NMR spectroscopy

Prepared by Dr. Upali Siriwardane

For

CHEM 466 Instrumental Analysis class

Objectives

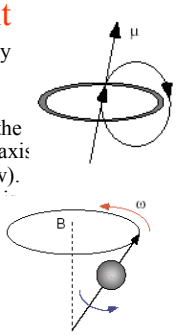
1. Student should gain better understanding of NMR spectroscopy.
2. Student should gain experience in the acquisition, processing, and displaying NMR data.
3. Student should gain experience in interpreting NMR data in order to establish structure for unknown organic molecules.
4. Student should gain understanding in advanced 1Dimensional and 2Dimensional NMR techniques.

Introduction

- The Nobel Prize has been awarded twice for work related to NMR. **F. Bloch** and **E.M. Purcell** received the Nobel Prize in Physics, in 1952, for the first experimental verifications of the phenomenon, and Prof. R.R. **Ernst** received the Nobel Prize in Chemistry, in 1991, for the development of the NMR techniques.
- Since its discovery 50 years ago, in 1945, it has spread from physics to chemistry, biosciences, material research and medical diagnosis.

The Physical Basis of the NMR Experiment

- Imagine a charge travelling circularily about an axis builds up a magnetic moment
- It rotates (spins) about its own axis (the blue arrow) and **precesses** about the axis of the magnetic field B (the red arrow). The frequency of the precession (ω) proportional to the strength of the magnetic field:



- ω = γ B_0

γ = magnetogyro ratio

Magnetic field mrasured in Tesla

1 T = 10,000 gauss

Magnetogyric ratio(γ)

The larger the value of the magnetogyric ratio, the larger the

Magnetic moment (μ) of the nucleus and the easier it is to see by NMR spectroscopy.

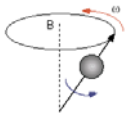
Energy difference (ΔE) between I_z = +1/2 and I_z = -1/2.

The Physical Basis of the NMR Experiment:

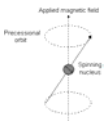
- Nuclear magnetic resonance, or NMR as it is abbreviated by scientists, is a phenomenon which occurs when the nuclei of certain atoms are immersed in a static strong magnetic field and exposed to a second oscillating magnetic field in the form of radiofrequency pulses, it is possible to transfer energy into the spin system and change the state of the system. After the pulse, the system relaxes back to its state of equilibrium, sending a weak signal that can be recorded.

Larmour frequency

- **Precession**: The circular movement of the magnetic moment in the presence of the applied field.
- **Larmour frequency** : The angular frequency of the precessionis related to the external magnetic field strength B_0, by the gyromagnetic ratio γ :



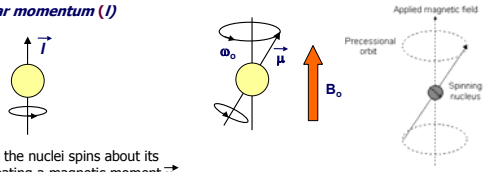
$$\omega_0 = \gamma B_0$$



Classical View of NMR (*compared to Quantum view*)

Precession or ***Larmor*** frequency: $\omega = 2\pi\nu \Rightarrow \omega_o = \gamma B_o$ (radians)

angular momentum (I)



Simply, the nuclei spins about its axis creating a magnetic moment $\vec{\mu}$

Maxwell: Magnetic field ≡ Moving charge

Apply a large external field (B_o) and $\vec{\mu}$ will precess about B_o at its Larmor (ω) frequency.

Important: This is the same frequency obtained from the energy transition between quantum states

Quantum-mechanical treatment:

- The dipole moment μ of the nucleus is described in quantum-mechanical terms as

$$\mu = \gamma J$$

- Therein, J is the **spin angular momentum** and γ the magnetogyric ratio of the spin. When looking at single spins we have to use a quantum-mechanical treatment.
- Therein, the z-component of the angular momentum J is **quantitized** and can only take **discrete values**

$$\langle J_z \rangle = m\frac{h}{2\pi}$$

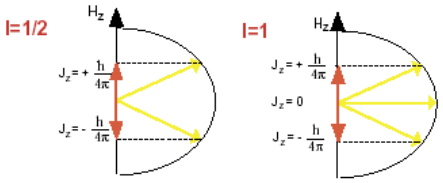
- J is related to spin quantum number of the nuclei I

  -I,…,o,…,+I

Spin quantum number(I)

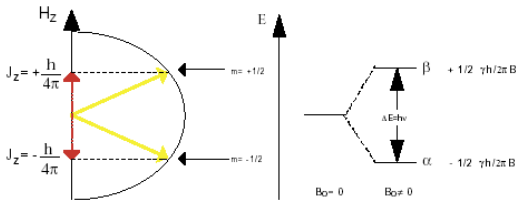
- Nuclear spin is characterized by a spin number, I, which can be zero or some positive integer multiple of 1/2 (e.g. 1/2, 1, 3/2, 2 etc.). Nuclei whose spin number, I= 0 have no magnetic moment(μ);eg. ^{12}C and ^{16}O show no NMR signal. Elements such as ^{1}H, ^{13}C, ^{19}F and ^{31}P have I=1/2, while others have even higher spin numbers:
- I=1 ^{14}N, ^{2}H
- I=3/2 ^{11}B, ^{35}Cl, ^{37}Cl, ^{79}Br, ^{81}Br.
- As the values for I increase, energy levels and shapes of the magnetic fields become progressively more and more complex.

z-component of the angular momentum J



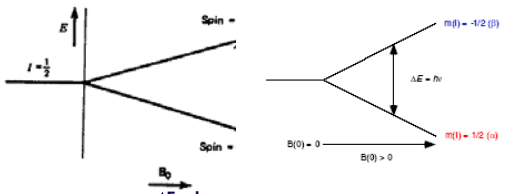
For I=1/2 nuclei, **m** can only be +1/2 or -1/2, giving rise to two distinct energy levels. For spins with I=1 nuclei three different values for Jz are allowed:

The energy difference ΔE,



- ***Zeeman effect***: splitting of energy levels in magnetic field
- The energy difference ΔE, which corresponds to the two states with m=±1/2, is then (the quantum-mechanical selection rule states, that only transitions with m= +1 are allowed):

A Nuclei with I= 1/2 in a Magnetic Field



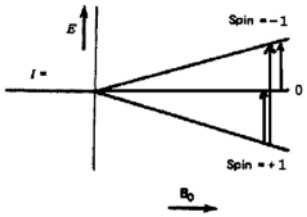
$\Delta E = h\nu$

$\nu = \gamma B_o / 2\pi$

$\Delta E = \gamma h B_o / 2\pi$

number of states = **2I+1**

A Nuclei with I= 1 in a Magnetic Field



number of states = **2I+1**

Semi-Quantum Mechanical Approach to the Basis of NMR,

Boltzmann Distribution of Spin States

- In a given sample of a specific nucleus, the nuclei will be distributed throughout the various spin states available. Because the energy separation between these states is comparatively small, energy from thermal collisions is sufficient to place many nuclei into higher energy spin states. The numbers of nuclei in each spin state are described by the Boltzman distribution

Boltzman distribution

$$\frac{N_{upper}}{N_{lower}} = e^{-\gamma_N Hh/kT}$$

- where the N values are the numbers of nuclei in the respective spin states, is the magnetogyric ratio, **h** is Planck's constant, **H(B)** is the external magnetic field strength, k is the Boltzmann constant, and T is the temperature.
- In NMR, the energy separation of the spin states is comparatively very small and while NMR is very informative it is considered to be an insensitive technique .

Example: Boltzman distribution

- For example, given a sample of ^1H nuclei in an external magnetic field of 1.41 Tesla
- ratio of populations = $e^{((-2.67519x10e8\ rad.s\text{-}1.T\text{-}1\ *\ 1.41T\ *\ 6.626176x10\text{-}34\ J.s)\ /\ (1.380662x10e\text{-}23\ J.K\text{-}1\ *K\ 293))} = 0.9999382$
- At room temperature, the ratio of the upper to lower energy populations is 0.9999382. In other words, the upper and lower energy spin states are almost equally populated with only a very small excess in the lower energy state.
- If $N_0 = 10^6$ or 1,000,000 then N_j 999,938
- $N_0 - N_j = 1{,}000{,}000 - 999{,}938 = 62$
- 62 ppm excess in the ground state

Saturation

The condition that exists when the upper and lower energy states of nuclei are equal. (no observed signal by NMR)

Electron Spin Resonance Spectroscopy ESR

ESR or Electron Paramagnetic Resonance (EPR) Spectroscopy

Provides information about the electronic and molecular structure of paramagnetic metal centers. Measurement of the spin state, *S*, the magnitude of hyperfine interactions with metal and ligand nuclei, and the zero-field splitting of half-integer $S > 1/2$ electronic states, allows a researcher to identify the paramagnetic center, and to potentially identify ligating atoms.

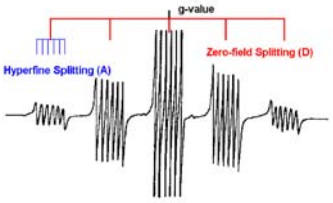
- **Nuclear hyperfine coupling constants**

ESR Spectroscopy

Uses microwave radiation on species that contain unpaired electrons placed ina magnetic fieled

1. Free radicals
2. Odd electron molecules
3. Transition-metal complexes
4. Lanthanide ions
5. Triplet-state molecules

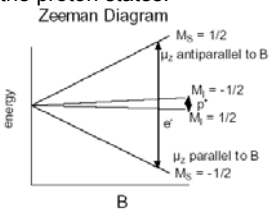
ESR of Mn^{2+}



- Mn^{2+} is d^5 term symbol is D (-3,-2,-1,0,+1,+2,+3) $M_L = \pm 1$ five main spin transitions due to the D term. Hyperfine interaction each of these lines is in turn split into six components (the Mn^{2+} nuclear spin is I = 5/2) (2I+1)

Electron Spin Resonance Spectroscopy ESR

- A magnetic field splits the $M_S = \pm 1/2$ spin states into two energy levels, separated by. Because of the difference in mass of p+ and e-, a given field **B** will
- split the electron states about 2000-fold further than the proton states.

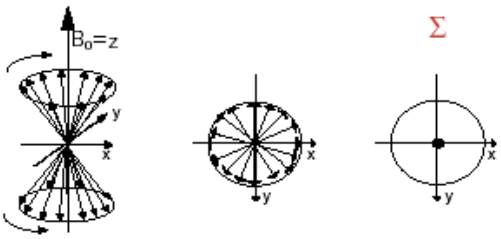


Since the signal intensity of magnetic resonance techniques is directly proportional to the difference in the two populations, EPR is intrinsically more sensitive Than NMR (other things being equal).

The macroscopic view

- The NMR experiment measures a largenumber **of spins** derived from a huge number of molecules. Therefore, we now look at the macroscopic bevaviour.
- The sum of the dipole moments of all nuclei is called **magnetization.** In equilibrium the spins of I=1/2 nuclei are either in the α or β-state and precess about the axis of the static magnetic field. However, their phases are *not correlated*.
- For each vector pointing in one direction of the transverse plane a corresponding vector can be found which points into the *opposite* direction:

Vector representation

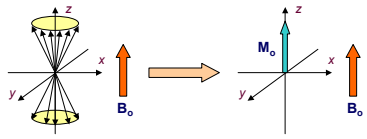


Bulk magnetization (M_o)

Now consider a real sample containing numerous nuclear spins:

$\mathbf{M_o} \triangleq (N\alpha - N\beta)$

$\vec{\mu} = \mu_x i + \mu_y j + \mu_z k$

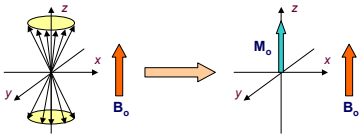


Since μ is precessing in the xy-plane, $\mathbf{M_o} = \sum \mu_z k - \mu_{-z} k$

μ is ***quantized*** (α or β), $\mathbf{M_o}$ has a ***continuous*** number of states, bulk property.

An NMR Experiment

We have a net magnetization precessing about B_o at a frequency of ω_o with a net population difference between aligned and unaligned spins.

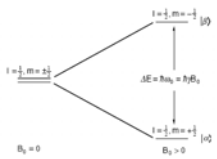


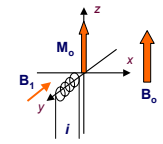
Now What?

Perturbed the spin population or perform spin gymnastics
Basic principal of NMR experiments

An NMR Experiment

To perturbed the spin population need the system to absorb energy.





Transmitter coil (y)

Two ways to look at the situation:
(1) quantum – absorb energy equal to difference in spin states
(2) classical - perturb M_o from an excited field B_1

An NMR Experiment

resonant condition: frequency (ω_1) of B_1 matches *Larmor* frequency (ω_o)
energy is absorbed and population of $\downarrow\alpha$ and $\beta\uparrow$ states are perturbed.

And/Or: *M_o now precesses about B_1 (similar to B_o) for as long as the B_1 field is applied.*

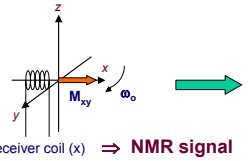
Again, keep in mind that individual spins flipped up or down (a single ***quanta***), but $\mathbf{M_o}$ can have a continuous variation.

Right-hand rule

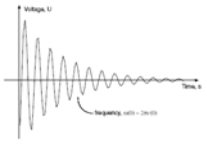
An NMR Experiment

What Happens Next?

The B_1 field is turned off and M_{xy} continues to precess about B_o at frequency ω_o.



Receiver coil (x) ⇒ **NMR signal**

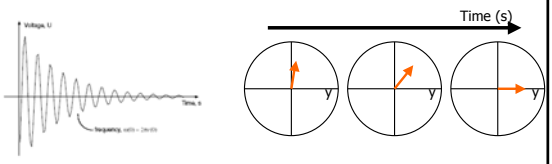


FID – Free Induction Decay

The oscillation of $\mathbf{M_{xy}}$ generates a fluctuating magnetic field which can be used to generate a current in a receiver coil to detect the NMR signal.

NMR Signal Detection - FID

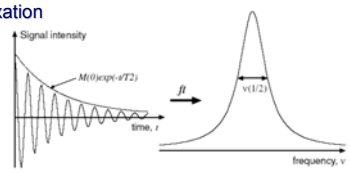
Mxy is precessing about z-axis in the x-y plane



The FID reflects the change in the magnitude of Mxy as the signal is changing relative to the receiver along the y-axis

Again, it is precessing at its Larmor Frequency (ω_o).

NMR Relaxation



$M_x = M_y = M_0 \exp(-t/T_2)$ → Related to line-shape → $\nu_{1/2} = \frac{1}{\pi T_2}$

(derived from Hisenberg uncertainty principal)

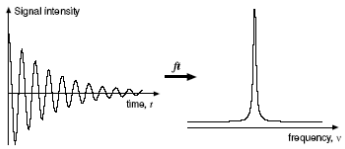
T_2 is the spin-spin (or transverse) relaxation time constant.
In general: $T_1 \geq T_2$

Think of T_2 as the "randomization" of spins in the x,y-plane

Please Note: Line shape is also affected by the magnetic fields homogeneity

NMR Signal Detection - Fourier Transform

So, the NMR signal is collected in the Time - domain



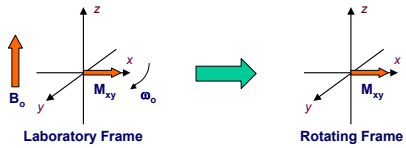
But, we prefer the frequency domain.

$F(\nu) \propto \int_{-\infty}^{\infty} f(t) e^{-i2\pi\nu t} dt$

Fourier Transform is a mathematical procedure that transforms time domain data into frequency domain

Laboratory Frame vs. Rotating Frame

To simplify analysis we convert to the rotating frame.



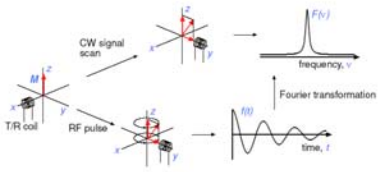
Simply, our axis now rotates at the Larmor Freguency (ω_o).
In the absent of any other factors, M_{xy} will stay on the x-axis

All further analysis will use the rotating frame.

Continuous Wave (CW) vs. Pulse/Fourier Transform

NMR Sensitivity Issue

A frequency sweep (CW) to identify resonance is very slow (1-10 min.)
Step through each individual frequency.



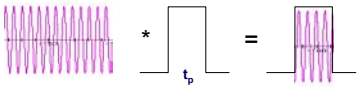
Pulsed/FT collect all frequencies at once in time domain, fast (N x 1-10 sec)

Increase signal-to-noise (S/N) by collecting multiple copies of FID and averaging signal.

S/N ∝ $\sqrt{\text{number of scans}}$

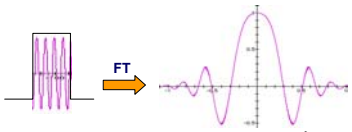
NMR Pulse

A radiofrequency pulse is a combination of a wave (cosine) of frequency ω_o and a step function



Pulse length (time, t_p)

The fourier transform indicates the pulse covers a range of frequencies

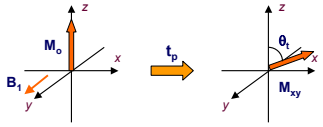


Hisenberg Uncertainty principal again: $\Delta\upsilon \cdot \Delta t \sim 1/2\pi$
Shorter pulse length – larger frequency envelope
Longer pulse length – selective/smaller frequency envelope

} Sweep Width f ~ 1/t

NMR Pulse

NMR pulse length or Tip angle (t_p)



$\theta_t = \gamma * t_p * B_1$

The length of time the B_1 field is on => torque on bulk magnetization (B_1)

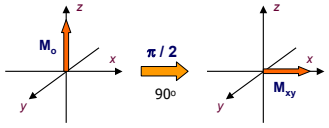
A measured quantity – instrument dependent.

NMR Pulse

Some useful common pulses

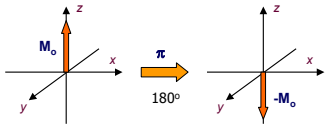
<u>90° pulse</u>

Maximizes signal in x,y-plane where NMR signal detected



<u>180° pulse</u>

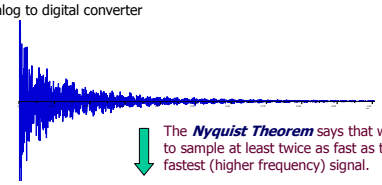
Inverts the spin-population. No NMR signal detected



Can generate just about any pulse width desired.

NMR Data Acquisition

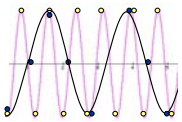
Collect *Digital* Data
ADC – analog to digital converter



The ***Nyquist Theorem*** says that we have to sample at least twice as fast as the fastest (higher frequency) signal.

Sample Rate

- ○ - Correct rate, correct frequency
- • -½ correct rate, ½ correct frequency Folded peaks! Wrong phase!



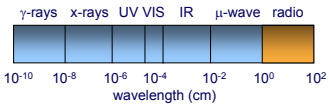
$SR = 1 / (2 * SW)$

SR – sampling rate

Information in a NMR Spectra

1) Energy $E = h\upsilon$

h is Planck constant
υ is NMR resonance frequency



Observable	Name	Quantitative	Information
Peak position	Chemical shifts (δ)	δ(ppm) = $\upsilon_{obs} - \upsilon_{ref}/\upsilon_{ref}$ (Hz)	chemical (electronic) environment of nucleus
Peak Splitting	Coupling Constant (J) Hz	peak separation (intensity ratios)	neighboring nuclei (torsion angles)
Peak Intensity	Integral	unitless (ratio) relative height of integral curve	nuclear count (ratio) T_1 dependent
Peak Shape	Line width	$\Delta\upsilon = 1/\pi T_2$ peak half-height	molecular motion chemical exchange uncertainty principal uncertainty in energy

NMR Sensitivity

NMR signal depends on: signal (s) $\propto \gamma^4 B_o^2 N B_1 g(\upsilon)/T$

1) Number of Nuclei (N) (limited to field homogeneity and filling factor)
2) Gyromagnetic ratio (in practice γ^2)
3) Inversely to temperature (T)
4) External magnetic field ($B_o^{2/3}$, in practice, homogeneity)
5) B_1^2 exciting field strength

$N_\alpha / N_\beta = e^{\Delta E / kT}$ $\Delta E = \gamma h B_o / 2\pi$

Increase energy gap -> Increase population difference -> Increase NMR signal

$\uparrow\Delta E \equiv \uparrow B_o \equiv \uparrow\gamma$

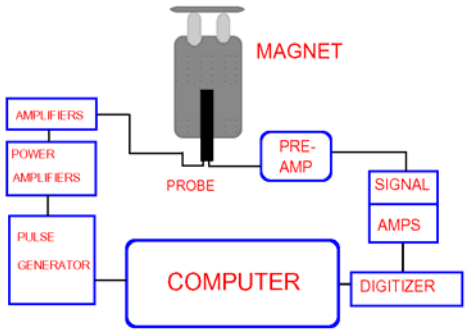
γ - Intrinsic property of nucleus can not be changed.

$(\gamma_H/\gamma_C)^3$ for ^{13}C is 64x $(\gamma_H/\gamma_N)^3$ for ^{15}N is 1000x

^1H is ~ 64x as sensitive as ^{13}C and 1000x as sensitive as ^{15}N !

Consider that the natural abundance of ^{13}C is 1.1% and ^{15}N is 0.37% relative sensitivity increases to ~6,400x and ~$2.7x10^5$x !!

Basic NMR Spectrometer



How NMR is achieved

- Liq N_2 Liq He Magnet

Instrument and Experimental Aspects

- Sample Preparation,
- Standards,
- The probe, Probe
- Tuning and Matching,
- Locking, and Shimming.

Nuclear Magnetic Resonance

- Sample Preparation

NMR samples are prepared and run in 5 mm glass NMR tubes. Always fill your NMR tubes to the same height with lock solvent

Deuteron resonance serves as lock- signal for the stabilisation of the spectrometer magnetic fieled.

Common NMR solvents

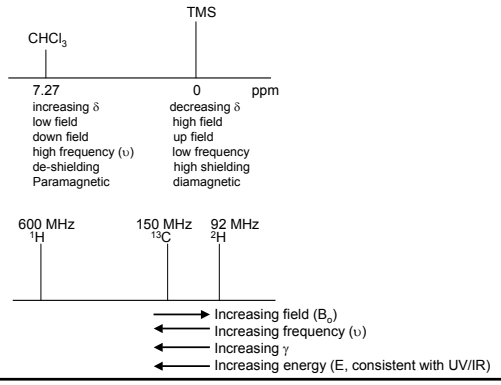
- Acetone- d_6 Ethanole- d_6 Acetonitrile- d_3
- Formic acid- d_2 Benzene- d_6 Methanole- d_4
- Chloroform- d_1 Nitromethane- d_3 Deuteriumoxide-D_2O
- Pyridine- d_5 Dichloromethane- d_2 1,1,2,2- Tetrachloroethane- d_2
- Dimethylformamide- d_7 Tetrahydrofurane- d_8 Dimethylsulfoxide- d_6
- Toluene- d_8 1,4- Dioxane- d_8 Trifluoroacetic acid- d_1

- NMR solvents are used as reference peaks
- to adjust the ppm values in the spectrum
- relative to TMS (tetramethyl silane)

NMR probes

- NMR probes designed creating different radio frequency singnals and detectors for dealing with varuous magnetic nuclie have become more advanced and allow progressively smaller samples. Probe diameters and correspondingly sample volumes have progressively decreased.
- ^{1}H NMR Probe High frequency (270 MHz)probes
- ^{19}F NMR Probe High frequency (254 MHz) probes
- ^{13}C NMR Probe Low frequncy(< 254 MHz) probes
- Broad band probe High/Low frequency tunable probes

NMR Spectra Terminology

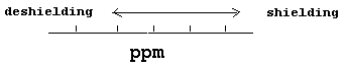


Shielding and Deshielding of Nuclei

- The magnetic field at the nucleus, B, (the effective field) is therefore generally less than the applied field, B_o, by a fraction .
- $B = B_o (1-\sigma)$
- peaks move to right due to shileding
- peaks move to left due to deshileding: beeing attached more electronegitve atoms or experiencing ring currents as in benezne

Chemical Shift

- The chemical shift of a nucleus is the difference between the resonance frequency of the nucleus and a standard, relative to the
- standard. This quantity is reported in ppm and given the symbol delta, δ.
- $\delta = (n - n_{REF}) \times 10^6 / n_{REF}$



Chemical Shift

Up to this point, we have been treating nuclei in general terms.
Simply comparing ^1H, ^{13}C, ^{15}N etc.

If all ^1H resonate at 500MHz at a field strength of 11.7T, NMR would not be very interesting

The *chemical environment* for each nuclei results in a unique *local* magnetic field (B_{loc}) for each nuclei:

$$B_{eff} = B_o - B_{loc} \text{ --- } B_{eff} = B_o(1 - \sigma)$$

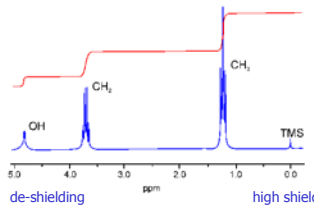
σ is the ***magnetic shielding*** of the nucleus

Chemical Shift

Again, consider Maxwell's theorem that an electric current in a loop generates a magnetic field. Effectively, the electron distribution in the chemical will cause distinct local magnetic fields that will either add to or subtract from B_o

$HO-CH_2-CH_3$

$B_{eff} = B_o(1 - \sigma)$



de-shielding high shielding

Shielding – local field opposes B_o

Aromaticity, electronegativity and similar factors will contribute to chemical shift differences

The NMR scale (δ, ppm)

$B_o >> B_{loc}$ -- MHz compared to Hz

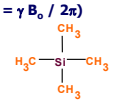
Comparing small changes in the context of a large number is cumbersome

$$\delta = \frac{\omega - \omega_{ref}}{\omega_{ref}}$$ **ppm (parts per million)**

Instead use a relative scale, and refer all signals (ω) in the spectrum to the signal of a particular compound (ω_{ref}).

IMPORTANT: absolute frequency is field dependent ($\nu = \gamma B_o / 2\pi$)

Tetramethyl silane (**TMS**) is a common reference chemical

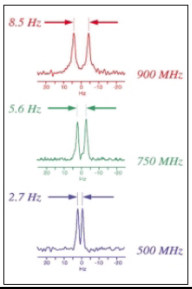


The NMR scale (δ, ppm)

Chemical shift (δ) is a relative scale so it is independent of B_o. Same chemical shift at 100 MHz vs. 900 MHz magnet

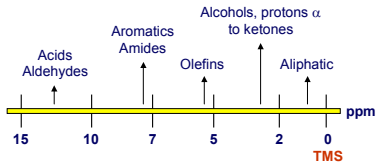
IMPORTANT: absolute frequency is field dependent ($\nu = \gamma B_o / 2\pi$)

At higher magnetic fields an NMR spectra will exhibit the same chemical shifts but with higher resolution because of the higher frequency range.



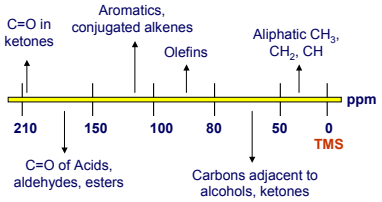
Chemical Shift Trends

• For protons, ~ 15 ppm:



Chemical Shift Trends

• For carbon, ~ 220 ppm:



Predicting Chemical Shift Assignments

Numerous Experimental NMR Data has been compiled and general trends identified

- Examples in Handout
- See also:
  - "Tables of Spectral Data for Structure Determination of Organic Compounds" Pretsch, Clerc, Seibl and Simon
  - "Spectrometric Identification of Organic Compounds" Silverstein, Bassler and Morrill
- Spectral Databases:
  - Aldrich/ACD Library of FT NMR Spectra
  - Sadtler/Spectroscopy (UV/Vis, IR, MS, GC and NMR)

Spin-Spin Coupling

- Nuclei which are close to one another exert an influence on each other's effective magnetic field. This effect shows up in the NMR spectrum when the nuclei are nonequivalent. If the distance between non-equivalent nuclei is less than or equal to three bond lengths, this effect is observable. This effect is called spin-spin coupling or J coupling.

Spin-Spin Coupling

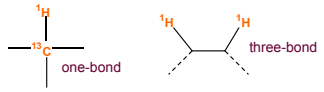
- For the next example, consider a molecule with spin 1/2 nuclei, one type A and type B

Configuration	Peak Ratios
A	1
AB	1:1
AB_2	1:2:1
AB_3	1:3:3:1
AB_4	1:4:6:4:1
AB_5	1:5:10:10:5:1
AB_6	1:6:15:20:15:6:1

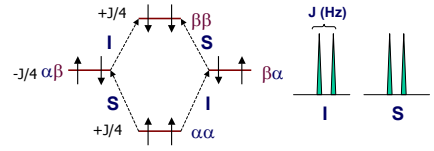
- This series is call[illegible]ulated from the coefficients of the expansion of the equation $(x+1)^n$

Coupling Constants

Energy level of a nuclei are affected by covalently-bonded neighbors spin-states



Spin-States of covalently-bonded nuclei want to be aligned.



The magnitude of the separation is called ***coupling constant*** (**J**) and has units of Hz.

Coupling Constants

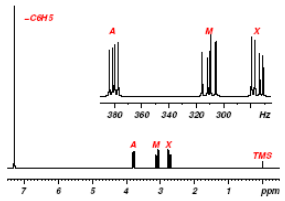
IMPORTANT: Coupling constant pattern allow for the identification of bonded nuclei.

Multiplets consist of 2nI + 1 lines
I is the nuclear spin quantum number (usually 1/2) and
n is the number of neighboring spins.

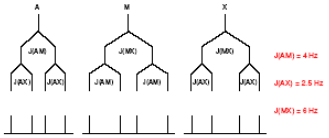
The ratios between the signal intensities within multiplets are governed by the numbers of Pascals triangle.

Configuration	Peak Ratios
A	1
AX	1:1
AX_2	1:2:1
AX_3	1:3:3:1
AX_4	1:4:6:4:1

Coupling Constants



The *first order* analysis of the styreneoxide spectrum:



The types of information accessible via high resolution NMR include

1. Functional group analysis (chemical shifts)
2. Bonding connectivity and orientation (J coupling)
3. Through space connectivity (Overhauser effect)
4. Molecular Conformations, DNA, peptide and enzyme sequence and structure.
5. Chemical dynamics (Lineshapes, relaxation phenomena).

Multinuclear NMR

- Spin angular momentum number of I =1/2, of which examples are ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{31}P

How NMR Signals are Created, Relaxation

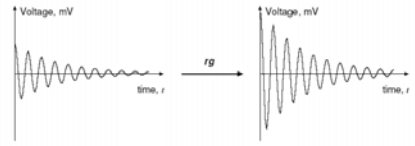
FT-NMR Experimental Method

- Data Acquisition and Storage,
- Digital Resolution,
- Folding,
- Quadrature Phase Detection.

Data Treatment

- Apodization or Window Functions,
- Zero Filling,
- Fourier Transformation,
- Phase Correction.

Receiver Gain

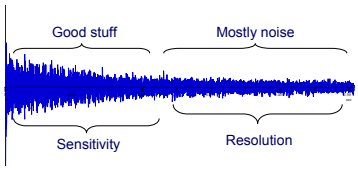


The NMR-signal received from the resonant circuit in the probehead needs to be amplified to a certain level before it can be handled by the computer.

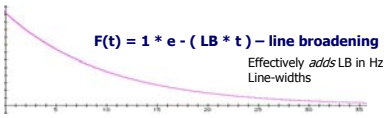
The detected NMR-signals vary over a great range due to differences in the inherent sensitivity of the nucleus and the concentration of the sample.

Data Processing – Window Functions

The NMR signal M_{xy} is decaying by T_2 as the FID is collected.



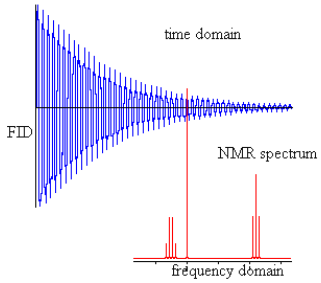
Emphasize the signal and decrease the noise by applying a mathematical function to the FID



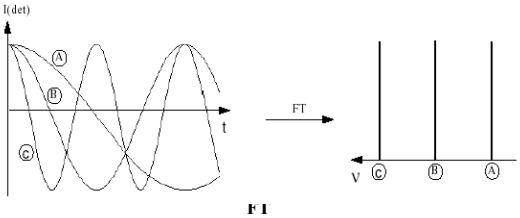
F(t) = 1 * e - (LB * t) – line broadening

Effectively *adds* LB in Hz to peak Line-widths

Fourier Transformation



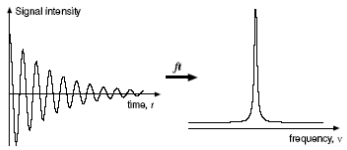
Fourier Transformation- FT



Time domain (FID) → FT frequency domain

NMR Signal Detection - Fourier Transform

So, the NMR signal is collected in the Time - domain

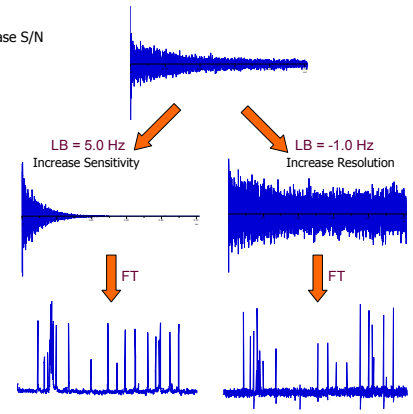


But, we prefer the frequency domain.

$$F(\nu) \propto \int_{-\infty}^{\infty} f(t) e^{-i2\pi\nu t}\, dt$$

Fourier Transform is a mathematical procedure that transforms time domain data into frequency domain

Can either increase S/N
or
Resolution
Not
Both!



NMR Data size

A Number of Interdependent Values (calculated automatically)

digital resolution (DR) as the number of Hz per point in the FID for a given spectral width.

DR = SW / SI

SW - spectral width (Hz)
SI - data size (points)

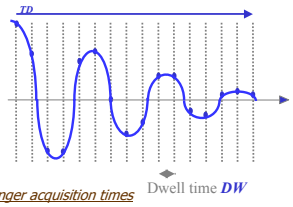
Remember: SR = 1 / (2 * SW)

Also: SW = 1/2DW

Total Data Acquisition Time:

*AQ = TD * DW= TD/2SWH*

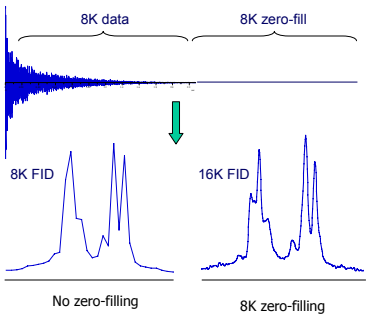
Should be long enough to allow complete delay of FID



Higher Digital Resolution requires longer acquisition times

Zero Filling

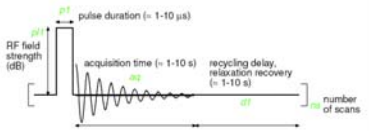
Improve digital resolution by adding zero data points at end of FID



MultiDimensional NMR

Up to now, we have been talking about the basic or 1D NMR experiments

1D NMR



More complex NMR experiments will use multiple "time-dimensions" to obtain data and simplify the analysis.

In a 1D NMR experiment the FID acquisition time is the time domain (t_1)

Multidimensional NMR experiments may also observe multiple nuclei (^{13}C,^{15}N) in addition to ^{1}H.
But usually detect ^{1}H.

The Proton NMR

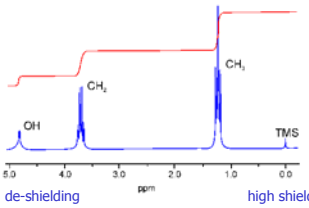
- Stereochemical Equivalent/Non-equivalent Protons
- Chemical Shift
- Spin Coupling

Chemical Shift

Again, consider Maxwell's theorem that an electric current in a loop generates a magnetic field. Effectively, the electron distribution in the chemical will cause distinct local magnetic fields that will either add to or subtract from B_o

$HO-CH_2-CH_3$

$B_{eff} = B_o(1 - \sigma)$



de-shielding high shielding

Shielding – local field opposes B_o

Aromaticity, electronegativity and similar factors will contribute to chemical shift differences

Simplification of proton NMR Spectra

- :Spin Decoupling,
- Higher Field NMR Spectra,
- Lanthanide Shift Reagents.

Carbon NMR Spectroscopy

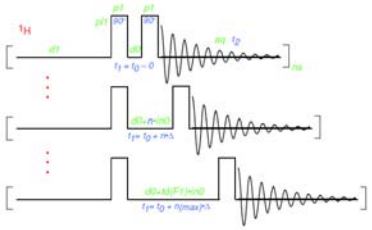
- Introduction,
- Chemical Shifts,
- Experimental Aspects of 13C NMR Spectroscopy.

2D NMR

- Experimental Aspects of 2D NMR Spectroscopy.
- Preparation, Evolution and Mixing,
- Data Acquisition,
- Spectra Presentation.

MultiDimensional NMR

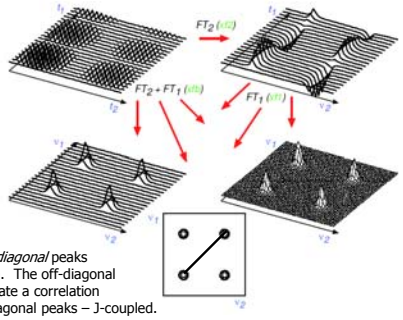
2D COSY (Correlated SpectroscopY):
Correlate J-coupled NMR resonances



A series of FIDs are collected where the delay between 90° pulses (t1) is incremented. t_2 is the normal acquisition time.

MultiDimensional NMR

During the t_1 time period, peak intensities are modulated at a frequency corresponding to the chemical shift of its coupled partner.



Solid line connects *diagonal* peaks (normal 1D spectra). The off-diagonal or *cross-peaks* indicate a correlation between the two diagonal peaks – J-coupled.

2D Homonuclear Correlated NMR Experiments

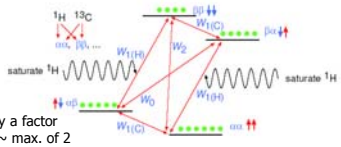
- COSY (**Correlation Spectroscopy**)
- NOESY(**NOE Nuclear Overhauser effect Spectroscopy)**
- **TOCSY experiment correlates all protons of a spin system**
- ROESY- NOE in the Rotating Frame
- HETCOR -heteronuclear correlation spectroscopy

Nuclear Overhauser Effect (NOE)

Interaction between nuclear spins mediated through empty space (~5Å) (like ordinary bar magnets). ***Important: Effect is Time-Averaged!***

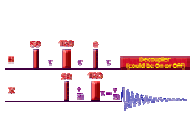
Give rise to dipolar relaxation (T1 and T2) and specially to cross-relaxation and the NOE effect.

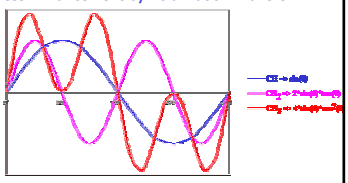
Perturb ^1H spin population affects ^{13}C spin population NOE effect

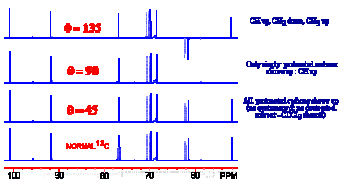


the ^{13}C signals are enhanced by a factor
$1 + \eta = 1 + 1/2 \cdot \gamma(^1H)/\gamma(^{13}C) \sim$ max. of 2

DEPT Experiment: Distortionless Enhancement by Polarization Transfer



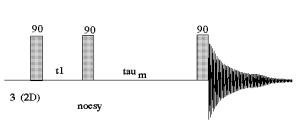


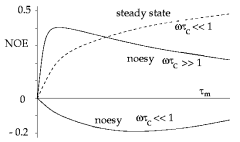


^{13}C spectra is perturbed based On the number of attached ^1H

Takes advantage of different patterns of polarization transfer ^1H-^{13}C NOE

2D NOESY (Nuclear Overhauser Effect)



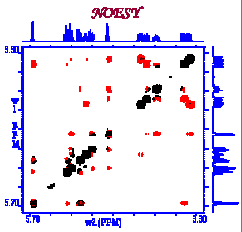


Diagonal peaks are correlated by through-space Dipole-dipole interaction.

NOE is a relaxation factor that builds-up during The "mixing-time (τ_m)

The relative magnitude of the cross-peak is Related to the distance ($1/r^6$) between the Protons (≥ 5Å).

Basis for solving a Structure!



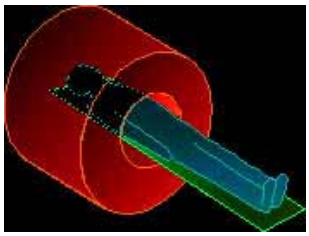
Hetero- 2D Nuclear Correlated NMR Experiments

- HETCOR
- HMBC
- HMQC.

Magnetic Resonance Imaging (MRI)

- Another growing field of interest in NMR is MR-imaging. The water content of the human body allows the making of proton charts or images of the whole body or certain tissues. Since static magnetic fields or radiopulses have been found not to injure living organisms, MR-imaging is competing with x-ray tomography as the main diagnostic tool in medicine. The MR-imaging technique has been applied to material research as well.

Magnetic Resonance Imaging (MRI)



Functional Nuclear magnetic resonance(FMRI)

- **patient is placed in a tube with magnetic fields The way the ^{1}H in body responds to those fields is noted and sent to a computer along with information about where the interactions occurred. Myriads of these points are sampled and fed into a computer that processes the information and creates an image.**
- **Thoughts Image Mapping by Functional Nuclear magnetic resonance FMRI**