

# Lecture 23

## Nuclear Magnetic Resonance Spectroscopy

# Nuclear Magnetic Resonance spectroscopy

- Over the past fifty years nuclear magnetic resonance spectroscopy, commonly referred to as **NMR**, is used for determining the structure of organic compounds.
- Although larger amounts of sample are needed than for mass spectroscopy, **NMR is non-destructive to the substance, and with modern instruments good data may be obtained from samples weighing less than a milligram, liquid or gas. Pure substances in solution or gas are analyzed.**
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- It is based on the effect of interaction of magnetic field with nuclear spin. Absorption spectroscopy measures transitions between energy levels that appear due to interaction of nuclear spin with magnetic field. An NMR spectrum is a plot of the radio frequencies that causes absorption.

# Nuclear spin

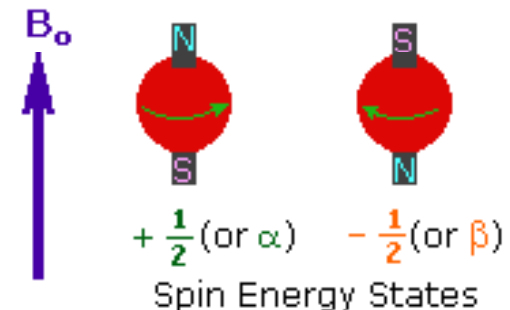
- The nuclei of many elemental isotopes have a characteristic spin ( $I$ ).
- Some nuclei have integral spins (e.g.  $I = 1, 2, 3 \dots$ ),
- some have fractional spins (e.g.  $I = 1/2, 3/2, 5/2 \dots$ ),
- and a few have no spin,  $I = 0$  (e.g.  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{32}\text{S}$ ,  $\dots$ ).
- Only Isotopes with fractional nuclear spin can be used for NMR, (e.g.  $I = 1/2, 3/2, 5/2 \dots$ ),
- isotopes of particular interest are  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{19}\text{F}$  and  $^{31}\text{P}$ , all of which have  $I = 1/2$ .

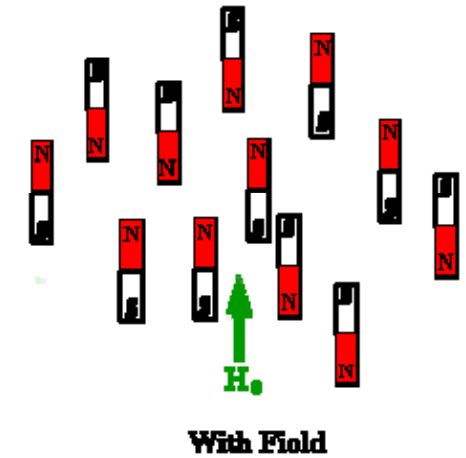
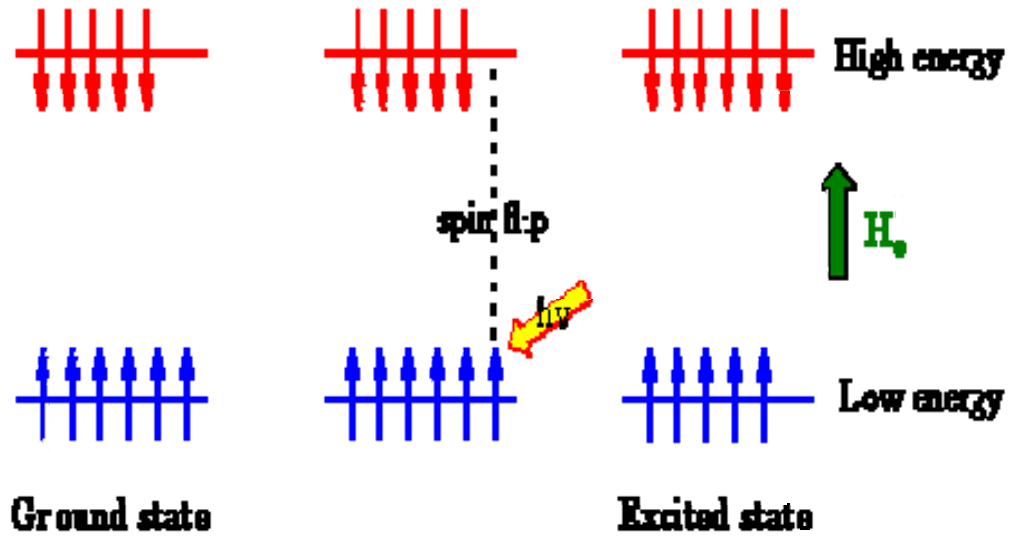
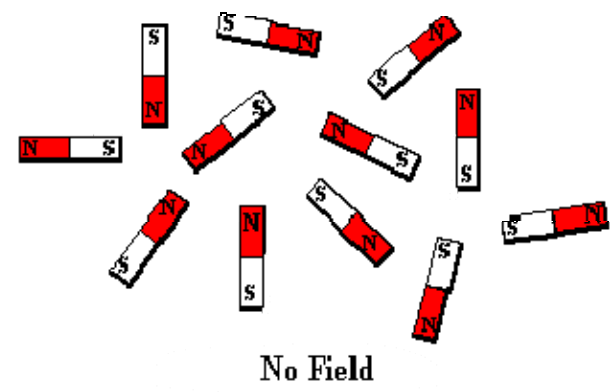
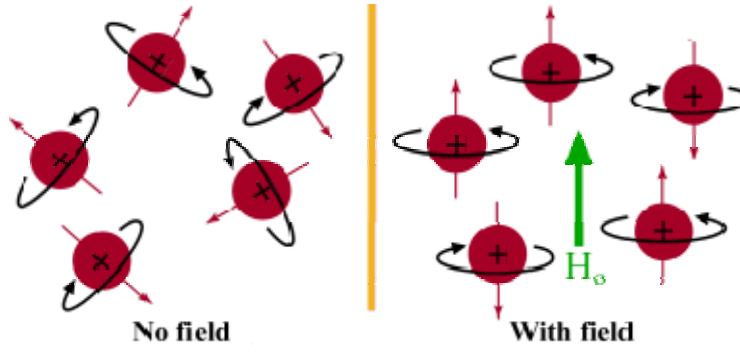
# Nuclear spin in magnetic field

- 1. A spinning charge generates a magnetic field.  
The resulting spin-magnet has a magnetic moment ( $\mu$ ) proportional to the spin:  $\mu = \gamma \hbar x I$   
 $\gamma$ - nuclear gyro-magnetic ratio

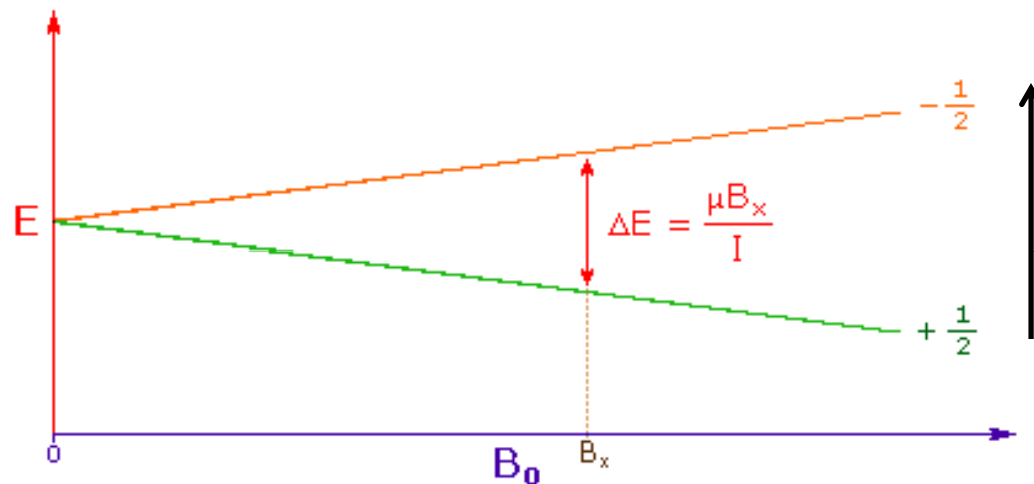


- 2. In the presence of an external magnetic field ( $B_0$ ), two spin states exist, **+1/2** and **-1/2**.  
The magnetic moment of the lower energy +1/2 state is aligned with the external field, but that of the higher energy -1/2 spin state is opposed to the external field. Note that the arrow representing the external field points North





# Energy level splits in magnetic field



If we apply electromagnetic radiation with frequency  $\nu$  of the right energy, transition will occur (spin flip) and energy is absorbed

$$\nu = \gamma B,$$

$\gamma$ - nuclear gyro-magnetic ratio  
 $B$ - magnetic field

- **3.** The difference in energy between the two spin states is dependent on the external magnetic field strength, and is always very small. The following diagram illustrates that the two spin states have the same energy when the external field is zero, but diverge as the field increases. At a field equal to  $B_x$  a formula for the energy difference is given (remember  $I = 1/2$  and  $\mu$  is the magnetic moment of the nucleus in the field).

# Different atoms have different energy differences/frequencies

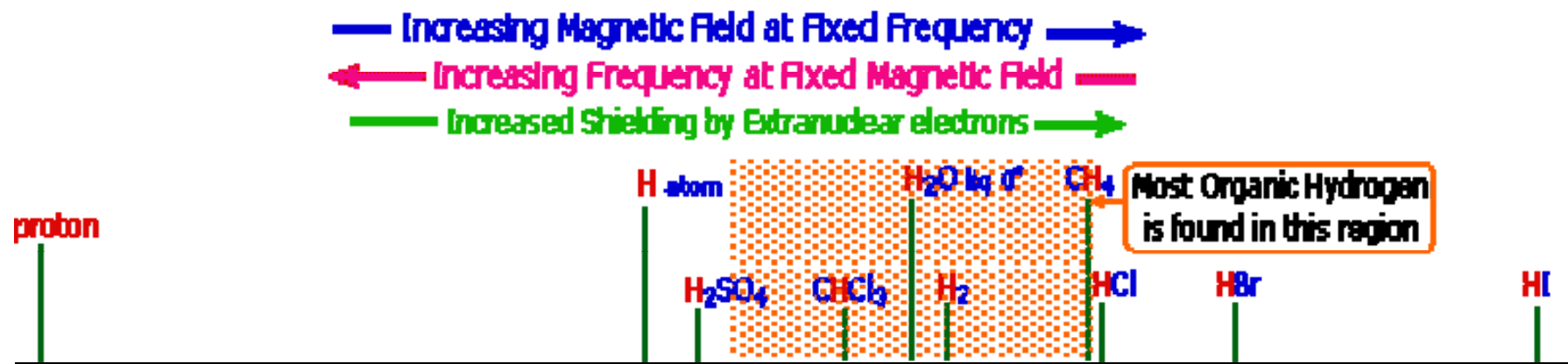
$B_0 = 2.35 \text{ T}$

$$\nu = \frac{\mu B_0}{hI} = \frac{4.68\mu}{h}$$



- **4.** For spin 1/2 nuclei the energy difference between the two spin states at a given magnetic field strength will be proportional to their magnetic moments. For the four common nuclei noted above, the magnetic moments are:  $^1\text{H} \mu = 2.7927$ ,  $^{19}\text{F} \mu = 2.6273$ ,  $^{31}\text{P} \mu = 1.1305$  &  $^{13}\text{C} \mu = 0.7022$ .
- These moments are in nuclear magnetons, which are  $5.05078 \cdot 10^{-27} \text{ JT}^{-1}$ . The following diagram gives the approximate frequencies that correspond to the spin state energy separations for each of these nuclei in an external magnetic field of 2.35 T.
- The formula in the colored box shows the direct correlation of frequency (energy difference) with magnetic moment ( $h$  = Planck's constant =  $6.626069 \cdot 10^{-34} \text{ Js}$ ).

# NMR spectrum of different protons



- Since protons all have the same magnetic moment, we might expect all hydrogen atoms to give resonance signals at the same field / frequency values. Fortunately for chemistry applications, this is not true.
- from independent measurement and calculation it has been determined that a naked proton would resonate at a lower field strength than the nuclei of covalently bonded hydrogens. With the exception of water, chloroform and sulfuric acid, which are examined as liquids, all the other compounds are measured as gases.



# Chemical shift

- An NMR spectrum is a plot of the **radio frequency applied** against **absorption**.
- A signal in the spectrum is referred to as a **resonance**.
- The frequency of a signal is known as its **chemical shift**.

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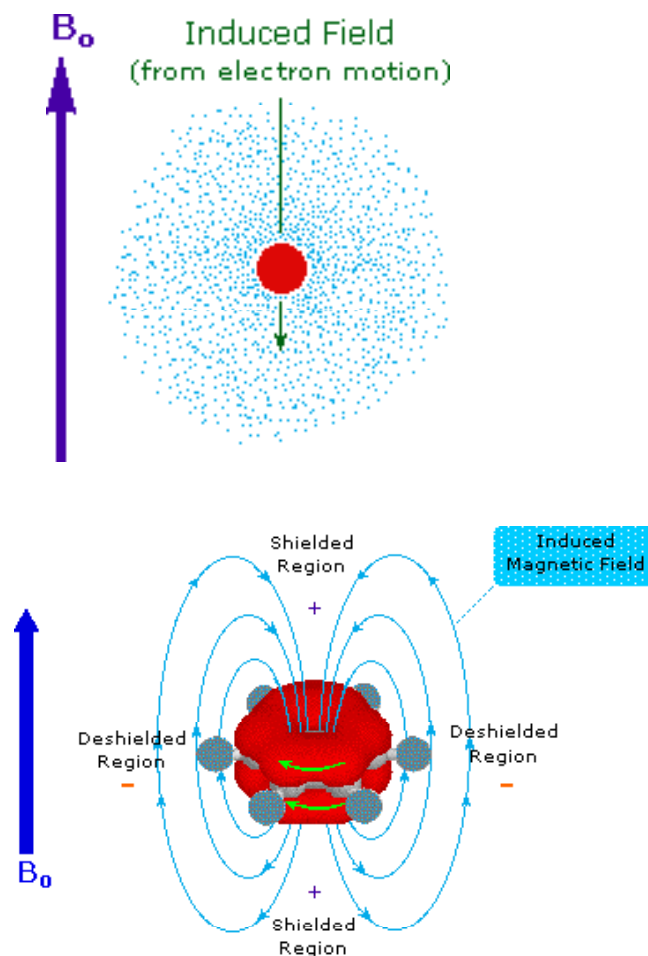
$$\text{Chemical shift, } \delta = \frac{\text{frequency of signal} - \text{frequency of reference}}{\text{spectrometer frequency}} \times 10^6$$

- The chemical shift in absolute terms is defined by the frequency of the resonance expressed with reference to a standard compound which is defined to be at 0 ppm. The scale is made more manageable by expressing it in parts per million (**ppm**) and is **independent** of the spectrometer frequency.
- **Tetramethylsilane**, (CH<sub>3</sub>)<sub>4</sub>Si, usually referred to as **TMS**, is used as the reference compound of choice for proton and carbon nmr.

## Why should the proton nuclei in different compounds behave differently in the NMR experiment ?

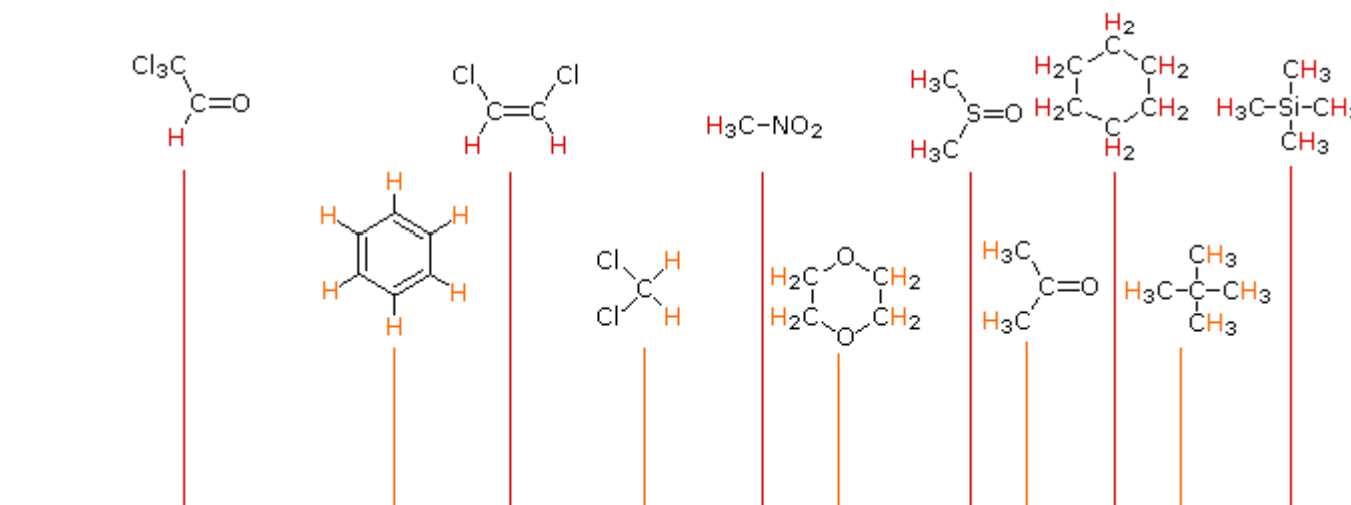
The answer to this question lies with the electron(s) surrounding the proton in covalent compounds and ions. Since electrons are charged particles, they move in response to the external magnetic field ( $B_0$ ) so as to generate a secondary field that opposes the much stronger applied field.

- This secondary field **shields** the nucleus from the applied field, so  $B_0$  must be increased in order to achieve resonance (absorption of rf energy). As illustrated in the drawing on the right,  $B_0$  must be increased to compensate for the induced shielding field. In the previous diagram, those compounds that give resonance signals at the higher field side of the diagram ( $\text{CH}_4$ ,  $\text{HCl}$ ,  $\text{HBr}$  and  $\text{HI}$ ) have proton nuclei that are more shielded than those on the lower field (left) side of the diagram.
- $\pi$  electrons induce shielding too

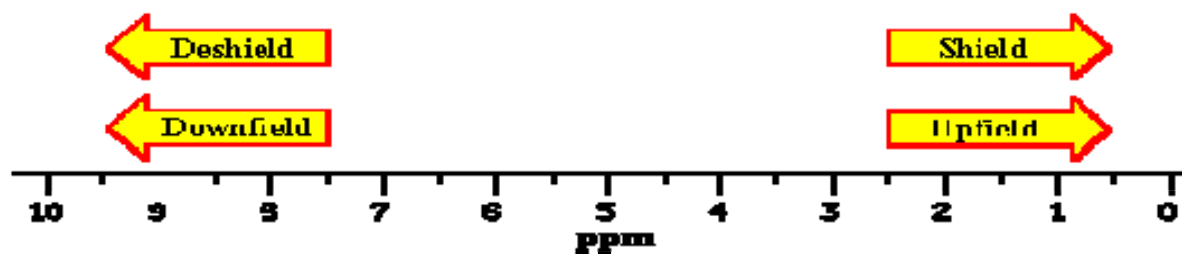


# shielding

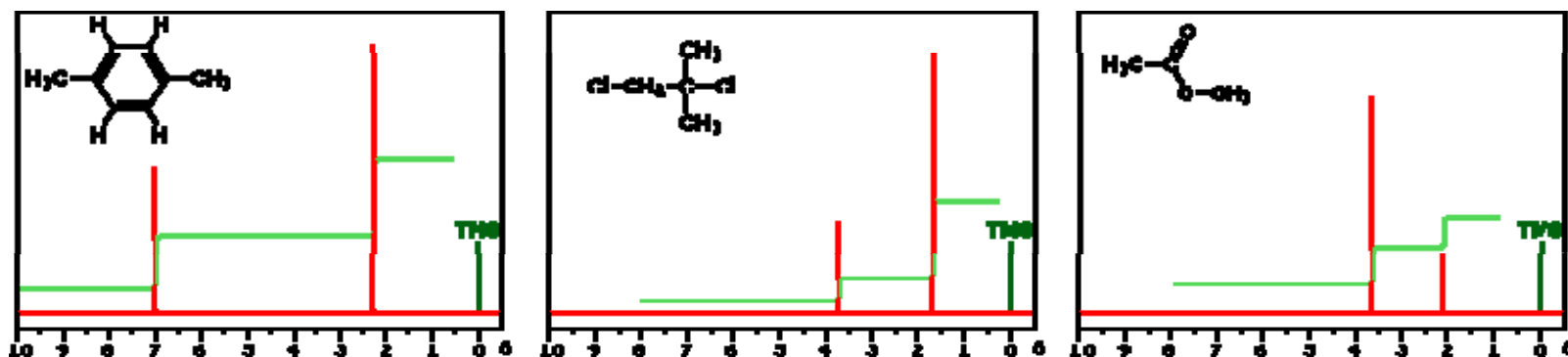
- Increasing Magnetic Field at Fixed Frequency —→
- ← Increasing Frequency at Fixed Magnetic Field ←
- Increased Shielding by Extranuclear electrons —→



$^1\text{H}$  NMR Resonance Signals for some Different Compounds

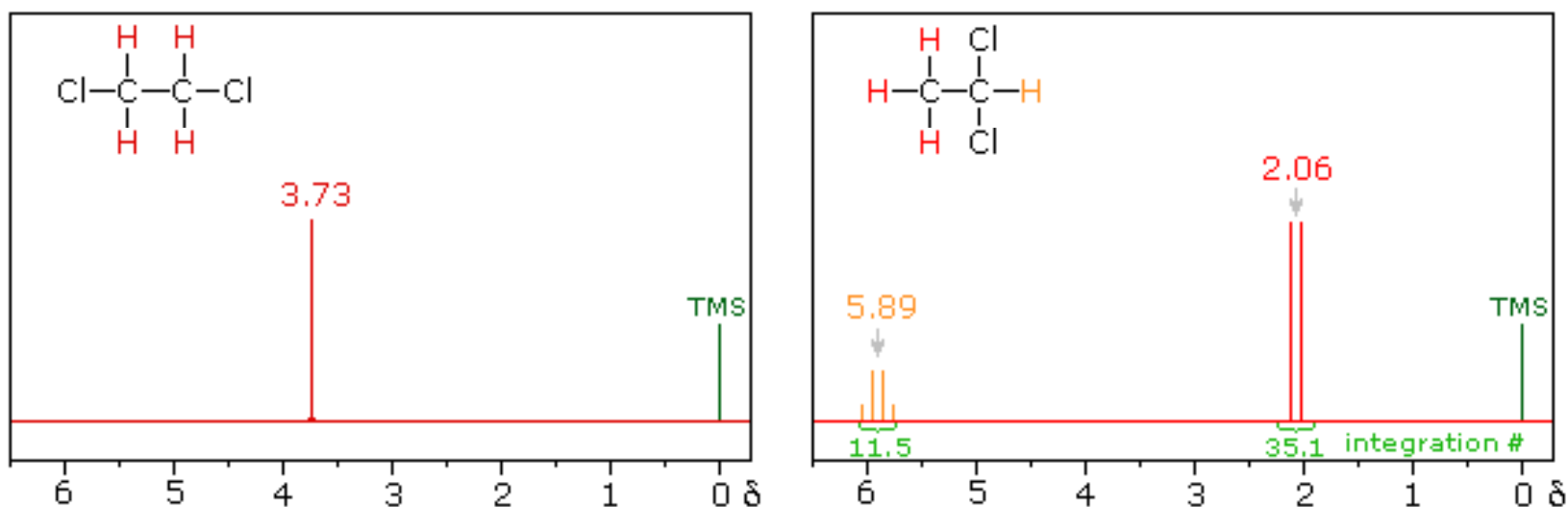


# Signal strength



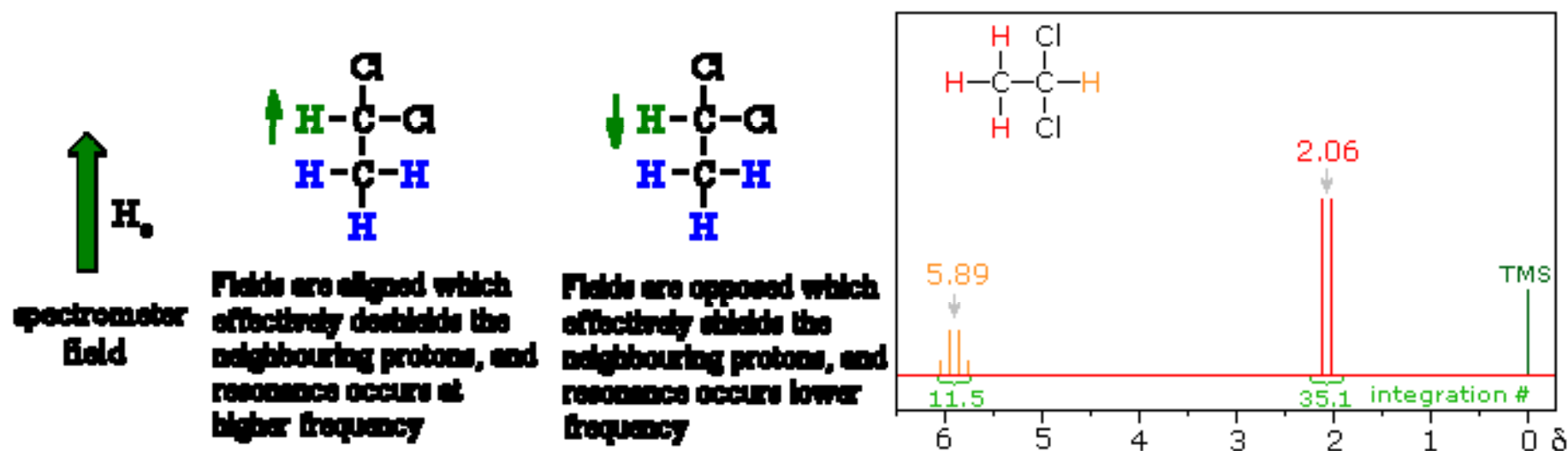
- The **magnitude or intensity** of NMR resonance signals is displayed along the vertical axis of a spectrum, and **is proportional to the molar concentration** of the sample. Thus, a small or dilute sample will give a weak signal, and doubling or tripling the sample concentration increases the signal strength proportionally. If we take the NMR spectrum of equal molar amounts of benzene and cyclohexane in carbon tetrachloride solution, the resonance signal from cyclohexane will be twice as intense as that from benzene because cyclohexane has twice as many hydrogens per molecule. This is an important relationship when samples incorporating two or more different sets of hydrogen atoms are examined, since it allows the ratio of hydrogen atoms in each distinct set to be determined.

# Spin-Spin Interactions-coupling



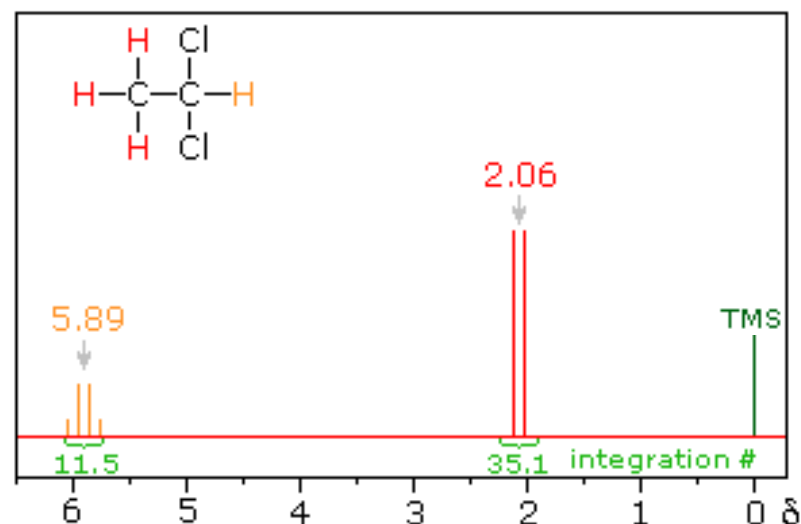
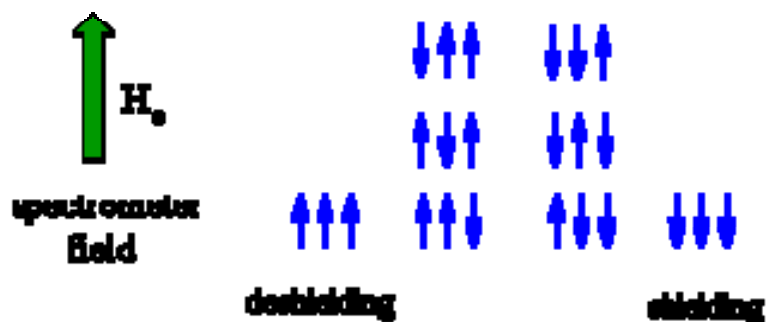
- So far the H-NMR spectra that we have looked at have all had different types of protons that are seen as **singlets** in the spectra. This is *not* the normal case.... spectra usually have peaks that appear as groups of peaks due to **coupling** with neighbouring protons, for example
- The nmr spectrum of 1,1-dichloroethane (up right) is more complicated than 1,2-dichloro-isomer (up left), which displays a single resonance signal from the four structurally equivalent hydrogens, the two signals from the different hydrogens are split into close groupings of two or more resonances. This is a common feature in the spectra of compounds having different sets of hydrogen atoms bonded to adjacent carbon atoms. The signal splitting in proton spectra is usually small, ranging from fractions of a Hz to as much as 18 Hz, and is designated as **J** (referred to as the coupling constant). In the 1,1-dichloroethane example all the coupling constants are 6.0 Hz.

- Now, what about the coupling patterns ? Coupling arises because the magnetic field of adjacent protons influences the field that the proton experiences. To understand the implications of this we should first consider the effect the **-CH** group has on the adjacent **-CH<sub>3</sub>**.



The methine **-CH** can adopt two alignments with respect to the applied field. As a result, the signal for the adjacent methyl **-CH<sub>3</sub>** is split in two lines, of equal intensity, a **doublet**.

- Now consider the effect of the **-CH<sub>3</sub>** group has on the adjacent **-CH**
- The methyl **-CH<sub>3</sub>** protons give rise to 8 possible combinations with respect to the applied field. However, some combinations are equivalent and there are four magnetically different effects. As a result, the signal for the adjacent methine **-CH** is split into four lines, of intensity ratio 1:3:3:1, a **quartet**.



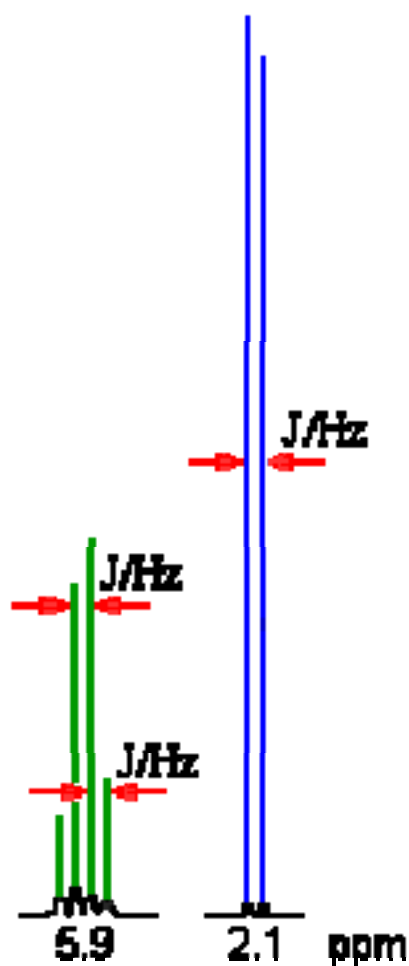
The proximity of "n" equivalent H on neighbouring carbon atoms, causes the signals to be split into "n+1" lines.

This is known as the **multiplicity** or **splitting** or **coupling pattern** of each signal.

Equivalent protons (or those with the same chemical shift) **do not couple** to each other.

If the neighbours are not all equivalent, more complex patterns arise.

# Coupling Constant, J

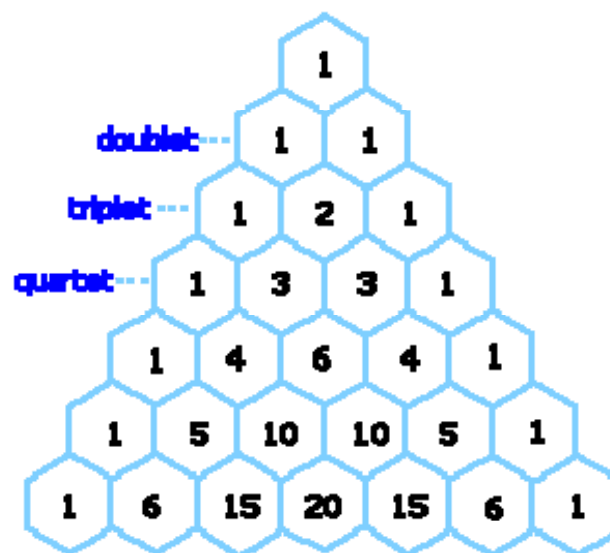
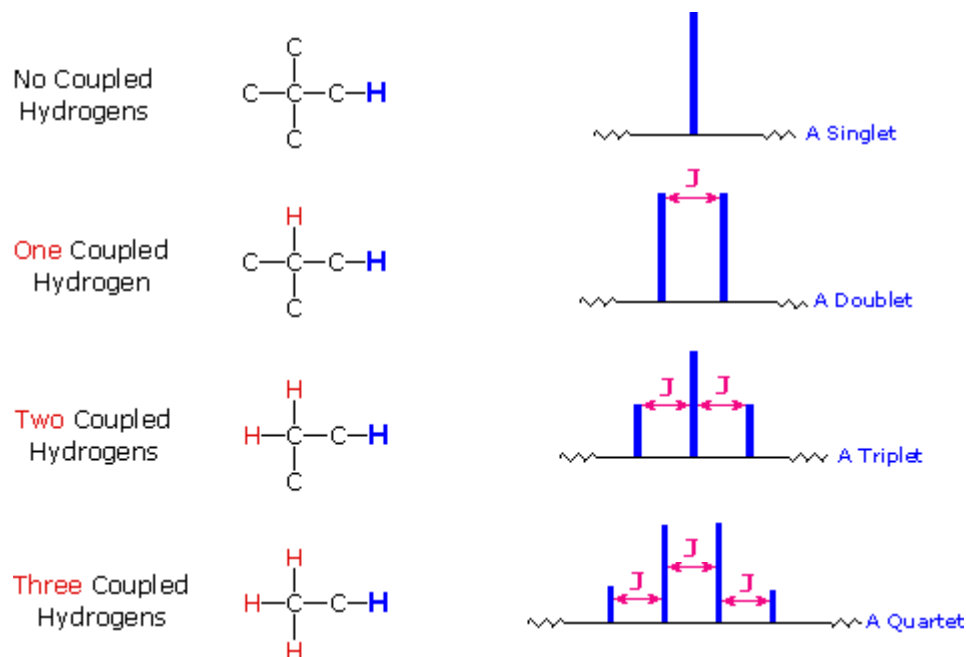


The coupling constant,  $J$  (usually in frequency units, Hz) is a measure of the interaction between a pair of protons. In a vicinal system of the general type, **Ha-C-C-Hb** then the coupling of **Ha** with **Hb**,  $J_{ab}$ , **MUST BE EQUAL** to the coupling of **Hb** with **Ha**,  $J_{ba}$ , therefore  $J_{ab} = J_{ba}$ .

The implications are that the spacing between the lines in the coupling patterns are the same as can be seen in the coupling patterns from the H-NMR spectra of 1,1-dichloroethane



# Pascal's Triangle



**Pascal's Triangle**

- The relative intensities of the lines in a coupling pattern is given by a binomial expansion or more conveniently by Pascal's triangle.
- Individual resonances are split due to coupling with "n" adjacent protons
- Number of lines in coupling pattern,  $L = n + 1$
- So for H-NMR a proton with zero neighbours,  $n = 0$ , appears as a single line, a proton with one neighbour,  $n = 1$  as two lines of equal intensity, a proton with two neighbours,  $n = 2$ , as three lines of intensities  $1 : 2 : 1$ , etc.

# NMR spectroscopy summary

- **Nuclear magnetic resonance spectroscopy**, most commonly known as **NMR spectroscopy**, is a research technique that exploits the magnetic properties of certain atomic nuclei to determine physical and chemical properties of atoms or the molecules in which they are contained. It relies on the phenomenon of nuclear magnetic resonance and can provide detailed information about the **structure, dynamics, reaction state, and chemical environment of molecules**.
- Most frequently, NMR spectroscopy is used by chemists and biochemists to investigate the properties of organic molecules, though it is applicable to any kind of sample that contains nuclei possessing spin.
- Small compounds as well as large proteins or nucleic acids can be analyzed in solutions and solid state.
- **Nuclear magnetic resonance is used in MRI and related imaging techniques**

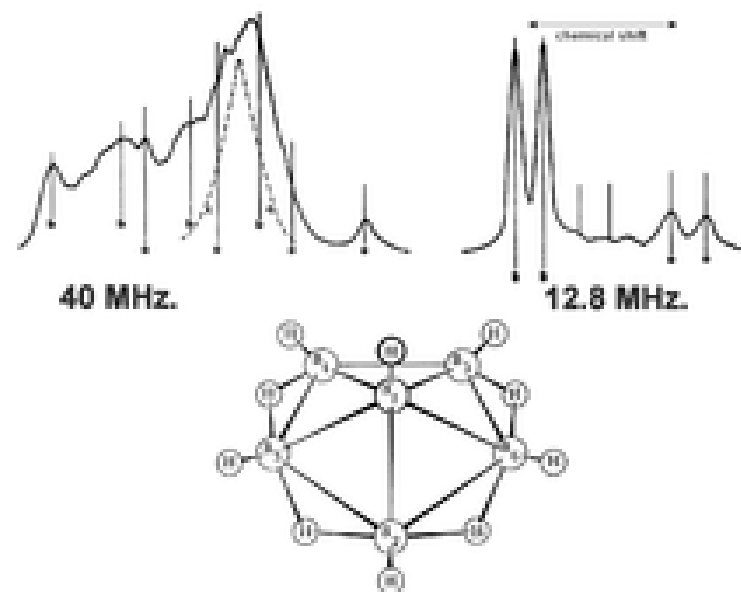
# NMR spectroscopy



A 900MHz NMR instrument with a 21.1 T magnet at HWB-NMR, Birmingham, UK



The NMR sample is prepared in a thin-walled glass tube - an NMR tube.



NMR spectrum of hexaborane  $B_6H_{10}$  showing peaks shifted in frequency, which give clues as to the molecular structure.