Identification of functional groups

Classical methods were “wet” chemistry

An alkene decolorizes bromine

An aldehyde gives a metallic silver mirror when treated with alkaline silver nitrate

Larger molecules are cleaved into small fragments, for example, by ozonolysis, and fragments identified

Modern methods are instrumental

1. Require much less sample
2. Can detect some functional groups when several are present
3. Fast
4. More accurate
5. Easily linked to databases

Spectroscopy

Study of the interaction of energy with matter

When energy is applied to matter, it may be
1. Transmitted without change
2. Reflected without change
3. Absorbed
4. Emitted
5. Cause a chemical change

Spectroscopy is used to elucidate the structure of a molecule

Infrared (IR) Spectroscopy (Chapter 2)

Infrared energy causes bonds to stretch and bend
Useful for identifying functional groups in a molecule

Nuclear Magnetic Resonance (NMR)

Energy applied in a strong magnetic field causes absorption by the nuclei of some elements (H and C-13)
Used to identify connectivity of atoms in a molecule

Mass Spectrometry (MS)

Molecules are converted to ions
The ions formed may remain intact (M+), or they may fragment
The mixture of ions is sorted by mass/charge ratio (m/z)
Molecular weight and chemical formula may be derived from the unfragmented M+ and M+1 ions
Molecular structure may be deduced from the fragment ions
Light = travels in waves
Length of wave determines perceived color

Shorter wave length = higher frequency (more crests per second)

Basic Principle of Spectroscopy

- Energy in molecules is quantized
- Energy $E$ is absorbed only when the frequency matches the Energy Gap
- $E = hf$
- $h = Planck's$ constant (1.58 x 10^-34 cal•s)

Molecular vibrations are quantized and fall in the infrared range

Regions of Organic Spectroscopy

- X-ray – collision with atoms produces patterns that can be analyzed with computers to get molecular shapes
- UV/VIS – determines spacing of electron levels, useful for conjugated molecules
- Infrared (IR) – determined by molecular vibrations, useful for functional groups
- Radiofrequencies (NMR) – Lowest energy, observes nuclear and electron spins, useful for specific environments of nuclei

Infrared Spectroscopy- overview

An Instrumental Method for Detecting Functional Groups

- Electromagnetic radiation in the infrared range is absorbed by a molecule at certain characteristic frequencies

1. The bonds behave like tiny springs connecting the atoms
2. As energy is absorbed by the bonds, they vibrate faster
3. The bonds can absorb energy and vibrate faster only when the added energy is of a particular resonant frequency
4. The frequencies of absorption are very characteristic of the type of bonds contained in the sample molecule

Infrared Spectrometer

Detects the frequencies absorbed by the sample molecule

Light of all IR frequencies is transmitted to the molecule and certain frequencies are absorbed

The absorption frequencies are specified as wavenumbers in units of reciprocal centimeters (cm\(^{-1}\))

\[ \bar{v} = \frac{1}{\lambda} \quad (\text{with } \lambda \text{ in cm}) \]

- The spectrum is a plot of frequency on the horizontal axis versus strength of absorption on the vertical axis
- Higher wavenumbers (cm\(^{-1}\)) = more energy needed to stretch bonds
Various stretching and bending vibrations are induced by the absorption of infrared.

The actual relative frequency of vibration can be predicted.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>BOND</th>
<th>FREQUENCY RANGE (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkyl</td>
<td>C–H</td>
<td>2835–2962</td>
</tr>
<tr>
<td>Alcohol</td>
<td>O–H</td>
<td>3300–3500</td>
</tr>
<tr>
<td>Amine</td>
<td>N–H</td>
<td>3300–3500</td>
</tr>
</tbody>
</table>

Bonds with lighter atoms vibrate faster than those with heavier atoms.

Stronger bonds require more energy to stretch.

<table>
<thead>
<tr>
<th>BOND</th>
<th>FREQUENCY RANGE (CM⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C≡C</td>
<td>2100–2260</td>
</tr>
<tr>
<td>C≡N</td>
<td>2220–2260</td>
</tr>
<tr>
<td>C≡C</td>
<td>1620–1680</td>
</tr>
<tr>
<td>C≡O</td>
<td>1630–1780</td>
</tr>
</tbody>
</table>

C-C and C-O single bonds are less useful, but occur around 1000 cm⁻¹.

Two major application of IR

- Fingerprint for a molecule
  - The variety of bonds produces a mixture of vibrations and overtones which is often unique
- Specific functional groups
  - Generally only certain peaks are interpreted in the IR
  - Those peaks that are large and above 1400 cm⁻¹ are most valuable

Hydrocarbons

- The C-H stretching region is from 2800–3300 cm⁻¹
- Characteristic of the type of C-H bond
  - If C-H bond has more s character, it is shorter and stronger and vibrates at higher frequency
    - C-H bonds at sp centers appear about 3300 cm⁻¹
    - C-H bonds at sp² centers appear about 3080 cm⁻¹
    - C-H bonds at sp³ centers appear at about 2800-3000 cm⁻¹
- C-C bond stretching frequencies are only useful for multiple bonds
  - C-C double bonds give peaks at 1620-1680 cm⁻¹
  - C-C triple bonds give peaks at 2100-2260 cm⁻¹
  - These peaks are absent in symmetrical double and triple bonds
Octane

1-hexyne

**Alkenes**
- The C-H bonding vibration peaks located at 600–1000 cm\(^{-1}\) can be used to determine the substitution pattern of the double bond.

**Example: 1-hexene**

**Aromatic Compounds**
- The C-C bond stretching gives a set of characteristic sharp peaks between 1450–1600 cm\(^{-1}\).
- Substitution pattern shown between 650 and 1000 cm\(^{-1}\).

**Carbonyl groups – very characteristic frequency**
- Carbonyl group gives a strong peak which occurs at 1630–1780 cm\(^{-1}\).
- The exact location depends on the actual functional group.

**Alcohols**
- The O-H stretching absorption is very characteristic.
  - In very dilute solutions, hydrogen bonding is absent and there is a very sharp peak at 3580–3550 cm\(^{-1}\).
  - In concentrated solutions, the hydroxyl groups hydrogen bond to each other, giving a broad and large peak occurs at 3200–3550 cm\(^{-1}\).
Carboxylic Acids

The carbonyl peak at 1710-1780 cm\(^{-1}\) is very characteristic. The presence of both carbonyl and O-H stretching peaks is a good indication of the presence of a carboxylic acid.

Example: propanic acid

Amines and Amides

- Dilute solution of 1° and 2° amines give sharp peaks at 3300-3500 cm\(^{-1}\) for the N-H stretching
- 1° amines give two peaks
- 2° amines give one peak
- 3° have no N-H bonds and do not absorb in this region
- More concentrated solutions of amines have broader peaks
- Amides have amine N-H stretching peaks and a carbonyl peak

Which will have a strong absorption at 1730 cm\(^{-1}\)?

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>

Six most useful IR frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Appearance</th>
<th>Bond</th>
<th>Functional group</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;3200</td>
<td>strong, broad</td>
<td>OH</td>
<td>Alcohol, carboxylic acid</td>
</tr>
<tr>
<td>~3200</td>
<td>medium</td>
<td>N-H, sp C-H</td>
<td>Amine, amides, terminal alkyne</td>
</tr>
<tr>
<td>~3000</td>
<td>weak to medium</td>
<td>C=O</td>
<td>Alkyne</td>
</tr>
<tr>
<td>1700-2300</td>
<td>sharp</td>
<td>C=O</td>
<td>Ketone, aldehyde, acid, ester, amide</td>
</tr>
<tr>
<td>1450-1500</td>
<td>very strong, sharp</td>
<td>C=C</td>
<td>Alkene, nitrile</td>
</tr>
<tr>
<td>1300-1400</td>
<td>medium</td>
<td>C=C</td>
<td>Alkene, nitrile</td>
</tr>
</tbody>
</table>

Region of 1000-700 cm\(^{-1}\) useful to identify substitution pattern of an alkene or substituted benzene ring

Nuclear Magnetic Resonance (NMR) Spectroscopy

- The spinning nuclei of protons (\(^1\)H) and carbon-13 (\(^{13}\)C), and certain other elements and isotopes, behave as tiny bar magnets.
- When placed in a magnetic field, the energies of two spin states become separated and we can do spectroscopy.
- Spacings are tiny so absorb in radio frequency range.
- Precise frequencies depend on the chemical environments.

Continuous-Wave (CW) NMR Spectrometers

- The older type of NMR spectrometer
- The magnetic field is varied as the electromagnetic radiation is kept at a constant frequency.
- Different nuclei absorb the electromagnetic energy based on their chemical environment and produce peaks in different regions of the spectrum.
Continuous-Wave (CW) NMR Spectrometer

Scan by varying either the frequency or magnetic field

Fourier Transform (FT) NMR Spectrometers

- The sample is placed in a constant, very strong magnetic field
- The sample is irradiated with a short broad pulse of radio frequency energy that excites all nuclei at once
- The resulting signal contains information about all of the absorbing nuclei at once
- This signal is converted to a spectrum by a Fourier transformation
- FT NMR allows signal-averaging, which leads to enhancement of real spectral signals versus noise
- The strong, superconducting magnets used in FTNMR spectrometers lead to greater sensitivity and much higher resolution than continuous wave instruments

FT signal to conventional signal

Information from NMR

1. Number of signals
2. Intensity of each signal
3. Position of each signal
4. Splitting of each signal

Special effects such as long range molecular interactions or rate dependence may also be useful

Nuclear Magnetic Resonance Spectroscopy

Peak Positions in NMR Spectra – the Chemical Shift

- Nuclei in different chemical environments in a molecule will absorb at slightly different frequencies
- The position of the signals in the spectrum is called the “chemical shift”
- There are two reasons for differences in the magnetic environment for a proton
  1. The magnetic field generated by electrons circulating around the nucleus giving the signal
  2. Local magnetic fields generated by electrons elsewhere in the molecule
Information

1. Number of signals = number of unique H’s
2. Intensity of signal = proportional to the number of such H’s.

Intensity ratios: 1:1 3:2 3:2:3

The Origin of NMR Signals

- The nuclei of certain elements and isotopes have spin states that are quantized
- $^1$H has a spin quantum number $I = \frac{1}{2}$ and has allowed spin states of $+\frac{1}{2}$ or $-\frac{1}{2}$
- Other nuclei with $I = \frac{1}{2}$ are $^{13}$C, $^{19}$F and $^{31}$P and these also respond to an external magnetic field
- Nuclei with $I = 0$ do not have spin ($^{12}$C and $^{16}$O) and do not respond to an external magnetic field

How many $^1$H signals?

A. 1  B. 2  C. 3  D. 4

Same question for cyclohexene
Nuclei aligned with the magnetic field are lower in energy than those aligned against the field. The nuclei aligned with the magnetic field can be flipped to align against it if the right amount of energy is added. The amount of energy required depends on the strength of the external magnetic field. The stronger the external magnetic field, the higher the radio frequency energy required to tip the nuclear spin.

Absorption frequency depends on the total magnetic field and therefore electron density around a nucleus. High electron density around a nucleus shields the nucleus from the external magnetic field. The stronger the external magnetic field, the higher the radio frequency energy required to flip the nuclear spin.

Shielding requires a higher magnetic field to bring the nucleus into resonance - the signals are upfield in the NMR spectrum. Lower electron density around a nucleus deshields the nucleus from the external magnetic field. Deshielding causes absorption of energy at lower frequencies - the signals are downfield in the NMR spectrum.

Electron withdrawing groups (Cl, O) pull electrons away, reduce the shielding, and thus shift signals downfield. The induced field can reinforce or diminish the external field sensed by a proton (depending on the location of the proton), causing deshielding or shielding, respectively. Alkene and aromatic ring hydrogens are deshielded by the circulation of π electrons. A terminal alkyne hydrogen is shielded by the circulation of π electrons.

Circulation of π electrons leads to a local induced magnetic field. The induced field can reinforce or diminish the external field sensed by a proton (depending on the location of the proton), causing deshielding or shielding, respectively. Alkene and aromatic ring hydrogens are deshielded by the circulation of π electrons. A terminal alkyne hydrogen is shielded by the circulation of π electrons.

Chemical shifts are measured in relation to the internal reference tetramethylsilane (TMS). The protons of TMS are highly shielded, well away from other proton signals and a sharp single peak. The δ scale for chemical shifts is independent of the magnetic field strength of the instrument (whereas the absolute frequency depends on field strength).

Thus, the chemical shift in δ units for protons on benzene is the same whether a 60 MHz or 300 MHz instrument is used.
Circulation of $\pi$ electrons leads to a local induced magnetic field

- The induced field can reinforce or diminish the external field sensed by a proton (depending on the location of the proton), causing deshielding or shielding, respectively.
- Alkene and aromatic ring hydrogens are deshielded by the circulation of $\pi$ electrons.
- A terminal alkyne hydrogen is shielded by the circulation of $\pi$ electrons.

![Diagram showing circulation of $\pi$ electrons leading to induced magnetic field](image)

**Typical Range for $^1$H NMR chemical shifts**

![Diagram showing typical range for $^1$H NMR chemical shifts](image)

**Closer Look at Equivalent and Nonequivalent Protons**

- To predict the number of signals, must determine how many sets of protons are in unique environments.
- **Homotopic Hydrogens**
  - Hydrogens are chemically equivalent or homotopic if replacing each one in turn by the same group would lead to an identical compound.

![Diagram showing homotopic hydrogens](image)

**Enantiotopic Hydrogens**

- If replacement of each of two hydrogens by some group leads to enantiomers, those hydrogens are enantiotopic.
- In the absence of a chiral influence, enantiotopic hydrogens have the same chemical shift and appear in the same signal.

![Diagram showing enantiotopic hydrogens](image)

**Diastereotopic Hydrogens**

- If replacement of each of two hydrogens by some group leads to diastereomers, the hydrogens are diastereotopic.
  - Diastereotopic hydrogens have different chemical shifts and will give different signals.

![Diagram showing diastereotopic hydrogens](image)

**Signal Splitting: Spin-Spin Coupling**

- The signal from a given proton will be split by the effect of magnetic fields associated with protons on adjacent carbons.
- Characteristic peak patterns result from signal splitting that are related to the number of protons on adjacent carbons.
- The effect of signal splitting is greatest between atoms separated by 3 or fewer bonds.
- Signal splitting is not observed between homotopic or enantiotopic protons.
- Signal splitting occurs only when two sets of protons have different chemical shifts (i.e., are not chemical shift equivalent).
The magnetic field sensed by a proton (Hₐ) being observed is affected by the magnetic moment of an adjacent proton (Hₐ). When two adjacent protons Hₐ are coupled to Hₐ, there are four possible combinations of the magnetic moments for the two Hₐ.

- The general rule for splitting is that if there are n equivalent protons on adjacent atoms, these will split a signal into n + 1 peaks.
- Coupled peaks have the same coupling constants J.
- Comparison of coupling constants can help with the analysis of complex spectra.
- Several factors complicate analysis of NMR spectra.
- Splitting patterns in aromatic groups can be confusing.

Many more complex splitting can occur when two sets of adjacent protons split a particular set of protons. When three adjacent protons are coupled to Hₐ, there are 10 possible combinations of the magnetic moments for the Hₐ.

- The magnetic field sensed by a proton (Hₐ) being observed is affected by the magnetic moment of an adjacent proton (Hₐ). When two adjacent protons Hₐ are coupled to Hₐ, there are four possible combinations of the magnetic moments for the two Hₐ.

- Two of these combinations involve pairs of magnetic moments that cancel each other, causing no net displacement of signal.
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The observed proton (Hₐ) senses the two different magnetic moments of Hₐ, as a slight change in the magnetic field that one magnetic moment reinforces the external magnetic field, and the other subtracts from the applied magnetic field. The magnitude of the splitting is called the coupling constant J, and it is measured in Hertz (Hz).

The signal for Hₐ is split into a doublet with a 1:1 ratio of peak areas. The magnitude of the splitting is called the coupling constant J, and it is measured in Hertz (Hz).

The spectrum of 1-nitropropane shows splitting of Hₐ into only 6 peaks.
Proton NMR Spectra and Rate Processes
- An NMR spectrometer is like a camera with a slow shutter speed.
- The NMR spectrometer will observe rapid processes as if they were a blur, i.e., only an average of the changes will be seen.
- When a $^1H$ NMR spectrum of very pure ethanol is taken, the hydroxyl proton is split into a triplet by the two adjacent hydrogens.
- When an $^1H$ NMR of regular ethanol is taken, the hydroxyl proton is a singlet.

Impure ethanol contains acid and base impurities which catalyze the exchange of hydroxyl protons.
- This rapid exchange is so fast that coupling to the adjacent CH$_2$ is not observed.
- This process is called spin decoupling.

Spin decoupling is typical in the $^1H$ NMR spectra of alcohols, amines and carboxylic acids.
- The proton attached to the oxygen or nitrogen normally appears as a singlet because of rapid exchange processes.

Carbon-13 NMR Spectroscopy
- $^{13}C$ is only 1.1% of naturally occurring carbon.
- $^{13}C$ has no magnetic spin and produces no NMR signal.

One Peak for Each Unique Carbon Atom
- Since the $^{13}C$ isotope of carbon is present in only 1.1% natural abundance, there is only a 1 in 10,000 chance that two $^{13}C$ atoms will occur next to each other in a molecule.
- The low probability of adjacent $^{13}C$ atoms leads to no detectable carbon-carbon splitting.
- $^1H$ and $^{13}C$ do split each other, but this splitting is usually eliminated by adjusting the NMR spectrophotometer accordingly.
- The process of removing the coupling of $^1H$ to an attached carbon is called broadband (BB) proton decoupling.
- Most $^{13}C$ NMR, therefore, consist of a single peak for each unique carbon.

Off-Resonance Decoupled Spectra
- Broad-band decoupling removes all information about the number of hydrogens attached to each carbon.
- Off-resonance decoupling removes some of the coupling of carbons to hydrogens so that the coupled peaks will not overlap.
- Use of off-resonance decoupled spectra has been replaced by use of DEPT $^{13}C$ NMR.

DEPT $^{13}C$ NMR
- DEPT (distortionless enhanced polarization transfer) spectra are created by mathematically combining several individual spectra taken under special conditions.
- The final DEPT spectra explicitly show C, CH, CH$_2$, and CH$_3$ carbons.
- To simplify the presentation of DEPT data, the broadband decoupled spectrum is annotated with the results of the DEPT experiments using the labels C, CH, CH$_2$, and CH$_3$ above the appropriate peaks.

Example: 1-chloro-2-propanol
- (a) The broadband decoupled spectrum and (b) a set of DEPT spectra showing the separate CH, CH$_2$, and CH$_3$ signals.

$^{13}C$ Chemical Shifts
- Just as in $^1H$ NMR spectroscopy, chemical shifts in $^{13}C$ NMR depend on the electron density around the carbon nucleus.
- Decreased electron density causes the signal to move downfield (shielding).
- Increased electron density causes the signal to move upfield (deshielding).
- Because of the wide range of chemical shifts, it is rare to have two $^{13}C$ peaks coincidentally overlap.
- A group of 3 peaks at δ 77 comes from the common NMR solvent deuteriodichloroform and can be ignored.

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Introduction to Mass Spectrometry (MS)

- A mass spectrometer produces a spectrum of masses based on the structure of a molecule.
- A mass spectrum is a plot of the distribution of ion masses corresponding to the formula weight of a molecule and fragments derived from it.
- The x-axis of a mass spectrum represents the masses of ions produced.
- The y-axis represents the relative abundance of each ion produced.
- The pattern of ions obtained and their abundance is characteristic of the structure of a particular molecule.

The Mass Spectrometer

1. Ionization (the formation of ions)
   - A molecule is bombarded with a beam of high energy electrons.
   - An electron may be dislodged from the molecule by the impact, leaving a positively charged ion with an unpaired electron (a radical cation).
   - This ion is called the molecular ion (M+).

2. Fragmentation
   - Excess vibrational energy is imparted to the molecular ion by collision with the electron beam, causing fragmentation.
   - The fragmentation pattern is highly characteristic of the structure of the molecule.

The Mass Spectrum

- Mass spectrum can be represented as a graph or table.
- The most abundant (intense) peak in the spectrum is called the base peak and is assigned a normalized intensity of 100%.
- The data and fragmentation patterns for ammonia are as follows:
  - The base peak for ammonia is the molecular ion, but this is often not the case.

The Mass Spectrum

- The small peak at m/z 18 comes from the small amount of 15N1H3 because of the small natural abundance of 15N compared to 14N.
- This peak is called an M+1 peak.

Determination of Molecular Formulas and Molecular Weights

- The Molecular Ion and Isotopic Peaks
  - The presence of heavier isotopes one or two mass units above the common isotope yields small peaks at M+1 and M+2.
  - The intensity of the M+1 and M+2 peaks relative to the M peak can be used to confirm a molecular formula.
  - Example: In the spectrum of methane one expects an M+1 peak of 1.17% based on a 1.11% natural abundance of 13C and a 0.016% natural abundance of 2H.

### Table: Natural Abundance of Isotopes

<table>
<thead>
<tr>
<th>Element</th>
<th>Most Common Isotope</th>
<th>Natural Abundance of Other Isotopes (Based on 18 Atoms of Most Common Isotope)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>13C</td>
<td>1.11%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>14N</td>
<td>1.11%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>32P</td>
<td>0.79%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>32S</td>
<td>4.4%</td>
</tr>
<tr>
<td>Bromine</td>
<td>80Br</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

High-Resolution Mass Spectrometry

- Low-resolution mass spectrometers measure m/z values to the nearest whole number.
- High-resolution mass spectrometers measure m/z values to three or four decimal places.
- The high accuracy of the molecular weight calculation allows accurate determination of the molecular formula of a fragment.
- Example:
  - One can accurately pick the molecular formula of a fragment with a nominal molecular weight of 32 using high-resolution MS.

\[
\begin{align*}
O_3 & = 2(15.9949) = 31.9898 \\
N_2H_4 & = 2(14.0031) + 2(1.00783) = 32.0375 \\
CH_3O & = 2(12.0000) + 2(1.00783) + 15.9949 = 32.0262
\end{align*}
\]

Fragmentation

- In EI mass spectrometry the molecular ion is highly energetic and can break apart (fragment).
- Fragmentation pathways are predictable and can be used to determine the structure of a molecule.
- The processes that cause fragmentation are unimolecular.
- The relative ion abundance is extremely important in predicting structures of fragments.

1. Fragmentation by Cleavage at a Single Bond
   - Cleavage of a radical cation occurs to give a radical and a cation but only the cation is observable by MS.
   - The fragmentation proceeds to give mainly the most stable carbocations.
   - In the spectrum of propane the peak at 29 is the base peak (most abundant) 100%, and the peak at 15 is 5.6%.

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2^+ & \rightarrow \text{CH}_3\text{CH}_2^+ + \text{CH}_3 \\
\text{CH}_3\text{CH}_2\text{CH}_2^+ & \rightarrow \text{CH}_3\text{CH}_2^+ + \text{CH}_3
\end{align*}
\]

Writing the Fragmentation Equations

- The M+ ion is usually formed by loss of one of its most loosely held electrons.
- Nonbonding electrons on nitrogen and oxygen, and π electrons in double bonds are common locations for an electron to be lost (i.e., where the remaining unshared electron in M+ resides).
- In molecules with only C-C and C-H bonds, the location of the lone electron cannot be predicted and the formula is written to reflect this using brackets.

\[
\begin{align*}
[\text{CH}_3\text{CH}_2\text{CH}_2]^+ & \rightarrow \text{CH}_3\text{CH}_2^+ + \text{CH}_3 \\
[\text{CH}_3\text{CH}_2\text{CH}_2]^+ & \rightarrow \text{CH}_3\text{CH}_2^+ + \text{CH}_3
\end{align*}
\]

The spectrum of hexane

- Fragmentation of neopentane shows the propensity of cleavage to occur at a branch point leading to a relatively stable carbocation.
- The formation of the 3° carbocation is so favored that almost no molecular ion is detected.

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 & \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2^+ + \text{CH}_3 \\
[\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3] & \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2^+ + \text{CH}_3
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\]

Spectrum of neopentane

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[\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3] & \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2^+ + \text{CH}_3
\end{align*}
\]
Carbocations stabilized by resonance are also formed preferentially:
- Alkenes fragment to give resonance-stabilized allylic carbocations

Carbon-carbon bonds next to an atom with an unshared electron pair break readily to yield a resonance stabilized carbocation:
- Z=N, O, or S R may be H

Carbon-carbon bonds next to carbonyl groups fragment readily to yield resonance stabilized acylium ions
- Fragmentation by Cleavage of 2 Bonds
  - The products are a new radical cation and a neutral molecule
  - Alcohols usually show an M+18 peak from loss of water

Alkyl substituted benzenes often lose a hydrogen or alkyl group to yield the relatively stable tropylium ion
- Other substituted benzenes usually lose their substituents to yield a phenyl cation

Carbonyl compounds can undergo a McLafferty Rearrangement
- Y may be R, H, OH, OR etc.