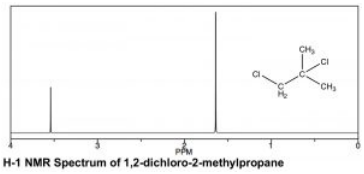
2.6: H-1 (proton) NMR

While $C-13$ NMR provides information about how many chemically distinct carbons there are in a compound, and something about their electronic environments, it does not tell us anything about how the molecules are organized or which carbons are connected together.[18] For that information, we often turn to NMR spectroscopy using the $H-1$ isotope. There are a number of advantages to $H-1$ NMR: $H-1$ is the naturally-occurring, most-abundant isotope of hydrogen, and is much more abundant than $C-13$. The result is that the concentration of $H-1$ in a sample is much greater than the concentration of $C-13$. It is therefore easier to obtain a spectrum and instruments with a lower field can be used. As we will see, $H-1$ NMR can provide information about which atoms are connected to each other. On the other hand, the resulting $H-1$ NMR spectra are more complex.



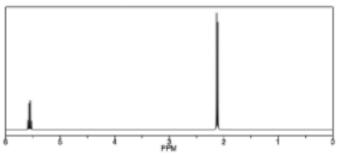
H-1 NMR Spectrum of 1,2-dichloro-2-methylpropane

The basic theory of both $H-1$ and $C-13$ NMR are the same and, in fact, both spectra can be recorded on the same instrument. The sample is placed in a magnetic field that splits the spin states of the $H-1$ nuclei; the energy required to flip the nuclei from one spin state to another is detected and is transformed into a spectrum such as the one below.

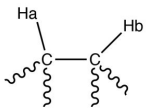
There are similarities and differences in the appearance of $H-1$ and $C-13$ NMR spectra. As can be seen in the spectrum of 1,2-dichloro-2-methylpropane (←), the scales over which the spectra are recorded are different. Both involve a chemical shift from a reference peak at 0, (TMS [tetramethylsilane] is used in both), but the shift range (often referred to as δ, as well as ppm, in proton NMR) is smaller for $H-1$ compared to $C-13$ NMR. Typically an $H-1$ NMR spectrum is recorded between $0-10\text{ppm}$ (as opposed to $0-200$ for $C-13$), although in this case it is truncated because there are no peaks between $4-10\text{ppm}$. That said, the same trends in chemical shifts are observed: the more de-shielded the atoms (in this case protons) are, the further downfield they appear. In the 1,2-dichloro-2-methylpropane spectrum above there are two peaks corresponding to the two types of chemically distinct hydrogens (that is, the two identical $-CH_3$ and the $-CH_2$ group). The peak's lowest field, around 3.6ppm can be assigned to the CH_2 (methylene) group, which is directly attached to the electron withdrawing chlorine atom, while the second peak, corresponding to the six equivalent hydrogens of the two methyl groups, is further upfield, around 1.6ppm.

In a proton NMR spectrum, the area under the peak is proportional to the number of protons that give rise to the signal. By integrating the area under the peak, we generate an estimate of the relative numbers of hydrogens giving rise to each signal. In the spectrum of 1,2-dichloro-2-methylpropane the ratio of the two peak areas is 1:3, thus supporting our assignment of the downfield peak to the CH_2 and the upfield peak to the two equivalent $-CH_3$ (six) methyl hydrogens. As a technical note, $C-13$ NMR signals are not reliably proportional to the number of equivalent carbons involved: they are dependent on the number of H's attached to them and so integration cannot provide a reliable estimate of the proportions of the types of carbon in a compound.[19]

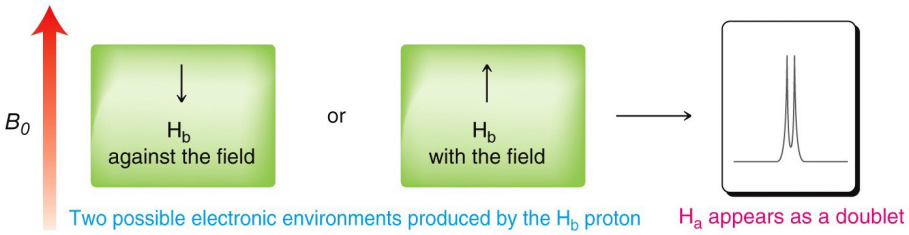
Spin-Spin Splitting



Another way that $H-1$ NMR differs from a $C-13$ NMR is shown in the spectrum of 1,1-dichloroethane →, which has two types of equivalent hydrogens. Each type gives rise to a distinct signal but each of those signals is split into multiple peaks. The upfield signal around 2ppm, from the 3 equivalent H's of the methyl group, appears as a doublet (two separate peaks) because each of the hydrogens in the methyl group is affected by the magnetic field generated by the neighboring hydrogen's possible spin state, thereby altering (adding to or subtracting from) the atoms' local field. The downfield signal around 5.5ppm is due to the single proton on $C-1$, de-shielded because of the proximity of the electronegative chlorine, but now it appears as a quartet.



For example, consider a molecule that has two non-equivalent protons (Ha and Hb) on adjacent carbons (→). Ha will experience the magnetic fields generated by Hb which has two spin states, which will produce two possible electronic environments for Ha, resulting in two signals for Ha.

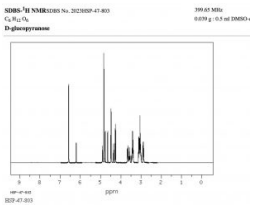


A single proton produces a doublet in the adjacent signal

The splitting effect is small and does not extend (in a significant way) beyond the protons on adjacent carbons. The local magnetic field also depends on the number of protons that do the splitting, for example if there are two protons on the adjacent carbon, the signal is split into a triplet, and for three adjacent protons the signal is a quartet. The general rule is that **for n adjacent protons, the signal is split into $n+1$ peaks.**

Three adjacent protons produce a quartet in the adjacent signal

The width, in Hz, of the splitting (that is, the distance between the split peaks) is called the coupling constant j. The value of j between the protons on adjacent carbons is the same. The number of split peaks therefore allows us to determine how many hydrogens there are on adjacent carbons, which in turn allows us to determine the how the atoms are connected together in the structure. Signals that are split by more than one kind of hydrogen can get quite messy as shown in the spectrum of D-glucopyranose (→).



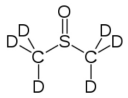
Fortunately, there are ways to simplify such spectrum by selectively irradiating particular frequencies but that is beyond the scope of this course (but something you can look forward to in the future!).

That said, this raises another question: why do $C-13$ NMR spectra appear as single lines for each carbon? Shouldn't the carbon signals also be split both by adjacent carbons, and by the hydrogens attached to them? There are two reasons that this does not happen. First, the abundance of $C-13$ is so low that the probability of finding more than one $C-13$ in a molecule is very low; in the absence of a second (or third) $C-13$, no splitting by adjacent carbon nuclei will occur, (recall $C-12$ does not generate a spin-based magnetic field). Second, when we originally introduced $C-13$ NMR spectroscopy we presented a simplified model. In fact, the carbon signals **are** split by the adjacent protons, but this leads to a complex spectrum that is often hard to interpret. Therefore, for most purposes, the sample is irradiated with a radiofrequency that promotes all the hydrogens to the higher-energy spin state. The carbon nuclei do not experience two (or more) magnetic field environments, and therefore only one signal is produced. This technique is called broadband decoupling, and these types of spectra are the most common examples of $C-13$ NMR.

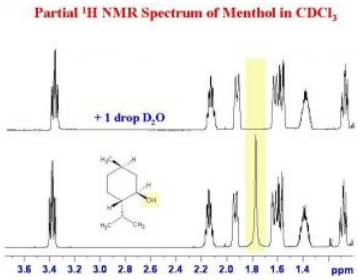
Solvents and Acidic hydrogens in the NMR

Most NMR spectra, whether $C-13$ or $H-1$, are recorded in solution (although it is possible to obtain spectra on solids—as evidenced by the fact that we can obtain MRI data on people, that say, people [biological systems] are mostly [$>70\%$] water). However, since the solvent is usually present in much greater concentration than the actual sample, as long as we use a solvent that does not generate a strong signal the effects of the solvent can be minimized; typically this involves solvents in which the

hydrogens present are replaced with deuterium (D), an isotope of hydrogen that is not NMR active. Common solvents are $CDCl_3$, (deuterated chloroform) and dimethylsulfoxide $d-6$ (DMSO) ($\rightarrow$).



Another instance in which deuterated solvents are used is to detect the presence of potentially acidic hydrogens. Proton transfer is a rapid and reversible process, and any hydrogen attached to an electronegative element is potentially available for exchange by reacting with even very weak base such as water.In fact, by adding a drop of D_2O ("heavy" water) to the NMR sample, the signal from any $O-H$ or $N-H$ disappears as the H is replaced by D.



As shown here ($\rightarrow$), the signal from the OH (shaded in yellow) disappears when the sample is shaken with D_2O.

Questions to Answer:

Type your exercises here.

- Draw a diagram of an atom and use it to explain why the electron density surrounding the nucleus affects the strength of the external field required to bring the nucleus to resonance (to flip the spin state).
- Using the table below, use your diagram from above and explain a) why the signals for $C-1$ in the three compounds are different, and b) why the signals for $C-1$ and $C-2$ are different (for any single compound).

Compound	Signal for $C-1$	Signal for $C-1(ppm)$
CH_3CH_2F	79.1	15.4
CH_3CH_2Cl	40.0	18.9
CH_3CH_2Br	27.5	19.3