Chapter 14.

Physical Basis of NMR Spectroscopy.

Today the most widely used method for determining the structure of organic compounds is nuclear magnetic resonance (NMR) spectroscopy. NMR spectroscopy involves putting a compound into a magnetic field and measuring the absorption of radio waves by the ^1H, ^{13}C, ^{19}F, ^{31}P, or other nuclei. Each nucleus in a different environment absorbs radio waves of a different energy.

For example, if one looks at the ^1H NMR spectrum for a compound like $(CH_3)_3C–CH_2–OH$, one sees one absorption for the OH ^1H, one for the CH_2 ^1H's, and one for the $C(CH_3)_3$ ^1H's. The ^{13}C NMR spectrum shows one absorption for each C atom in the compound. The NMR spectra thus give direct information about the nature of the chemical environment of each magnetically active nucleus in the molecule.

The physical basis of NMR spectroscopy is as follows.

•Like the electron, the nucleus has spin. The ^1H has a spin of 1/2, as do ^{13}C, ^{19}F, and ^{31}P, while ^{14}N and ^2H have spins of 1.

Only nuclei that contain odd mass numbers (such as ^1H, ^{13}C, ^{19}F, and ^{31}P) or odd atomic numbers (such as ^{14}N and ^2H) give rise to NMR signals because only nuclei with nuclear spin >0 can be detected by NMR spectroscopy.

•Since the nucleus has a charge and because of its "spin", nuclei act like tiny magnets. If one applies an external magnetic field B_0 to the nuclei, the tiny magnets of the nuclei align themselves with the field, some parallel and some anti-parallel. The parallel arrangement has a slightly lower energy than the anti-parallel arrangement.

•The difference in energy between the two alignments is directly proportional to the strength of the applied field. Because the two alignments are different in energy, there is a slightly higher population of nuclei in the lower energy state than in the higher energy state.

When an external energy source (radio waves) that matches the energy difference between the two states is applied, energy is absorbed, causing the nucleus to spin flip from one orientation to the other. Note that radio waves are very low energy radiation! There's not much difference in energy between the spin states (<0.1 cal), even with a very strong magnetic field.

•A nucleus is in resonance when it absorbs radiofrequency radiation and spin flips to a higher energy state.

Thus two variables characterize NMR: 1. An applied magnetic field, B_o; and 2, the frequency of the radiation used for resonance (in MHz). The frequency needed for resonance and the applied magnetic field strength are directly proportional. The stronger the applied magnetic field, the larger the energy difference between the two nuclear spin states, and the higher the frequency needed for resonance.

•Why should different ^1H nuclei in a compound absorb radio waves of different energies? Don't they experience the same external magnetic field? They do and they don't (**see p.500 and fig** 14.4.). The external magnetic field is indeed identical for all the nuclei. However, each nucleus is surrounded by electrons, which are charged, so when they experience a magnetic field, they circulate in such a way as to create an opposing magnetic field. This is called shielding. A ^1H nucleus surrounded by a large number of electrons (attached to electropositive elements) will experience a much smaller magnetic field than a ^1H nucleus surrounded by a small number of electrons (attached to electronegative elements). The ^1H attached to an electronegative element is said to be deshielded. The same is true of other nuclei.

•If we keep a magnetic field constant and vary the radio wave frequency, different nuclei will resonate at different frequencies. We can measure this resonance and plot it as a function of radio wave frequency. In practice, it's easier to keep the radio wave frequency constant and to vary the magnetic field. The most commonly used ^1H NMR spectrometers use radio waves with frequencies of 60 MHz to 500 Mhz, while the frequencies are one-fourth of this for ^{13}C NMR experiments.

We do the NMR experiment by dissolving the compound to be analyzed in a solvent that lacks any ^1H nuclei (CCl4 or a deuterated solvent like $CDCl_3$ or D_2O). The solution is placed in a tube, which is placed in a magnet. The sample is irradiated with radio waves of constant frequency as the magnetic field is slowly varied. At different magnetic field strengths, different absorbances are measured.

•When we vary the magnetic field, we only need to change its strength by a few millionths to observe all the different resonances of all the different atoms in the compound. This is why we measure the resonance of nuclei in ppm. Most ^1H nuclei resonate within a range of 10 ppm of each other. Most ^{13}C nuclei, on the other hand, resonate in a range of about 220 ppm of each other. The radio wave frequencies used for ^{13}C NMR spectroscopy are one fourth of those used for ^1H NMR spectroscopy.

•We use tetramethylsilane, or TMS, which has twelve identical ^1H nuclei, as a standard for ^1H and ^{13}C resonance. We arbitrarily define the magnetic field strength required for TMS to resonate with a given radio wave energy as 0 ppm. The resonances of other kinds of 1H's are then measured in ppm with respect to TMS (see p.495)). The resonance of a particular kind of ^1H is called its chemical shift, and it is often written as δ (delta). In the case of *neo*pentyl alcohol (2,2- dimethyl-1-propanol), three resonances are observed at about δ 3.3 1.7, and ~1.0 ppm downfield (more deshielded) of TMS. As I said, the ^1H's in most organic compounds resonate in the region 0-10 ppm, although there are exceptions to this rule.

^{13}C nuclei usually resonate in the range 0-220 ppm. (TMS was chosen as a standard because most ^1H and ^{13}C nuclei resonate downfield of the same nuclei in TMS.) When an NMR spectrum is plotted, 0 ppm is placed on the right, with increased deshielding as we move to the left. The right of the spectrum is called upfield, while the left of the spectrum is called downfield. The chemical shift values of the nuclei in a particular compound are independent of the radio wave frequency used to measure them.

Chemical shift = observed chemical shift in MHz/ frequency of spectrometer (MHz)

We can use a 60 MHz or 400 MHz instrument to measure the chemical shifts of the 1H's in ethanol, but the values are identical. The magnetic field strengths required for resonance are of course different, but the ppm change in magnetic field strength from TMS is not.

Interpreting NMR Spectra: Symmetry.

The first thing to predict is how many resonances a compound will exhibit. Just because a compound has x number of ^1H's doesn't mean that x number of resonances will be observed. Symmetry will often reduce the number of resonances. Let's look at *neo*pentyl alcohol again, $(CH_3)_3C$–CH_2–OH. We have three C atoms, each of which is a different kind — the methyl C's, the C attached to two C's (quaternary C), and the methylene C attached to one C and the OH— so we expect to see three different ^{13}C resonances. We have a total of 12 H atoms, but some of these have identical environments. The 9 H's in the three methyl groups attached to the quaternary C have the same connections and exchange their environments constantly by rapid rotation about C–C σ bonds, so they experience the same deshielding, so they resonate at the same frequency. They are said to be chemically equivalent. Likewise for the 2 H's in the methylene group. In the end we expect to see three ^1H resonances for this compound.