Nuclear Magnetic Resonance (NMR) Spectroscopy

The NMR spectrometer consists of two main parts: a magnet and a radio transmitter. (An MRI is just an NMR that can take images. The letter "N" was dropped from NMRI because the public falsely equates "nuclear" with "radioactive".)

NMR is the most powerful analytical tool currently available to an organic chemist and is one of the two main instruments to determine the structure of proteins.

NMR allows characterization of a very small amount of sample (10mg), and does not destroy the sample (non-destructive technique).

NMR spectra can provide vast information about a molecule's structure and can very often be the only way to prove what the compound *really* is.

Typically though, NMR is used in conjunction with other types of spectroscopy and chemical analysis to fully confirm a complicated molecule's structure.

NMR Theory
Any nucleus that has either an odd atomic number or an odd mass number has a nuclear spin that can be observed by an NMR spectrometer.

The proton is the simplest odd numbered atomic nucleus (and also the most useful for organic characterization).

NMR theory is reasonably simple.
(1) When a charged particle spins like a top, it sets up its own magnetic field. That is, it becomes a magnet with N and S poles. The spin of the proton of the H nucleus makes it have a magnetic field.

spinning proton

loop of current
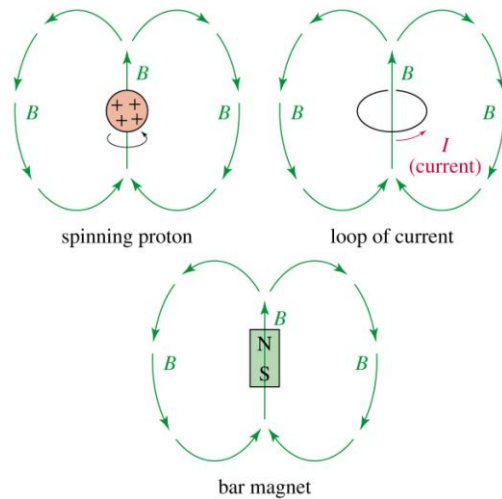
bar magnet

(2) When you put the H nucleus inside of another magnet, the N/S poles of the nucleus will align either with or against the N/S poles of the external magnet. (B_0 is the strength of the field of the external magnet.)

lower energy
more stable
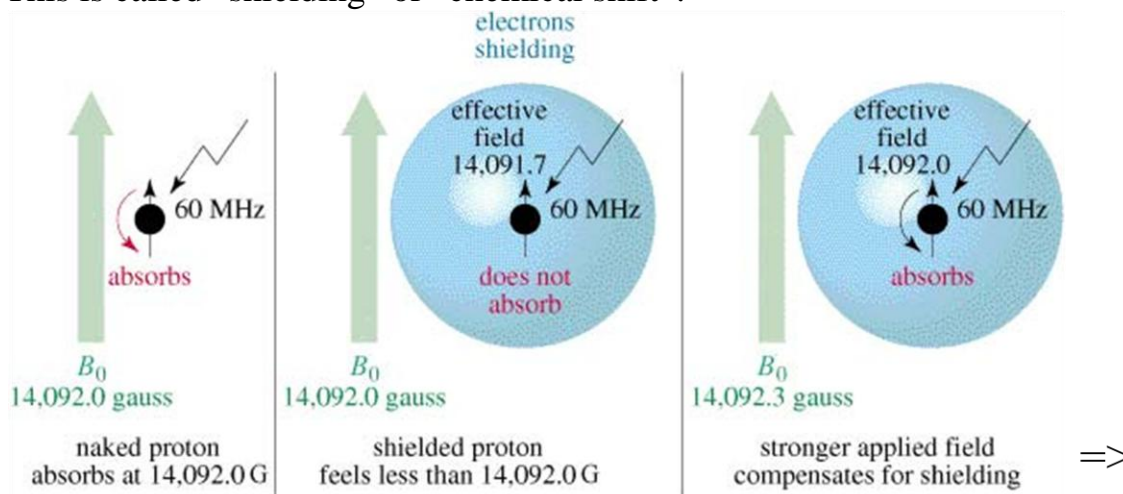
higher energy
less stable
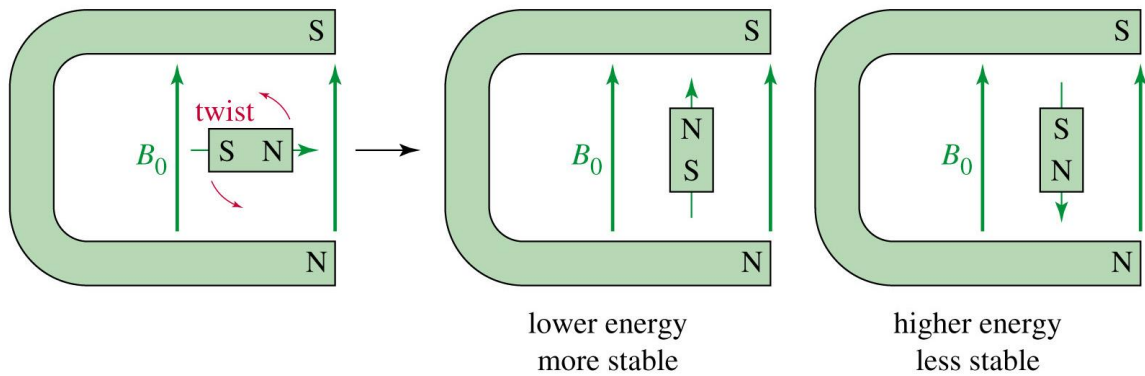
(3) Quantum Mechanics says that there will only be two states for the proton, spin up (aligned with the external field) or spin down (against the external field). The difference in energy levels between the two states depends on how strong the field (B_0) of the external magnet is. The greater is the B_0, the greater is ΔE.

β state

$hv = \Delta E$

B_0
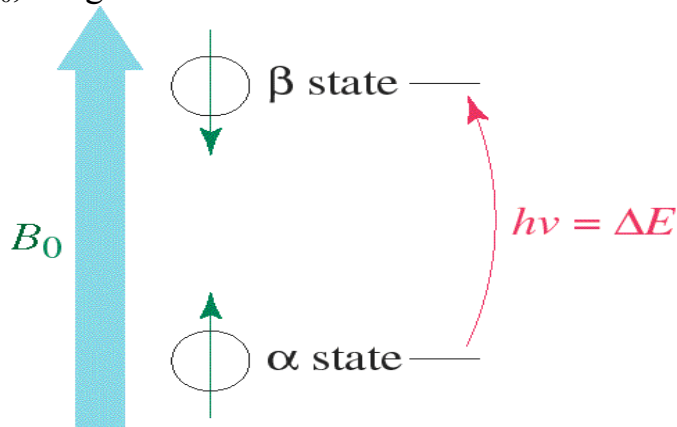
α state

(4) When radio waves with just the right frequency ν are absorbed by the proton, the proton "flips" its spin to the higher energy state.
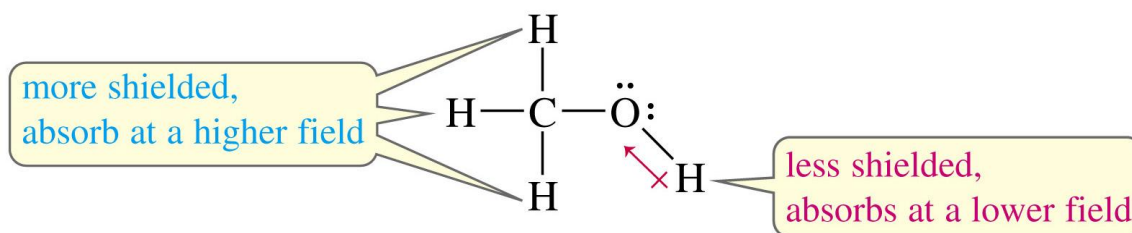
(5) Electrons also have spin and their own magnetic field B_e. The magnetic field of the electrons in a molecule must be added to that of the magnet to get the total external magnetic field. Effects such as electronegativity decrease or increase the electron density around an H atom in a molecule. This is called "shielding" or "chemical shift".

B_0 14,092.0 gauss	B_0 14,092.0 gauss	B_0 14,092.3 gauss
naked proton absorbs at 14,092.0 G	shielded proton feels less than 14,092.0 G	stronger applied field compensates for shielding

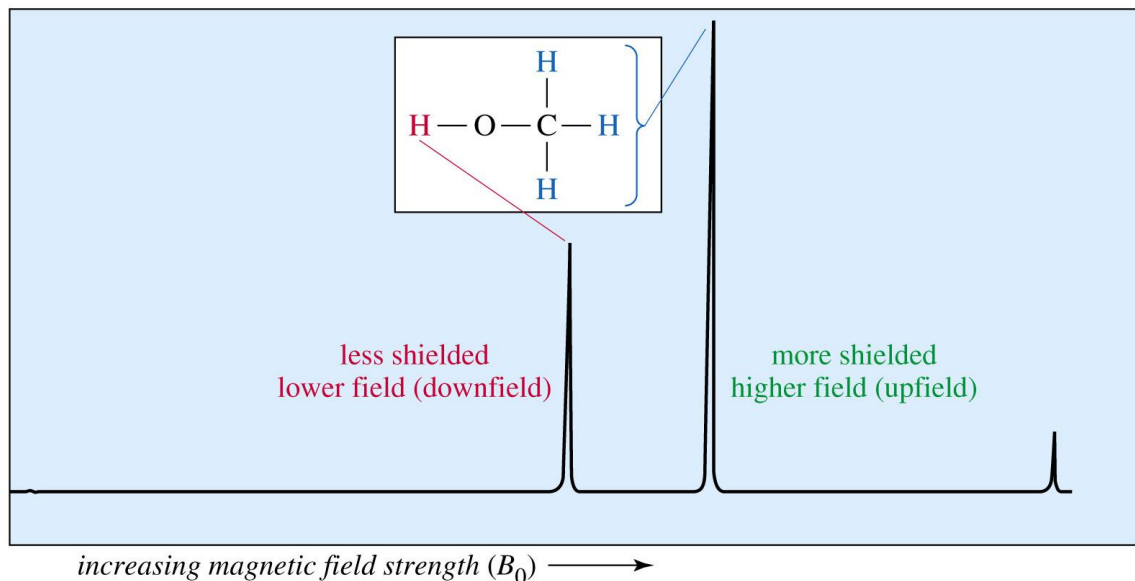The use of NMR can thus elucidate structures.

NMR spectroscopy important facts:
(1)   The number of different absorptions implies how many different types of hydrogens are present.
(2)   The amount of shielding (chemical shift) is determined by each hydrogen's environment, and so we get information about the local electronic surroundings for each hydrogen.
(3)   The intensities of the signals tell us the number of identical hydrogens.
(4)   The splittings of each signal tells us about the other groups proximate to the hydrogens in question.

more shielded, absorb at a higher field

less shielded, absorbs at a lower field

less shielded
lower field (downfield)

more shielded
higher field (upfield)
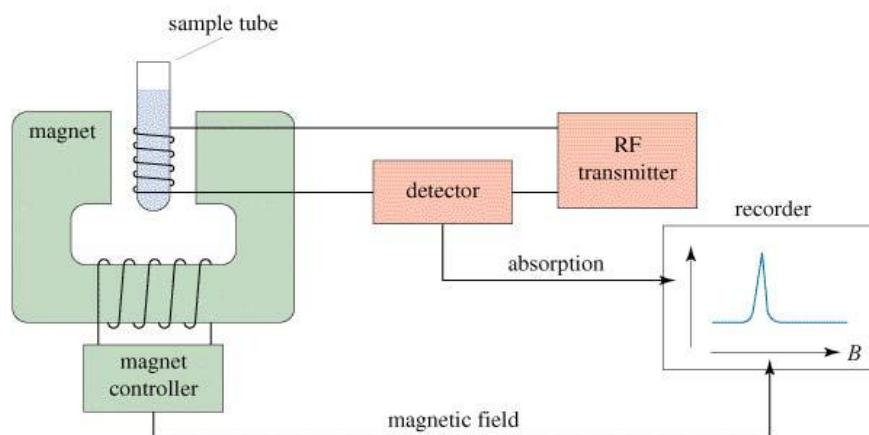
increasing magnetic field strength (B_0) ⟶

A Simple NMR Machine

An NMR machine consists of:

(1)　A powerful, supercooled magnet (stable, with sensitive control, producing a precise magnetic field).

(2)　A radio-frequency transmitter (emitting a very precise frequency).

(3)　A detector to measure the absorption of radiofrequency by the sample.

(4)　A recorder (to plot the output).

A simple NMR spectrum plots absorption on the y axis, and magnetic field strength on the x axis (Scale is in parts per million, and usually goes from 0-10 ppm).

The different positions of NMR absorptions are described as **chemical shifts** (δ).

A chemical shift is defined as <u>the difference in parts per million (ppm) between the resonance frequency of the observed proton and that of the tetramethylsilane (TMS) hydrogens</u>.
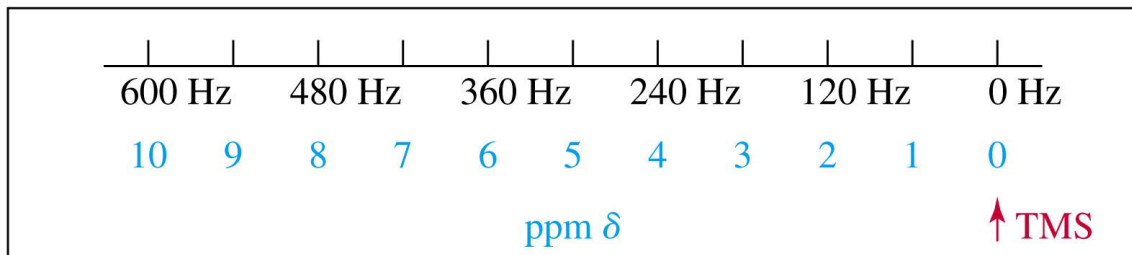
$$\text{H}_3\text{C}-\underset{\underset{\displaystyle \text{CH}_3}{|}}{\overset{\overset{\displaystyle \text{CH}_3}{|}}{\text{Si}}}-\text{CH}_3$$
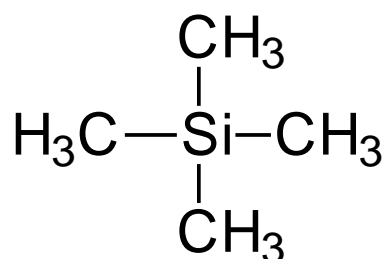
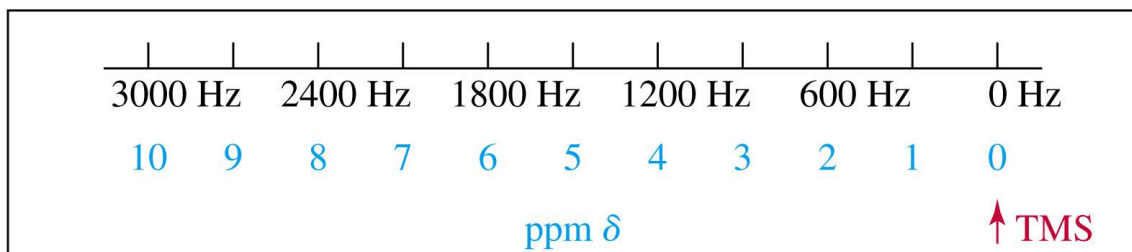TMS is the most common reference compound in NMR, it is set at δ=0ppm.

The chemical shift in ppm is calculated as the shift downfield from TMS in Hz, divided by the spectrometer operating frequency in MHz.

So if a 60MHz spectrometer records a proton resonance at a frequency of 426Hz downfield from TMS, this corresponds to a chemical shift of 426/60 = 7.10ppm.

chemical shift, ppm $\delta = \dfrac{\text{shift downfield from TMS (in Hz)}}{\text{spectrometer frequency (in MHz)}}$

| 600 Hz | 480 Hz | 360 Hz | 240 Hz | 120 Hz | 0 Hz |

10   9   8   7   6   5   4   3   2   1   0

ppm δ ↑ TMS

60 MHz

| 3000 Hz | 2400 Hz | 1800 Hz | 1200 Hz | 600 Hz | 0 Hz |

10   9   8   7   6   5   4   3   2   1   0

ppm δ ↑ TMS

300 MHz

	Chemical	
Compound	Shift	Difference

TABLE 13-2 Chemical Shifts of the Chloromethanes

H—C(H)(H)—H δ0.2

H—C(H)(H)—Cl δ3.0   2.8 ppm

H—C(H)(Cl)—Cl δ5.3   2.3 ppm

H—C(Cl)(Cl)—Cl δ7.2   1.9 ppm

Note: Each chlorine atom added changes the chemical shift of the remaining methyl protons by about 2 to 3 ppm. These changes are nearly additive.

The NMR spectrum of methanol shows only two resonances (and the reference TMS peak at 0ppm).
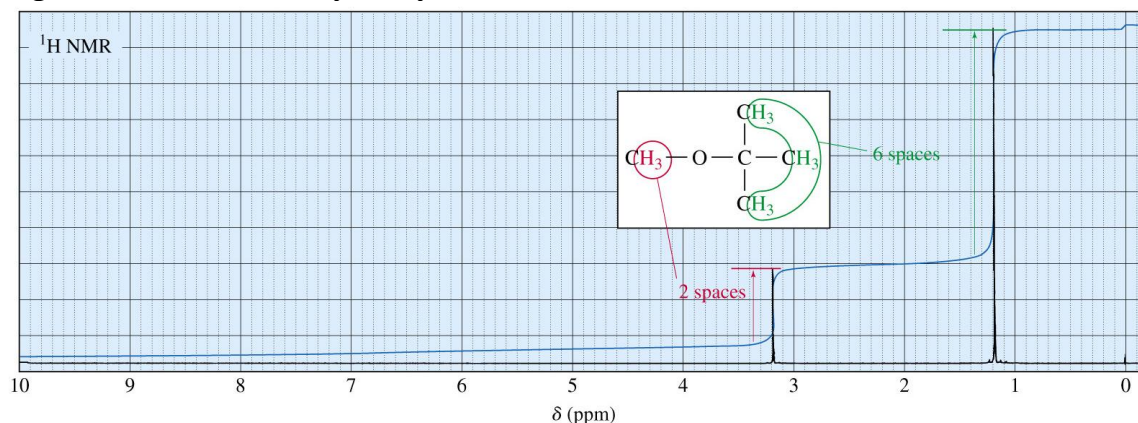
The hydrogens in the CH_3 group are all the same $\rightarrow$ 1 resonance
The OH proton gives a signal at different δ.

We can say that there are two **chemically different** hydrogens in methanol.

Different hydrogens absorb at **different** chemical shifts –

The number of signals tells us the number of chemically equivalent hydrogens in a molecule.

E.g. the NMR of methyl^{t}butylether

There are two types of chemically equivalent hydrogens $\rightarrow$ 2 separate resonances in the NMR spectrum.

Areas under the Peaks
NMR machines are equipped with **integrators**, which can calculate the area under each peak in the NMR spectrum.

This is very useful since the area under a peak is <u>equivalent to the number of identical hydrogens that contribute to that signal</u>.

Remember that this only gives the RATIO of the number of hydrogen, so a ratio of 1 : 2 : 3 is the same as a ratio of 2 : 4 : 6 and 0.5 : 1 : 1.5

This is where 'simple' NMR ends…