Chapter 13 – Nuclear Magnetic Resonance Spectroscopy

Introduction

NMR spectroscopy is a close relative of MRI.[1] It is also the single most important tool for determining the structure of organic molecules. Other kinds of spectroscopy (IR, MS, UV-vis) and physical measurements (mp, bp, etc.) should never be overlooked, but no other measurement is likely to provide the wealth of information that is available in a simple NMR spectrum: molecular symmetry, chemical environments of individual atoms (usually hydrogens and carbons), molecular connectivity and stereochemistry.

A large number of NMR "experiments" have been developed, but this unit covers only the two simplest and most widely used versions: the one-dimensional (or 1-D) ^{1}H NMR experiment and the 1-D proton-decoupled ^{13}C NMR experiment. The physics underlying NMR spectroscopy does not need to be understood in any depth, but try not to live with gross misunderstandings since these can be counterproductive. Mainly focus on learning how to use NMR spectral *data* as a tool for determining molecular structure.

Checklist

Although it is possible, in principle, to analyze ^{1}H and ^{13}C NMR spectra in exactly the same way, this is not routinely done. The checklist guides you through these distinctions by using "**[^{1}H only]**" to identify tasks that are specific to ^{1}H NMR. When you have finished studying Chapter 13, you should be able to:

Data Extraction (Spectrum → Data)

1. Extract all useful data from relatively simple ^{1}H and ^{13}C NMR spectra by
   a. Stating each pattern's chemical shift
   b. **[^{1}H only]** Stating each pattern's peak area (relative to other patterns)
   c. **[^{1}H only]** Labeling each coupling pattern as singlet, doublet, etc.
   d. **[^{1}H only]** Obtaining coupling constants (J values) from a coupling pattern

Data Prediction (Structure → Data)

2. Starting with a structural formula, predict ^{1}H and ^{13}C NMR parameters for relatively simple compounds by
   a. Identifying chemically equivalent and chemically distinct protons or carbons
      i) Homotopic nuclei are always chemically equivalent
      ii) Enantiotopic nuclei are chemical equivalent in an achiral medium (the usual scenario)
      iii) Diastereotopic nuclei are not chemically equivalent
   b. Using standard chemical shift charts to predict chemical shifts of protons and carbons
      i) **[^{1}H only]** alkane, alkene, alkyne, benzene, formyl, and carboxylic acid protons
      ii) **[^{13}C only]** alkane, alkene, alkyne, benzene, carbonyl carbons
      iii) Take into account the effects of α and β substituents on chemical shifts
   c. **[^{1}H only]** Identifying protons whose chemical shifts are affected by hydrogen bonding or rapid exchange
   d. **[^{1}H only]** Predicting relative peak areas for each group of chemically distinct protons
   e. **[^{1}H only]** Identifying protons that are likely to produce significant and observable spin-spin coupling
   f. **[^{1}H only]** Using standard coupling constant charts to predict the magnitude of these coupling constants

Spectrum Assignment (Data + Structure → Interpretation)

3. Given a compound's molecular structure, analyze its ^{1}H and ^{13}C NMR spectra by
   a. Assigning patterns to specific protons or carbons
   b. **[^{1}H only]** Assigning couplings to specific protons
   c. **[^{1}H only]** Identifying signals that are affected by hydrogen bonding or exchange
   d. Identifying signals due to impurities

[1] MR = Magnetic Resonance in both acronyms. An NMR spectroscopist once told me that doctors had to change the N (nuclear) in NMR to the I (imaging) in MRI because patients were deathly afraid of any technique labeled 'nuclear'.

Top 10 Problems for Chapter 13

All of these problems are drawn from the *Additional Problems* located at the end of the chapter 13.

The top 10 problems for chapter 13 are 39, 40, 42, 44, 49, 50,[2] 51, 54, 55, 60.

Supplement

Resources

Some NMR & IR charts can be found in the appendix of the online lab manual. Your lab text, Padias, is another good source of information and charts. In addition, three different spectroscopy books have been placed on reserve in the library and multiple copies of each are available:

1. T.N. Sorrell, "Interpreting spectra of organic molecules"
2. R.M. Silverstein et al., "Spectrometric identification of organic compounds"
3. E. Pretsch et al., "Tables of spectral data for spectrometric identification of organic compounds"

All of these books contain detailed tables and charts that are significantly more comprehensive than the tables in your textbook and the Chem 201/202 lab manual.

If you would like to *look* at more NMR spectral data, go to the online Sigma-Aldrich catalog. Many of the compounds listed there also have NMR spectra as freely available PDF files.

[2] We haven't covered mass spectroscopy yet. The mass spectral data in this problem tell you a) one atom in this molecule naturally exists as two isotopes, b) these isotopes differ in mass by 2 amu and they are equally abundant, c) the molecular mass of the molecule is 150 and 152 when the molecule contains the lighter or heavier isotope, respectively.

Data Extraction (Spectrum → Data)

1. Extract all useful data from relatively simple ^{1}H and ^{13}C NMR spectra

What we mean by all useful data depends on the nucleus. For a ^{1}H NMR spectrum, these data include chemical shifts (δ) + peak areas + coupling patterns + coupling constants (J). For a ^{13}C (decoupled) spectrum, useful data are mainly limited to chemical shifts.

It is tempting to focus on a single type of information, e.g., coupling patterns, and use only that information to arrive at an answer. Resist that temptation. A structure must be consistent with all of your NMR data.

To encourage you to look at all data, we recommend constructing a table like the one below for each spectrum. If you make this a habit, and carefully complete each row, you will be less likely to overlook important information.

δ (ppm)	#H	coupling (J in Hz)	Assignment
1.3	3	t (7.1)	CH_3
3.7	2	qd (7.1, 5.1)	CH_2
5.1	1	broad t (5.1)	OH

(based on spectrum in Figure 13.17A)

a. Stating each pattern's chemical shift

Measure the shift at the center of a coupling pattern.

b. Stating each pattern's peak area (relative to other patterns)

Peak areas are proportional to the number of protons responsible for making these signals. A CH_3CH_2 group creates two groups of signals and the relative areas of these signals are 3H:2H.

There are three ways to extract relative peak areas from an NMR spectrum:

- ✓ Some spectra list "#H" above each pattern. This means someone has already done the arithmetic for you. Use the "#H" values as *relative* peak areas.
- ✓ Some spectra show traditional "rising line" integrals. In this case, measure the "rise" over each

pattern and take this as proportional to the pattern's relative peak area.[3]

- ✓ Sometimes (but only sometimes) you can estimate relative peak areas from relative peak heights. This only works if the peak patterns are simple and all of the peaks in each pattern have the same width. (To get the "peak height" for a multi-peak pattern, add the heights of the peaks together.)

c. Labeling each coupling pattern as a singlet (s), doublet (d), etc.

A pattern containing only one peak is a *singlet*. A pattern created by a single type of spin-spin coupling will be a *doublet*, *triplet*, *quartet*, etc.. A pattern created by two independent and simultaneous spin-spin couplings will be a *doublet of doublets (dd)*, *triplet of doublets (td)*, and so on. Uninterpretable patterns are *multiplets (m).* **Note:** the learning activities we used in lab, L3 and L4, both define multiplet incorrectly as a pattern containing five or more peaks.

d. Obtain coupling constants (J values) from a coupling pattern

See Loudon, figures 13.10 for visual definitions of J. You must compare the positions of different peaks (in Hz) in a coupling pattern to get J. Any pattern larger than a doublet can yield several estimates of J depending on which peaks you select for your measurement. A triplet, for example, can yield two J values (figure 9.16). Although these values should be identical, experimental imprecision may lead to slight differences in which case you should report the average value.

If your spectrum displays peak positions in ppm instead of Hz, you can still calculate J in Hz as follows:

$$J\ (\text{Hz}) = J\ (\text{ppm}) \times \text{Spectrum Frequency (MHz)}$$

For example, suppose you are inspecting a doublet and the two peaks are separated by 0.02 ppm. If the spectrum frequency is 400 MHz, the coupling constant in Hz is obtained by multiplying $0.02 \times 400 = 8$ Hz.

[3] See NMR spectra in "Interpreting Spectra of Organic Molecules", T.N. Sorrell, p. 75 (Chem 201/202 Reserve). This book also contains several good problems.

Data Prediction (Structure → Data)

2. Predict ^{1}H and ^{13}C NMR parameters for relatively simple compounds by

Step 1 – Determine the number of *chemically unique* groups of protons (or carbons) in your structure (and note any protons that will be affected by hydrogen bonding)

Step 2 – Use a chemical shift chart, e.g. Loudon Table 13.1 and Figure 13.4, (p. 587-8) to estimate chemical shifts (remember that reliable predictions are difficult when a proton is affected by hydrogen bonding, see Loudon, 13.7D)

Step 3 – [^{1}H NMR only] Count the number of protons in each group (this is the "relative peak area")

Step 4 – Look for opportunities for spin-spin-coupling. Where these exist, predict the shape of the pattern and use a coupling constant chart, like the one at the end of this Supplement, to estimate coupling constants (J values).

[^{13}C NMR only] A decoupled ^{13}C NMR spectrum will not show coupling, but it is helpful to note how many protons are attached to each carbon because this information might be obtained from a coupled spectrum or a DEPT spectrum, and therefore might be available to you.

Spectrum Assignment (Data + Structure → Interpretation)

3. Given a compound's molecular structure, analyze its ^{1}H and ^{13}C NMR spectra by

c. Identifying signals that are affected by hydrogen bonding or exchange

Exchange refers to any process that moves a proton or carbon between two different chemical environments. When exchange is rapid, NMR spectra report only the *average* properties of these nuclei.

For example, Loudon Figure 13.19, shows the NMR spectrum of cyclohexane-d_{11} at several temperatures. Although at any given instant, the proton is either in an axial or equatorial position, its lifetime in that position may affect the spectrum's appearance. If the lifetimes are long (slow exchange), two separate signals are observed. If the

lifetimes are short (rapid exchange), only one peak is observed.

OH protons in ROH and RCO_2H also tend to exchange rapidly between molecules (see Loudon, 13.7D and 13.8). This exchange destroys spin-spin coupling, so these H generate *singlets* (the *singlets* may be narrow or broad depending on the rate of exchange). The signals of neighboring protons also show no evidence of spin-spin coupling with the OH protons.

d. Identifying signals due to impurities

The most important "impurities" are TMS or $(CH_3)_4Si$ (0 ppm) and $CHCl_3$ (7.2 ppm). The $CDCl_3$ used at Reed College reacts with water vapor and creates additional impurities. The most important of these is HCl (1.6 ppm).

The following coupling constant chart is adapted from one of the Chem 201/202 reserve books, "Interpreting Spectra of Organic Molecules" by Thomas N. Sorrell, University Science Books, Mill Valley, California, 1988, page 69.

Typical Spin-Spin Coupling Constants (J)

range (typical value) (in Hz)