NMR SPECTROSCOPY

SEM-4, CC-8
PART-2, PPT-14

Contents (Part-2)

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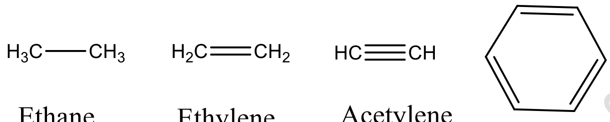
Nuclear Magnet Resonance (NMR) Spectroscopy (PART-2, PPT-14)

Equivalent Protons

The protons which are in an identical chemical environment in a compound and resonate at the same frequency are called equivalent protons. These Protons are identical in every way. They have the same magnetic environment, and they appear at the same position in the proton NMR spectrum in the compound.Equivalent protons in a compound show single signal. All the six protons in ethane, four protons in ethylene, two protons in acetylene, and six protons in benzene are all equivalent.



Ethane 1   Ethylene 2   Acetylene 3   Benzene 4

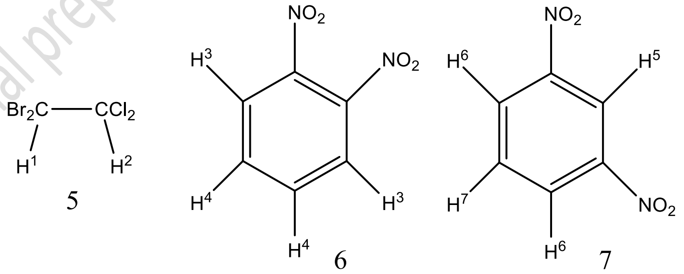
Molecules giving rise to one ^{1}H NMR signal

All protons in each molecule are Chemically Equivalent

Figure 1

Nonequivalent Protons

The protons which are in very different chemical environments in a molecule, each gives rise to an absorption and the absorptions are widely separated in the spectrum are called nonequivalent protons. The two protons (H^1 and H^2) in 5, two protons (H^3 and H$^{4)}$ in 6, and three protons (H^5, H^6, and H^7) in 7 are all nonequivalent (Figure 2).



5   6   7

1,1-Dibromo-2,2-dichloroethane   *o*-Dinitrobenzene   *m*-Dinitrobenzene

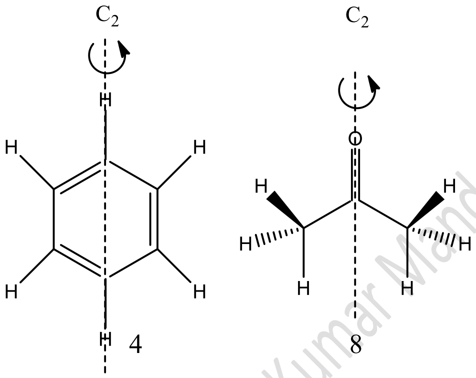
Figure 2

Nonequivalent protons have the different magnetic environment. These protons of a compound resonate at different frequencies. They appear at different positions in the proton NMR spectrum.

Number of Signals in a Compound

The number of signals in the proton NMR spectrum of a compound is generally equivalent to the number of different sets of equivalent protons in it. Each signal corresponds to a set of equivalent proton/s. All of the protons found in chemically identical environments within a molecule are chemically equivalent.

All the protons in tetramethyl silane [TMS, $(CH_3)_4Si$] or the protons in benzene, or in acetone are equivalent by symmetry considerations (Figure 3). Each such compound gives rise to a single absorption peak in its proton NMR spectrum. These “homotopic” protons in each compound are said to be chemically equivalent.

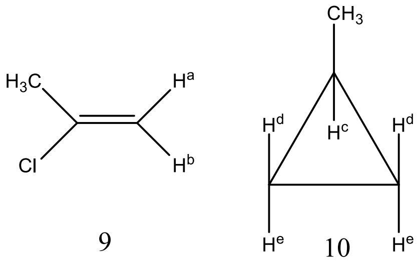


4 8

Benzene Acetone

Figure 3

On the other hand, a molecule that has sets of protons that are chemically distinct from one another may give rise to a different absorption peak from each set, in which case the sets of protons are chemically nonequivalent. Two olefinic protons (H^a and H^b) in 2-chloropropene (9) are diastereotopic. They reside in a different chemical environment, and absorbs separately. These two protons are, therefore, chemically nonequivalent.



9 10

2-Chloropropene Methyl cyclopropane

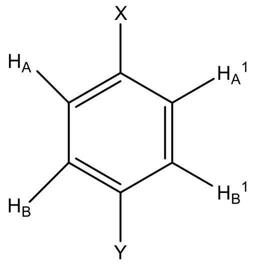
Figure 4

The protons H^d and H^e in methyl cyclopropane (10) are also nonequivalent for the same reason. Consequently, it shows four signals in ^{1}H-NMR spectrum.

Chemically Equivalent *vs* Magnetically Equivalent Protons

The number of peaks in ^{1}H NMR spectrum of a compound corresponds to the number of chemically distinct types of protons in the molecule. Often, protons that are chemically equivalent are also magnetically equivalent. However, *in some instances, protons that are chemically equivalent are not magnetically equivalent*.

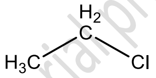
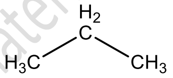
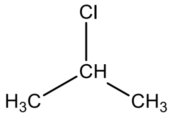
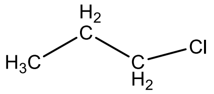
Two *ortho* protons (H_A and $H_A{}^1$) with respect to X, and two *ortho* protons (H_B and $H_B{}^1$) with respect to Y in 11 are chemically equivalent, but magnetically nonequivalent. Two protons are defined as being magnetically equivalent if each couples equally to a third neighbouring proton; otherwise they are magnetically nonequivalent.

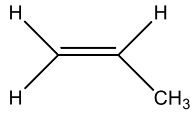
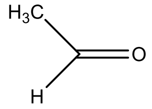
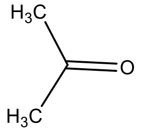
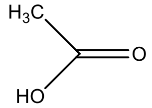


11
Unsymmetrically *p*-disubstituted benzene derivative
Figure 5

Number of Signals in a Compound

The number of signal/s a given compound shows/show in its proton NMR spectrum is simply equal to the number of nonequivalent protons present in it.

	Compound	Name	No. of Non-equivalent Proton/s	No. of Signal/s
1.	$H_3C—CH_3$	Ethane	1	1
2.		Ethyl chloride	2	2
3.		Propane	2	2
4.		2-Chloropropane	2	2
5.		1-Chloropropane	3	3

	Compound	Name	No of Non-equivalent Proton/s	No. of Signal/s
6.	$H_2C{=}CH_2$	Ethylene	1	1
7.		propene	4	4
8.		Acetaldehyde	2	2
9.		Acetone	1	1
10.		Acetic Acid	2	2

Home-WorK: Identify the nonequivalent protons in each of the following compounds
1. Nitrobenzene 2. Aniline 3. Benzaldehyde 4. Ethyl acetate 5. Toluene
6. Benzoic acid 7. Salicylaldehyde 8. Salicylamide 9. o-Nitroaniline 10. Phenol

Choice of Solvents

- The non-viscous samples give the sharpest NMR spectra. It is usually necessary to record the spectra of organic compounds in solution. If the compound, itself is a non-viscous liquid, the neat liquid can be used.
- The solvent should be capable of dissolving at least 10% of the substance under investigation.
- It is an advantage to use the aprotic solvents which do not themselves give an NMR spectrum to superimpose on that of the sample.
- The commonly used NMR solvents are normal organic solvents in which the hydrogen has been replaced by deuterium.
- Most FT NMR instruments maintain frequency accuracy by “locking” simultaneously to the deuterium NMR frequency, and in these instruments a deuterium containing solvent is essential. The common deuterated solvents used for organic compounds are $CDCl_3$, CD_3CN, CD_3OD, $(CD_3)_2CO$, C_6D_6, $(CD_3)_2SO$, D_2O, etc.
- These solvents differ considerably as regards their polarity. NMR spectrum of a compound measured in one solvent may be slightly different from that measured in another solvent of different polarity. Hence, it is important to mention the solvent used in an NMR spectrum.

- There is always some residual $CHCl_3$ (~0.01%) in $CDCl_3$. A small $CHCl_3$ peak at δ 7.26 ppm from the $CDCl_3$ solvent will cause no difficulty. This solvent signal usually does not overlap with the signal of the target sample in most cases.

Properties of the Selected Solvent

1. It should be chemically inert, and magnetically isotropic.
2. It should be devoid of hydrogen atom. Generally, deuterated solvent is used.
3. It should be inexpensive.
4. It should have low boiling point.
5. It should dissolve the sample to a reasonable extent (at least 10% of the substance under investigation).
6. *Note*: *It has been found that the NMR spectrum of even completely deuterated solvent does show one or more peaks. It is due to the presence of minor impurities in the solvent.*

Deuterated Solvents are used in NMR Experiments

Reason 1: To avoid swamping by the solvent signal

- There is usually much more solvent than sample in an NMR tube. Therefore, an ordinary proton containing solvent would give a huge solvent absorption that would dominate and spoil the ^{1}H-NMR spectrum.

Reason 2: To stabilize the magnetic field strength

- The field strength of superconducting magnets tends to drift slowly. Modern NMR spectrometers measure the deuterium absorption of the solvent, and adjust the magnetic field strength to keep the resonance frequency constant.
- The deuterium lock prevents changes in the static field (B_0) and radiofrequency (B_1) by maintaining a constant ratio between the two. It, therefore, ensures long-term stability of the magnetic field.
- If the ^{2}H lock is not applied, a drastic deterioration in the shape of the NMR lines is observed, due to magnetic field and radiofrequency inhomogeneities.

Reason 3: To accurately define 0 ppm

- The deuterium signal is used to accurately define 0 ppm as the resonant frequency of the lock solvent.

$CDCl_3$ as Common Solvent in NMR

- $CDCl_3$ is a common solvent used for NMR analysis. It is used because

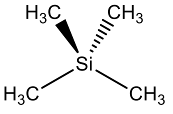
1. Most compounds dissolves in it.
2. It is volatile (b. p.: 61 °C), and therefore easy to get rid of from the precious compound of the sample.
3. It is non-reactive.
4. It does not exchange its deuterium with protons in the molecule being studied.

Internal Standards

- Each different proton in a molecule is in a slightly different chemical environment, and consequently has a slightly different amount of electronic shielding, which results in a slightly different resonance frequency. These differences in resonance frequency are very small.
- In a magnetic field strength of 1.4 T (60 MHz), the resonant frequencies for different protons (as many it can have) present in a compound differ only by 600 Hz. Thus, the resonant frequencies of different protons lie in the range 60000000-60000600 Hz in a magnetic field strength of 1.4 T.
- Therefore, it is extremely difficult to measure exact resonant frequencies of different protons in a molecule to a high precision. Hence, no attempt is made to measure the exact resonance frequency of any proton.
- Instead, a reference compound, called an internal standard, is placed in the solution of the substance to be measured, and the resonance frequency of each proton in the sample is measured relative to the resonance frequency of the protons of the reference substance. In other words, the frequency *difference* is measured directly under similar condition.

Common Internal Standards

- The standard reference substance that is used universally is tetramethylsilane [TMS, 12]. All the twelve protons of TMS are more shielded than those of most organic compounds. TMS, thus mark one end of the range. So, when another compound is measured, the resonances of its protons are reported in terms of how far (in Hertz) they are shifted from those of TMS.
- Since TMS is insoluble in deuterium oxide, it cannot be used with this solvent.



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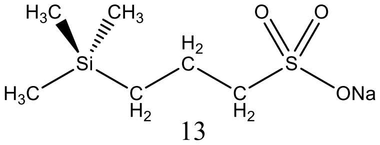
TMS



13

DSS

- A suitable reference for aqueous solutions appears to be the methyl groups of sodium 2,2-dimethyl-2-silapentane-5-sulphonate (DSS, 13). This standard has the disadvantage that it is non-volatile and has absorptions other than CH_3-Si (4 signals in total).

TMS as Internal Standard

- TMS is generally used as internal standard for measuring the position of ^{1}H, ^{13}C, and ^{29}Si in NMR spectroscopy. It is due to the following facts:

1. It is chemically inert and does not take part in any intermolecular associations with the sample.
2. It is magnetically isotropic.
3. It is highly volatile (b.p.: 27 °C) - so that the precious sample can be recovered very easily.
4. It is miscible with most organic solvents generally used.
5. It gives a single sharp absorption line. All its twelve protons in it are chemically and magnetically equivalent.
6. It resonates at the highest field compared to most organic protons.

The Position of Signals: Chemical Shift

The number of signals in an ^{1}H-NMR spectrum indicates the number of sets of equivalent protons in a molecule. The positions of the signals in the spectrum help to understand the nature of protons, *viz.*, aromatic, aliphatic, acetylenic, adjacent to some electron attracting or electron releasing group, etc. Each of these types of protons will have different chemical environments, and thus, they absorb at slightly different applied field strengths.

When a molecule is placed in a uniform external magnetic field, its electrons are induced to circulate, and thus, they produce a secondary magnetic field, i.e., induced magnetic field. Circulation of electrons about the proton itself generates a field which opposes the applied field. Thus, the field felt by the proton, is diminished and the proton is said to be shielded by the electron cloud.

Circulation of electrons (especially π-electrons) about the nearby nuclei generates a field that can either oppose or reinforce the applied field at that proton. If the induced field opposes the applied field, then the proton is said to be shielded. But if the induced field reinforces the applied field, the proton feels higher field strength, and thus, such a proton is said to be deshielded. Shielding shifts the absorption upfield and deshielding shifts the absorption downfield to get effective field strength necessary for absorption.

Such shifts (compared with the standard reference) in the positions of NMR absorptions which arise due to the shielding or deshielding of protons by the electrons are called chemical shifts. For measuring chemical shifts (δ) of various protons in a molecule, the signal for tetramethylsilane (TMS) is taken as a reference and chemical shifts for different kinds of protons are measured relative to it. Due to the low electronegativity of silicon, the shielding of equivalent protons in TMS is greater than most of the organic compounds.

NMR signal is usually plotted with magnetic field strength increasing to the right. Thus, the signal for TMS (highly shielded) appears at the extreme right of spectrum with δ=0 ppm. Greater the deshielding of protons, larger will be the value of δ. Deuterated solvents was supplied with a small amount (~ 0.1%) of TMS as an internal standard for calibrating the chemical shifts of each analyte proton.

Chemical Shifts

The separation of the absorption lines of protons from that of the standard reference compound whose resonance frequency is arbitrarily taken as zero is called chemical shift.

Chemical shift positions are normally expressed in δ (delta) units, which are defined as proportional differences, in parts per million (ppm), from an appropriate reference standard (Figure 6). The most widely used reference compound is tetramethylsilane (TMS). Protons with the same chemical shift are called equivalent protons. Nonequivalent protons have different chemical shifts.

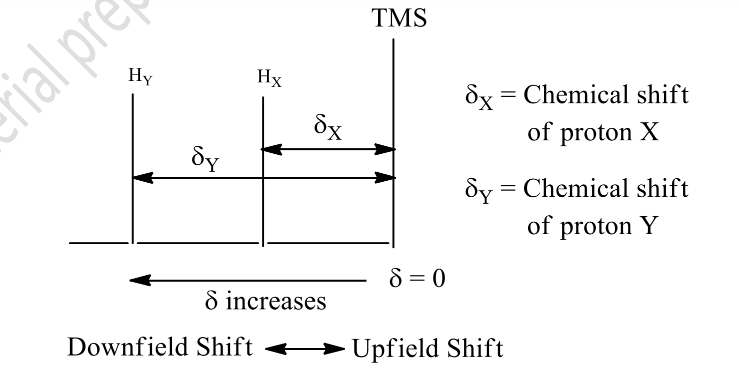


Figure 6

Units of Chemical Shifts

1. Cycles per second (cps)
2. Parts per million (ppm) (most commonly used)
3. τ (Tau) (= 10 – δ)

For TMS, $\delta = 0$, $\tau = 10$. Most chemical shifts have δ values between 0 and 10. In the τ scale, signal for the reference TMS is taken as 10 ppm.

Since the δ unit is proportionality, it is a dimensionless number. It is independent of the field strength and operating frequency of the instrument, so that a signal with a δ value of, say, 4.6 derived from a 60 MHz spectrum (1.4 T instrument) will be found exactly the same value, δ 4.6, on a 100 MHz (2.35 T instrument) or on a 600 MHz (14.1 T) instrument. The greater the δ value of a proton the lower be the field at which the proton resonates and vice-versa.

Calculation of Chemical Shifts

$$\boxed{\delta_x = \frac{\nu_x - \nu_{TMS}}{\nu_0 \text{ (in MHz)}} = \frac{\triangle\nu \text{ (in Hz)}}{\nu_0 \text{ (in MHz)}}}$$

- δ_x : Chemical shift of the proton x
- ν_x and ν_{TMS}: The resonant frequencies (in Hz) of the signals for x and TMS
- ν_0: The operating (oscillator) frequency in MHz.

If the observed shift from TMS is 250 Hz, and the operating frequency of the instrument is 100 MHz, then the chemical shift of that proton in terms of δ will be 2.5 ppm. Chemical shift is, thus, the resonant frequency of a nucleus relative to a standard in a magnetic field.

Problems on Chemical Shift

1. The OH signal of a compound appears at 144 Hz higher frequency than TMS in the ^{1}H-NMR spectrum at 60 MHz. How many δ units (ppm) does this correspond to?
2. The signal for the CH_2 protons in the proton NMR spectrum of benzyl alcohol appears at δ 4.6. Calculate the difference in frequency, expressed in hertz, between this and the TMS signal in a 300 MHz NMR spectrum.
3. How many hertz does 1 ppm (one unit on the scale) correspond to on instrument recording proton spectra at (a) 100 MHz, (b) 250 MHz, (c) 500 MHz?