Nuclear Magnetic Resonance Spectroscopy 10

Abstract

Nuclear magnetic resonance (NMR) spectroscopy is usually combined with infrared (IR) spectroscopy for the complete analysis of the structure of an unknown molecule. IR spectroscopy is used to detect a functional group in the sample, whereas NMR spectroscopy detects number of atoms and their type in sample. NMR technique can detect many nuclei but mostly identifies carbon-hydrogen frameworks. In this chapter, we have comprehensively discussed the NMR spectroscopy, its types, basic mechanism along with its instrumentation, applications, advantages, and disadvantages.

Keywords

Nuclear shielding · NMR spectra · Components of NMR spectroscopy · Types of NMR spectra

10.1 Introduction

NMR spectroscopy also known as magnetic resonance spectroscopy (MRS) is the most powerful analytical technique among all spectroscopic techniques. It visualizes single atom and molecule in various media, both in solution state and solid state. NMR is a nondestructive technique and it gives molar response that can be used for structure elucidation and quantification. Magnetic interactions which occur between the active nuclei and NMR along with covalent bonds result into spin–spin coupling. We can detect the space interactions by using the effect of nuclear Overhauser enhancement (NOE). These interactions are used for the elucidation of three-dimensional structure. However, 1-dimensional and 2-dimensional NMR data can also be collected. The 1-D NMR experiments are ^{1}H, ^{13}C, ^{19}F, and ^{31}P. The 1-D NMR techniques are used to study the chemical shift, spin–spin coupling, and

The original version of this chapter was revised: Section 10.12 has been updated. The correction to this chapter can be found at https://doi.org/10.1007/978-981-15-1547-7_20

M. S. H. Akash, K. Rehman, *Essentials of Pharmaceutical Analysis*,
https://doi.org/10.1007/978-981-15-1547-7_10

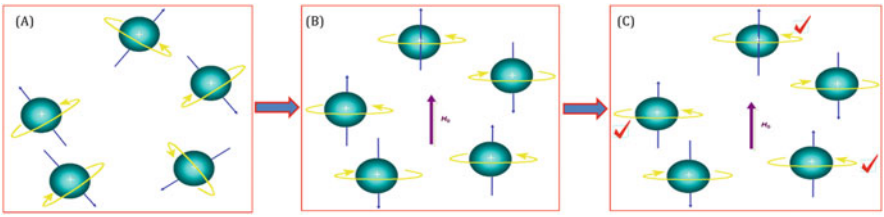

Fig. 10.1 Schematic representation of distribution of nuclear spins

intensities. Information regarding protons and its environment can be obtained with the help of chemical shift. Nuclei closer to each other exert an effect on other's effective magnetic field. This effect is shown in NMR spectrum when the nuclei are non-equivalent. If the distance between the non-equivalent nuclei is less than or equal to three bond lengths then this effect can be observed, the effect is called indirect spin–spin coupling. Radio waves are the energy source in NMR that has longer wavelengths, and hence has lesser energy and frequency. When low-energy radio waves interact with any molecule, then they change the nuclear spins of some elements, including ^{1}H and ^{13}C. The nuclear spins distribution is mostly random if there is no external magnetic field (Fig. 10.1a). But when an external magnetic field is applied then it aligns the nuclear magnetic moments with the applied field either in parallel or anti-parallel manner (Fig. 10.1b). If parallel alignment happens then nuclear magnetic moments will be slightly more (Fig. 10.1c).

Resonance: It is the process of amplification which occurs when the frequency of the applied force shows harmony with the system's natural frequency. It is related to the alteration in nuclear spin of systems from lower energy state to a higher energy state by the process of energy absorption. This can be done by the creating a magnetic field around the nuclei.

Spin: it is a number which is associated with the quantum mechanical property of nuclei. Its value must be an integer if mass number is even or half integer if mass number is odd.

Spin-lattice relaxation: Lattice is a term used for the nuclei which is held in the framework, whereas lattice field is generated when a magnetic field is created by vibration of sample nuclei. Magnetic field which shows equilibrium with the ground state energy field is known as spin-lattice relaxation.

Spin–spin relaxation: It is simply the interaction between the neighboring nuclei having same frequencies but having different magnetic quantum. In this state, the nuclei can exchange their quantum state with the nucleus which is excited in the lower energy state and with the excited nucleus which is relaxed to lower energy state.

Spin–spin coupling: It is the effect of spin state of one nucleus on the energy of another nucleus which is responsible for peak splitting. This effect is transmitted by intervening bonding electrons. Because of this effect, lines of NMR spectra are split.

Nuclear Overhauser enhancement (NOE): When spectrum of proton-decoupled ^{13}C is obtained then intensity of resonance of some carbon atoms is increased significantly than those observed in proton-coupled experiment. Carbon atoms which are attached directly to the hydrogen atoms are enhanced the most and

when more hydrogen atoms are attached (via saturation) this enhancement is increased. This effect is known as nuclear Overhauser effect and the degree of enhancement in the signal is called NOE.

Nuclear Shielding: The applied magnetic field is not equal to the magnetic field around the nucleus because the electrons present around the nucleus shield it from the applied field. The difference of both these magnetic fields is known as nuclear shielding whereas

$$\text{Chemical shift} = \text{nuclear shielding}/\text{applied magnetic field}$$

10.2 Types of Nuclear Shielding

1. *Local shielding*: it is the field created by local electrons on that nucleus.
2. *Low range shielding*: it is a field which I created by π-electrons that are not associated with the nucleus.

10.3 Intensities of Resonance Signals

These are of two types which are as follows:

10.3.1 ^{1}H NMR Signal Intensities

^{1}H-NMR is used to detect the type and number of H atoms in a molecule. The intensity or integral of a signal in the spectrum is thought to be the area under that signal. The ratios of protons present in a molecule of the compound can be determined with the comparison of signal intensities in the spectrum. If spectrum shows multiple readings then whole group of peaks should be integrated separately. The signal intensity is an important parameter to determine the structure of molecule and for quantitative analysis of molecule.

10.3.2 ^{13}C NMR Signal Intensities

^{13}C-NMR is used to detect the type of carbon atoms in the molecule (Fig. 10.2). ^{13}C-NMR signal is valuable in determining the total number of C-atoms responsible for the signal. Practically, low abundance and less sensitivity of the ^{13}C isotope will have an effect on the quantification of number of carbon atoms in the molecule. Therefore, the signals of carbon are usually not integrated in the spectrum of ^{13}C NMR. The quantification of ^{13}C signal can be made possible

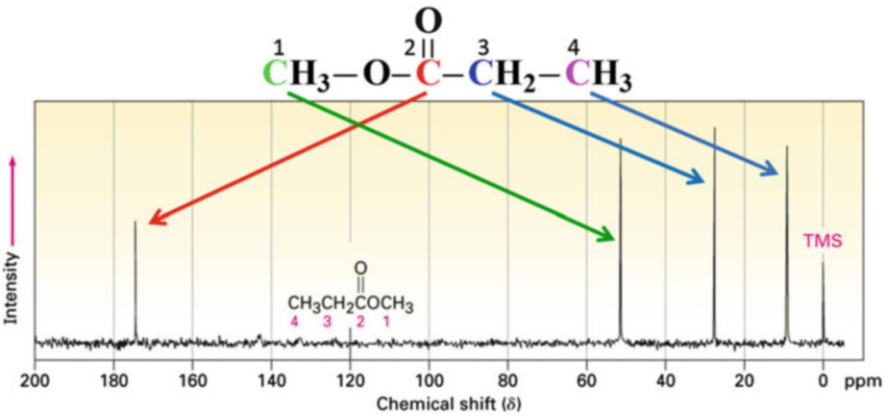

Fig. 10.2 A schematic representation of ^{13}C spectrum of methyl propionate obtained from NMR

with suppression of the NOE, high digital resolution, rate of pulse repetition which should not be too fast, high pulse power, and small spectral width.

10.4 One-Dimensional NMR Spectroscopy

The spectrum of 1D NMR spectroscopy has 2 dimensions, x-axis which is the frequency axis and y-axis which corresponds the signal intensities.

10.5 Two-Dimensional NMR Spectroscopy

In the spectrum of 2D NMR both x-axis and y-axis represent frequency and intensity is shown on the z-axis. In the spectrum of 2D J- resolved NMR, the chemical shifts are present along x-axis and coupling constants are plotted along y-axis. If both of the axes correspond to chemical shifts, then it is known as 2D (shift) correlated NMR spectrum. The correlations can be homo nuclear (^1H–^1H) or it can be hetero nuclear ($^1H/^{13}C$).

10.6 NMR Spectra

It is actually a graph between the intensity of peak and its chemical shift which is measured in ppm.

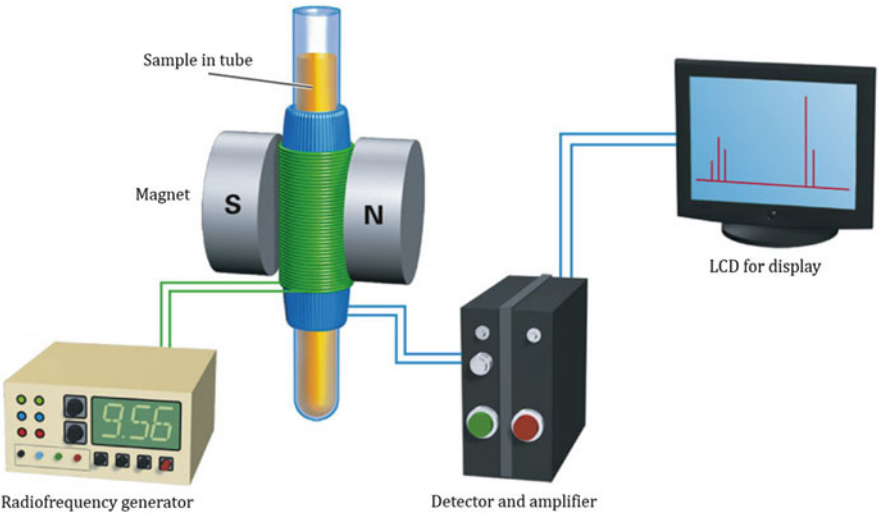

Fig. 10.3 Schematic representation of components of NMR spectrophotometer

10.7 Components of NMR Spectroscopy

General representation of basic components of NMR spectrophotometer has been illustrated in Fig. 10.3 and the detail description of individual component of NMR has been discussed in the following sub-sections.

10.7.1 The Magnet

In the absence of magnetic field, all nuclear spin states are well populated and therefore there is no net polarization. Therefore, an external magnetic field is applied to achieve a preferential population of nuclear energy spin states. A higher magnetic field leads to greater separation of energy levels and greater polarization at equilibrium. The magnet may be a powerful permanent magnet or a cryogenically cooled superconducting electromagnet. Both of these magnets align the nuclear spin in the sample.

10.7.2 A Radiofrequency Oscillator

It consists of radiofrequency synthesizers and amplifiers. They generate a pulse sequence containing radiofrequency pulses of specific frequency, phase, amplitude, shape, and time duration. Multiple radiofrequency oscillators are required as some

NMR experiments need simultaneous application of radiofrequency pulses having different frequencies.

10.7.3 The Sample Holder

It is used to load the sample under analysis. Mostly a glass tube is employed for the holding of both liquid and solid sample.

10.7.4 A Radiofrequency Receiver

It consisted of some components that are preamplifier, amplifier, mixer, and a converter which converts analog into digital.

10.7.5 A Recorder

A computer is used to display the results on its screen and record the data.

10.8 Solvents Used in NMR Spectra

The solvents should be:

- Chemically inert.
- Show magnetic isotropy.
- Must be volatile.
- And hydrogen atoms should be absent.

Most commonly used solvents are cadmium chloride, carbon tetrachloride, deuterium oxide, carbon disulfide, and hexa deuteriobenzene.

10.9 How to Interpret NMR Spectra

Before the interpretation of NMR spectra, it is very important to understand the role of chemical shift and reference peak during the interpretation of NMR spectra. Role of chemical shift and reference peak has been briefly elaborated in Fig. 10.4a. Similarly, how the chemical shift is moved across the NMR spectra, has been described in Fig. 10.4b.

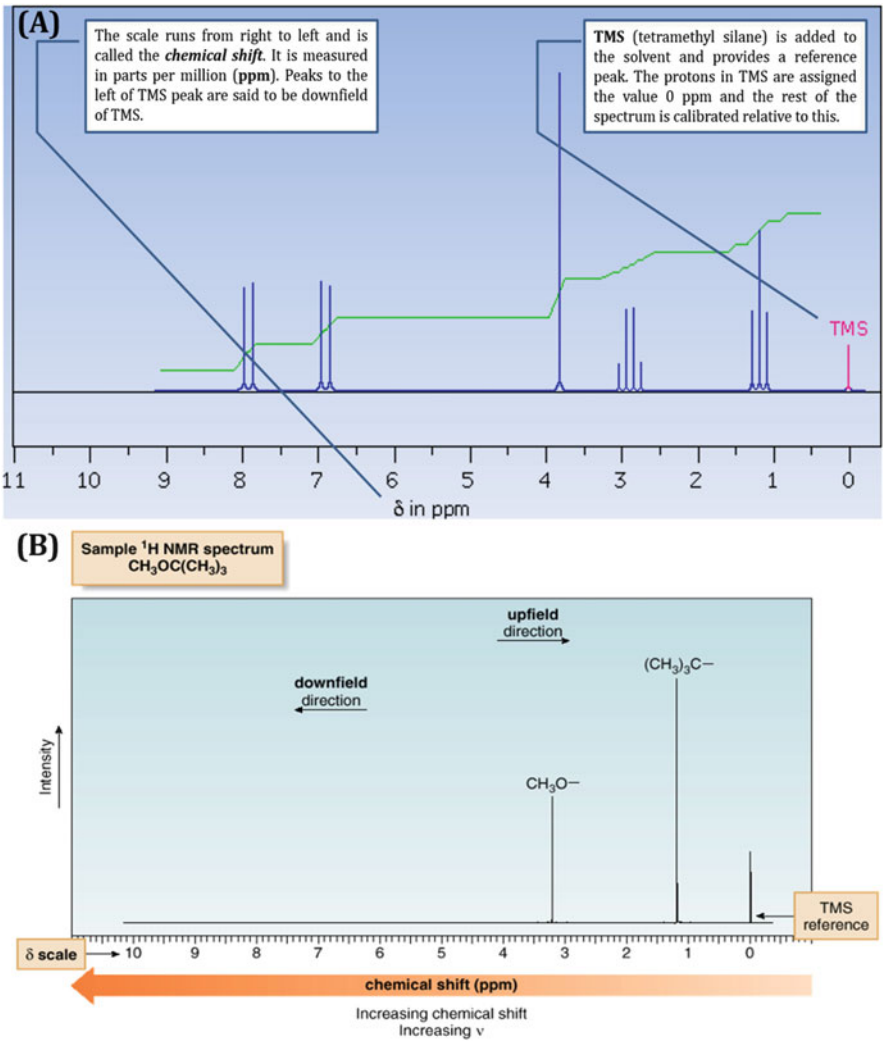

Fig. 10.4 The schematic representation of interpretation of NMR spectra

10.10 Types of NMR Spectra

There are many types of NMR spectra (Fig. 10.5) that depend on many factors including (a) type of the instrument being used, (b) nucleus and its type that is involved, (c) physical state of the analyte, (d) environment around the sample nucleus, and (e) object of data collection. Commonly, NMR spectra are of two types.

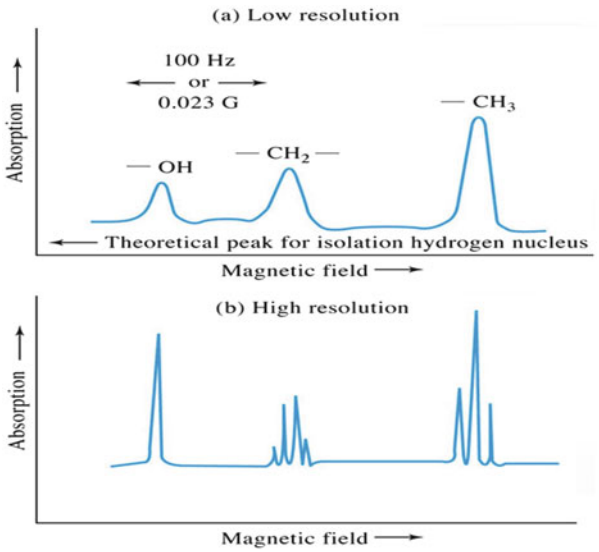

Fig. 10.5 Schematic representation of types of NMR spectra

10.10.1 Wide-Line Spectra

This is the spectra in which the bandwidths between lines are so large that we can elucidate the fine structure of the analyte because of chemical environment. Each species shows its own single peak.

10.10.2 High-Resolution Spectra

Most NMR spectrums have a high resolution and they are collected through instruments which differentiate very small frequency differences that can be of 0.01 ppm or less. For example, in the lower-resolution spectrum of ethanol, 3 peaks can be seen which formed due to the absorption by the protons of CH_3, CH_2, and OH, whereas in the higher resolution spectrum, 2 out of 3 peaks are resolved into the additional peaks.

10.11 Advantages

1. High resolution.
2. High flexibility.
3. Non-destructive method.
4. Analytically tractable.
5. Highly predictable for small molecules.

10.12 Disadvantages

1. Highly expensive.
2. Not able to differentiate the same compounds.
3. Time consuming.

10.13 Applications

1. In the field of natural product chemistry, NMR can be used for the structural and chemical elucidation of isolated compounds.
2. In the field of synthetic and organic chemistry, it can be used as an analytical tool of choice by synthetic and organic chemists.
3. It can be used for the determination of study of dynamic processes like reaction kinetics and study of equilibrium.
4. It is also used for 3-dimensional studies of proteins, protein-ligand complexes, polysaccharides, DNA < RNA and protein-DNA complexes.
5. In the field of drug design, it is also used for the determination of structure activity relationship.
6. In the field of medicine, it is also used for the detection of tumors, amino acids, proteins. RNAs and DNAs. It is also used in metabolic fingerprints from biological fluids.
7. It can also be used for the purity determination of any compound provided that molecular weight of structure of that compound is known.
8. It can also be used for diagnostic purposes, e.g., to determine the metabolic products in body fluids.
9. It is widely used for the study liposomes.
10. This technique allows easy and non-destructive of many components involved in biodiesel standardization, e.g., water, phosphorus, alcohol, and glycerol content.
11. In the field of food sciences, this technique is used to analyze moisture content, solid fat content, etc.

Further Reading

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