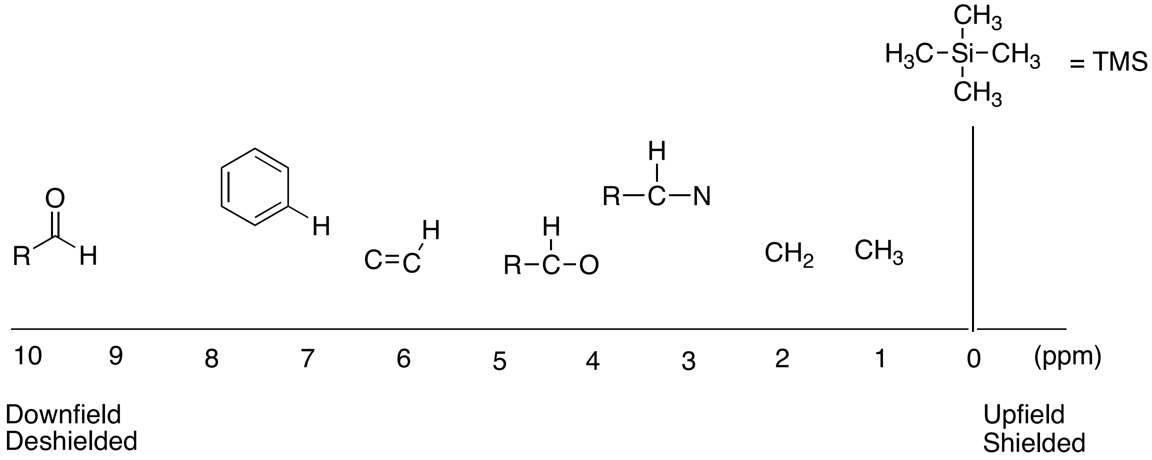


Chemical Shift

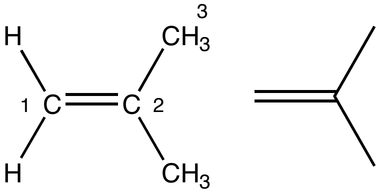
Chemical shift measures the change in the frequency of absorption. The chemical shift is typically shown in units of parts per million (ppm), and is compared to a reference. For ^{1}H NMR, this reference is usually tetramethylsilane (TMS).

The hydrogen atoms in TMS are highly shielded, and the signal for TMS is set at 0 ppm.

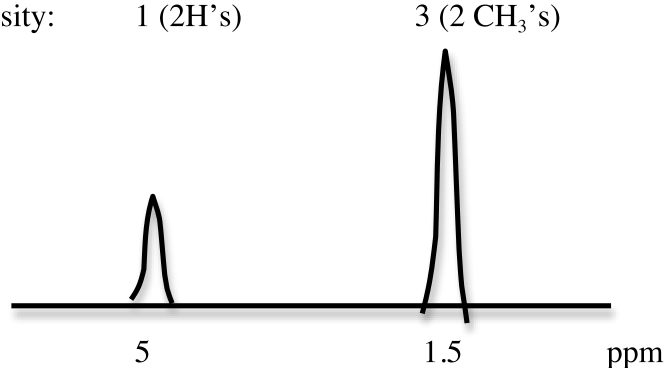
Deshielding occurs when electrons are pulled away from a hydrogen atom, which can be caused by the presence of an electron-withdrawing group (e.g. a carbonyl). When the electrons are pulled away, the nucleus is more exposed to the magnetic field, resulting in a **downfield** chemical shift.



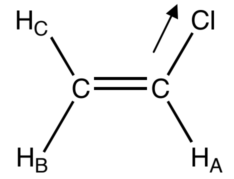
Examples:

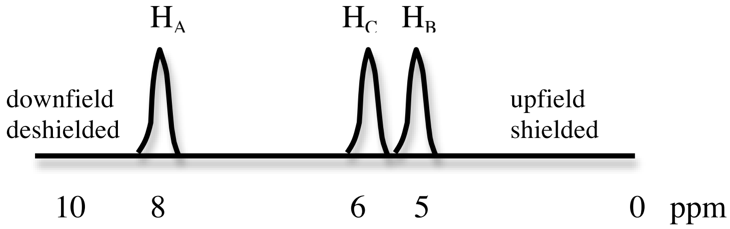


2-methyl-1-propene

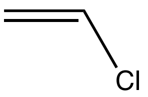


The intensity (area under the peak) depends on the number of hydrogen atoms, in this case 2:6 which is the same as 1:3



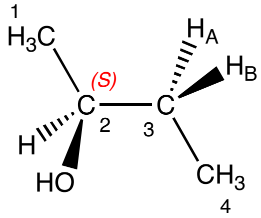


1-chloroethene
chloroethylene
vinyl chloride



H_A is deshielded by the electron-withdrawing Cl.
H_B and H_C are different due to the distance from the Cl.
H_B is trans to the Cl, while H_C is cis.
H_C is more deshielded than H_B because it is closer to Cl.

Diastereotopic Hydrogens



(S)-2-butanol
butan-2-ol

What kinds of H does it have?

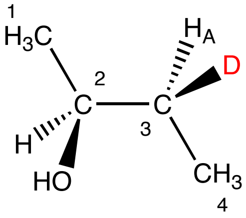
- O-H
- H at C_2
- CH_3 at C_1
- CH_3 at C_4
- H_A (Pro-R)
- H_B (Pro-S)

The methyl group shows only one signal because the C-C bond can freely rotate and NMR cannot distinguish between the Hs on that carbon. The barrier to bond rotation is only a few kilocalories per mole (1-3 kcal/mole) and about 15 to 20 kilocalories per mole of energy are available at room temperature. Hence rotation is very rapid and the methyl hydrogens are all in the same chemical environment.

C-2 is a stereogenic centre, and there is no plane of symmetry in the molecule. H_A and H_B are in different chemical environments and have different chemical shifts, therefore they are **diastereotopic.**

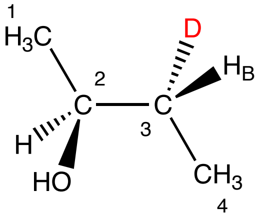
If you substitute H_A or H_B with deuterium (labeled as D (^{2}H; an isotope of hydrogen with one proton and one neutron)) you get diastereomers. These two hydrogens are called diastereotopic hydrogens.

Note: The chemical shifts of two diastereotopic protons may not always be very different.



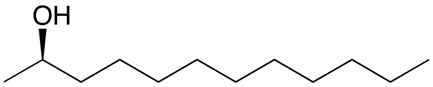
SS isomer

diastereomers



SR isomer

Example:

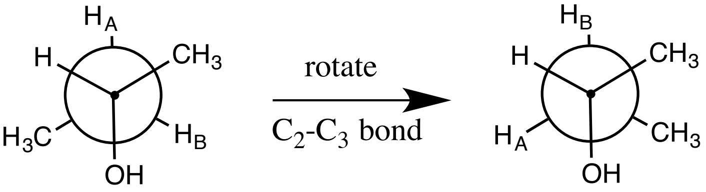


(R)-2-dodecanol

Every CH_2 group in this molecule has two diastereotopic protons.

Newman Projections

The round circle in the structure below is the back carbon (C-3 of 2-butanol) – carbon 2 is directly attached to it and is represented as the dot (point) where the bonds meet in front.



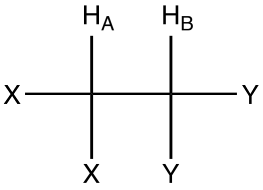
(H_B is pro S and H_A is pro R)

anti or staggered conformation gauche conformation

Pro R - precursor to an R stereogenic center
(If you substitute it with deuterium, you will form an R stereogenic center)
Pro S - precursor to an S stereogenic center

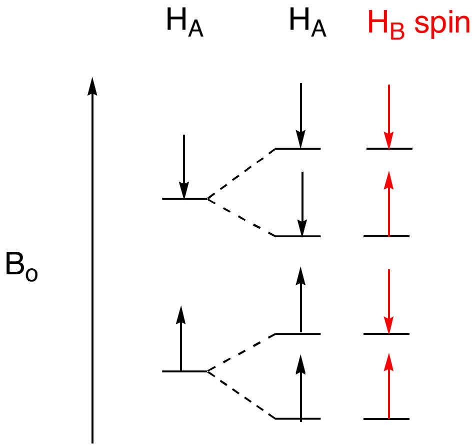
When there is a stereogenic center present, the two hydrogens, H_A and H_B, of the methylene (CH_2) group cannot be brought into the same chemical environment. Bond rotation can bring H_B to the position where H_A was before, as represented by the above Newman projections of the two conformations, but the CH_3 groups are occupying different positions and therefore the two methylene H's are not in the same chemical environment.

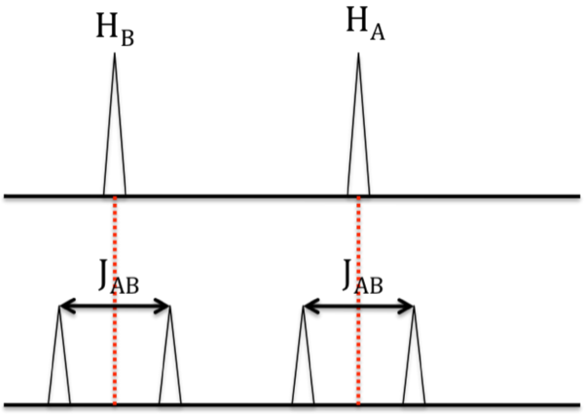
Spin-Spin Splitting (Coupling)



$X \neq Y$

H_A is not a singlet due to the influence of H_B on its spin, and vice versa. This diagram below shows the energy for H_A, and the spins for H_B are shown (in red) only to show the effect on H_A





J_{AB} = **Coupling constant** between atoms A and B, measured in Hertz (Hz)

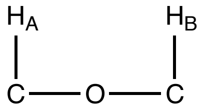
The H_A coupling constant corresponds to the energy differences caused by the H_B proton in alignment with and in opposition to the field. This energy difference is equal to the effect that the H_A proton has on H_B, so both of these coupling constants are equal.

The coupled signal is centered around the same chemical shift value that the signal would have if there were no coupling.

Limitations of Coupling

1. 2 to 3 bonds separating nuclei (coupling is typically not seen between nuclei that are further apart than 3 bonds)
2. Usually no coupling across O, N, S, C=O

Example: In the following structure, H_A and H_B would not couple due to being 4 bonds apart (too far) and oxygen is in between



$$\overset{H_A}{\overset{|}{C}}-O-\overset{H_B}{\overset{|}{C}}$$

Note: There are exceptions to these rules