

## Welcome to Organic II

Organic chemistry II, CHM 2211, section 2

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## Tools for Structure Determination

### Infrared Spectroscopy – Ch. 2 Nuclear Magnetic Resonance and Mass Spectrometry: Ch. 9

## 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 data bases

## 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

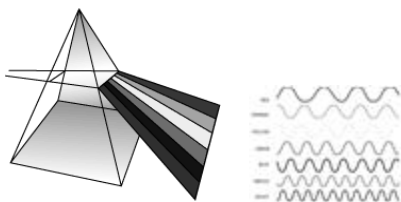
### ◆ Nuclear Magnetic Resonance (NMR)

- 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)

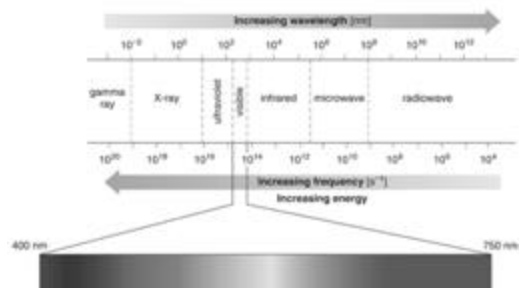
- Molecules are converted to ions
- The ions formed may remain intact ( $M^+$ ), or they may fragment
- The mixture of ions is sorted by mass/charge ratio ( $m/z$ )
- Molecular weight and chemical formula may be derived from the unfragmented  $M^+$  and  $M+1$  ions
- Molecular structure may be deduced from the fragment ions

Light = travels in waves  
Length of wave determines perceived color



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

Light is only a small portion of the  
Electromagnetic Spectrum



### Basic Principle of Spectroscopy

- ◆ Energy in molecules is quantized
- ◆ Energy  $E$  is absorbed only when the frequency  $\nu$  matches the Energy Gap
- ◆  $E = h\nu$
- ◆  $h = \text{Planck's constant } (1.58 \times 10^{-34} \text{ cal}\cdot\text{s})$



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

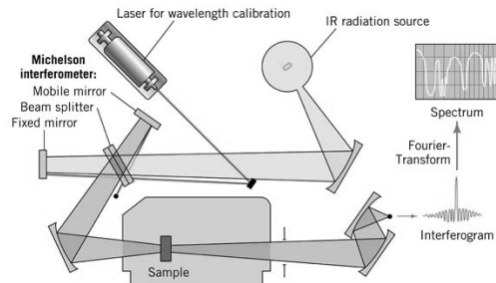
### Infrared Spectrometer

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 ( $\text{cm}^{-1}$ )

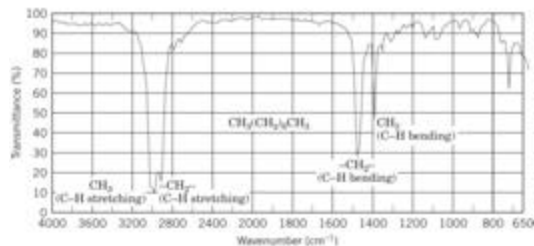
$$\bar{\nu} = \frac{1}{\lambda} \quad (\text{with } \lambda \text{ in cm})$$

- The spectrum is a plot of frequency on the horizontal axis versus strength of absorption on the vertical axis
- Higher wavenumbers ( $\text{cm}^{-1}$ ) = more energy needed to stretch bonds

## Schematic View of IR Spectrometer



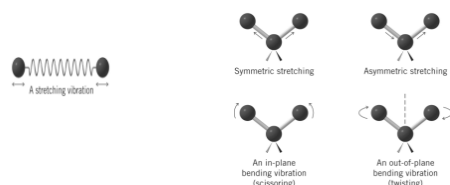
## Example: IR of Octane



Higher energy

Lower energy

## Various stretching and bending vibrations are induced by the absorption of infrared



The actual relative frequency of vibration can be predicted

Bonds with lighter atoms vibrate faster than those with heavier atoms

GROUP	BOND	FREQUENCY RANGE (CM <sup>-1</sup> )
Alkyl	C—H	2853–2962
Alcohol	O—H	3590–3650
Amine	N—H	3300–3500

## Stronger bonds require more energy to stretch

BOND	FREQUENCY RANGE (CM <sup>-1</sup> )
C≡C	2100–2260
C≡N	2220–2260
C=C	1620–1680
C=O	1630–1780

C-C and C-O single bonds are less useful, but occur around 1000 cm<sup>-1</sup>

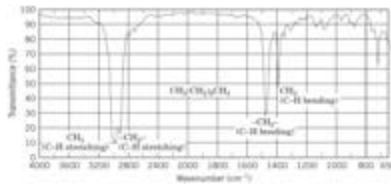
## Two major application of IR

- ◆ 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<sup>-1</sup> are most valuable

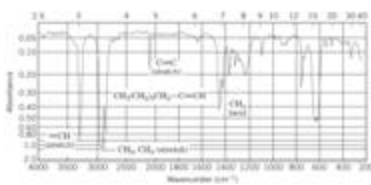
## Hydrocarbons

- ◆ The C-H stretching region is from 2800-3300 cm<sup>-1</sup>
- ◆ 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<sup>-1</sup>
  - C-H bonds at sp<sup>2</sup> centers appear about 3080 cm<sup>-1</sup>
  - C-H bonds at sp<sup>3</sup> centers appear at about 2800-3000 cm<sup>-1</sup>
- ◆ C-C bond stretching frequencies are only useful for multiple bonds
  - C-C double bonds give peaks at 1620-1680 cm<sup>-1</sup>
  - C-C triple bonds give peaks at 2100-2260 cm<sup>-1</sup>
  - These peaks are absent in symmetrical double and triple bonds

**Octane**

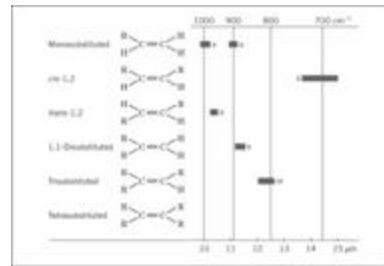


**1-hexyne**

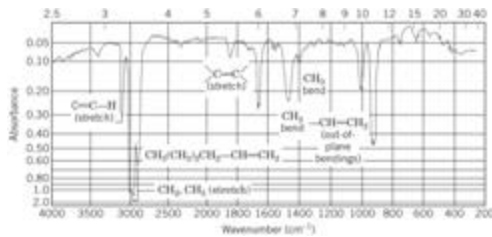


**Alkenes**

➔ The CH bending vibration peaks located at 600-1000 cm<sup>-1</sup> can be used to determine the substitution pattern of the double bond

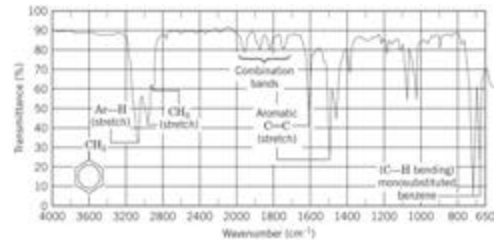


**Example: 1-hexene**



**Aromatic Compounds**

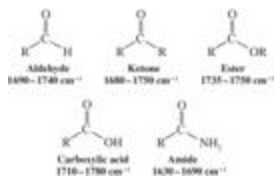
➔ The C-C bond stretching gives a set of characteristic sharp peaks between 1450-1600 cm<sup>-1</sup>  
 ➔ Substitution pattern shown between 650 and 1000 cm<sup>-1</sup>



**Carbonyl groups – very characteristic frequency**

◆ carbonyl group gives a strong peak which occurs at 1630-1780 cm<sup>-1</sup>

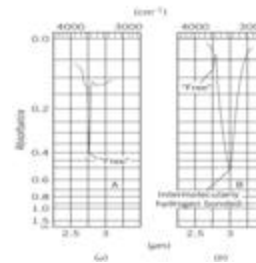
The exact location depends on the actual functional group



**Alcohols**

• The O-H stretching absorption is very characteristic

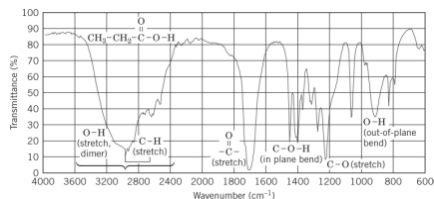
- In very dilute solutions, hydrogen bonding is absent and there is a very sharp peak at 3590-3650 cm<sup>-1</sup>
- In concentrated solutions, the hydroxyl groups hydrogen bond to each other, giving a broad and large peak occurs at 3200-3550 cm<sup>-1</sup>



## Carboxylic Acids

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

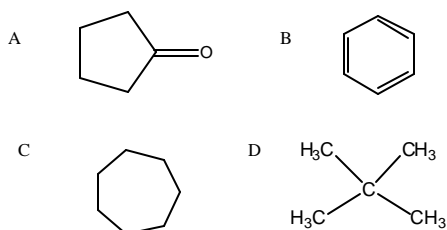
- Example: propanoic acid



## Amines and Amides

- ◆ Dilute solution of  $1^\circ$  and  $2^\circ$  amines give sharp peaks at  $3300-3500\text{ cm}^{-1}$  for the N-H stretching
  - $1^\circ$  amines give two peaks
  - $2^\circ$  amines give one peak
  - $3^\circ$  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  $1730\text{ cm}^{-1}$ ?



## Six most useful IR frequencies

Frequency	Appearance	bond	Functional group
>3200	strong, broad	OH	Alcohol, carboxylic acid
>3200	medium	NH, sp <sup>3</sup> C-H	Amine, amides, terminal alkyne
~3100	weak to medium	sp <sup>2</sup> C-H	alkene
2100-2300	sharp	Triple bond	Alkyne, nitrile
~1700	very strong, sharp	C=O	Ketone, aldehyde, acid, ester, amide
~1650	medium	C=C	Alkene, benzene ring

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

## Nuclear Magnetic Resonance Spectroscopy

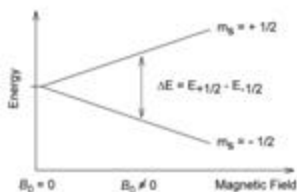
NMR = the most powerful technique for structure determination in organic chemistry

## NMR = Protons and Carbon 13

- ◆ Certain atomic nuclei have a spin ( $I$ )
- ◆ Recall Hund's rule; electron has two spin states
- ◆ Spin of  $\frac{1}{2}$  for protons ( $^1\text{H}$ ) and carbon-13 ( $^{13}\text{C}$ )
- ◆ Spin zero for carbon 12 and oxygen
- ◆  $I = 1$  for nitrogen 14, but for our purposes, it has no effect
- ◆ Other useful  $I = \frac{1}{2}$  :  $^{19}\text{F}$  and  $^{31}\text{P}$

## Nuclear Magnetic Resonance (NMR) Spectroscopy

- ◆ Spin  $\frac{1}{2}$  nuclei like  $^1\text{H}$  or  $^{13}\text{C}$  behaves 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 depends on the chemical environments

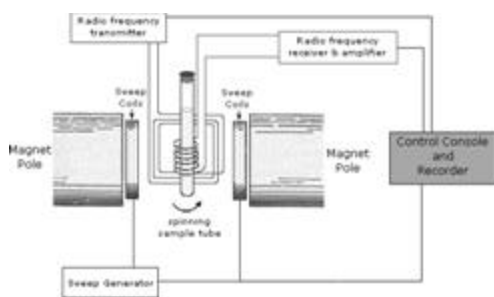


## Nuclear Magnetic Resonance (NMR) Spectroscopy

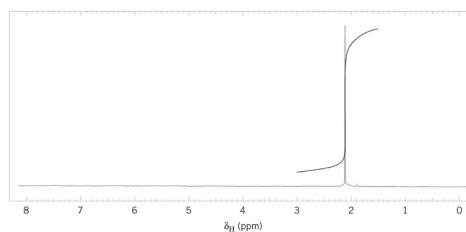
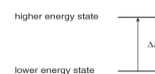
### ◆ Continuous-Wave (CW) NMR Spectrometers

- 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



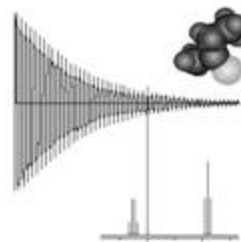
Scan by varying either the frequency or magnetic field



## 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 (only in  $^1\text{H}$ )
3. Position of each signal
4. Splitting of each signal

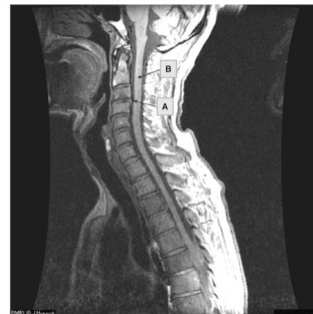
### Special effects:

- ◆ long range molecular interactions
- ◆ rate dependence may also be useful

## Nuclear Magnetic Resonance Spectroscopy

Figure 15.15 An MRI image of the neck

An MRI instrument is especially useful for visualizing soft tissue. In 2002, 60 million MRI procedures were performed. The 2003 Nobel Prize in Physiology or Medicine was awarded to chemist Paul C. Lauterbur and physicist Sir Peter Mansfield for their contributions in developing magnetic resonance imaging.

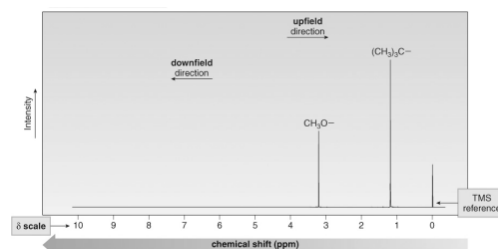


A: Spinal cord compression from a herniated disc  
B: Spinal cord (would not be visualized with conventional X-rays)

## 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

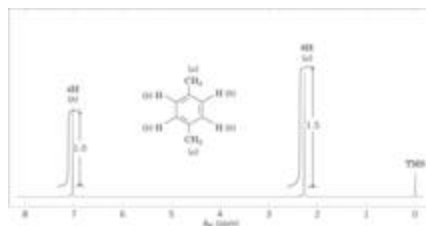
## Proton NMR of Methyl t-butyl ether



Lower field  
Deshielded

High field  
Shielded

## Proton NMR of 1,4-dimethylbenzene

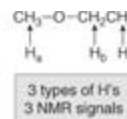
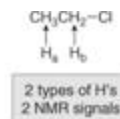
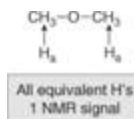


Lower field  
Deshielded

High field  
Shielded

## 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

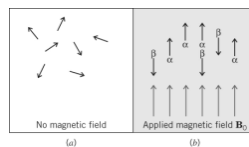
## How many $^1\text{H}$ signals?

- A. 1      B. 2      C. 3      D. 4

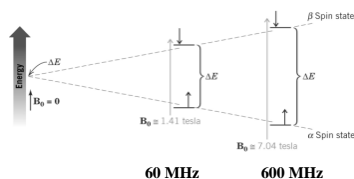
Same question for cyclohexene

## The Origin of NMR Signals

- ◆ The nuclei of NMR-active nuclei behave like tiny bar magnets
- ◆ In the absence of an external magnetic field these bar magnets are randomly orientated
- ◆ In an external magnetic field they orient either with (a spin state) or against (b spin state) the magnetic field

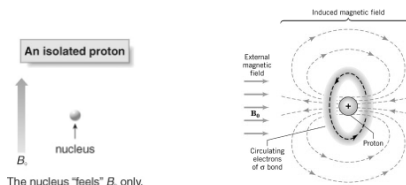


- Nuclei aligned with the magnetic field are lower in energy than those aligned against the field
- The nuclei aligned with the magnetic field can be flipped to align against it if the right amount of energy is added ( $\Delta E$ )
- The amount of energy required depends on the strength of the external magnetic field
  - ◆ The stronger the external magnetic field, the higher the radio frequency energy required to flip the nuclear spin



## Position of the Signal - Shielding and Deshielding

- ◆ 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



This nucleus is shielded:  
Needs greater  $B_0$  for resonance

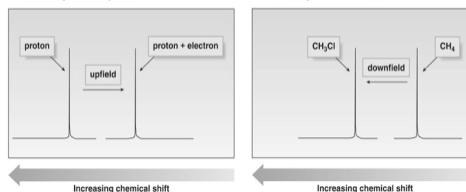
## Shielding and Deshielding

- ◆ 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

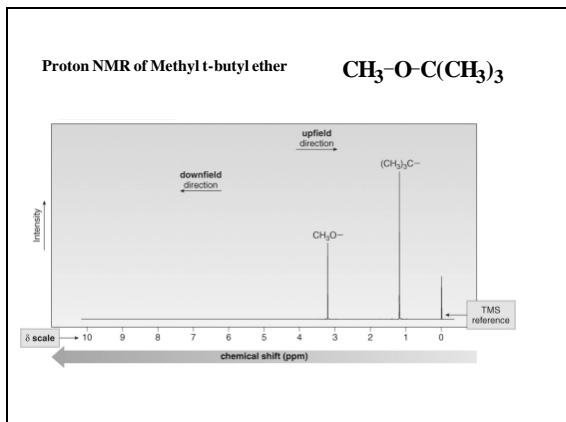


## Shielding and Deshielding

- [a] Shielding effects
- An electron shields the nucleus.
  - The absorption shifts upfield.
- [b] Deshielding effects
- Decreased electron density deshields a nucleus.
  - The absorption shifts downfield.



Electron withdrawing groups (Cl, O) pull electrons away, reduce the shielding, and thus shift signals downfield



Circulation of p electrons leads to a local induced magnetic field

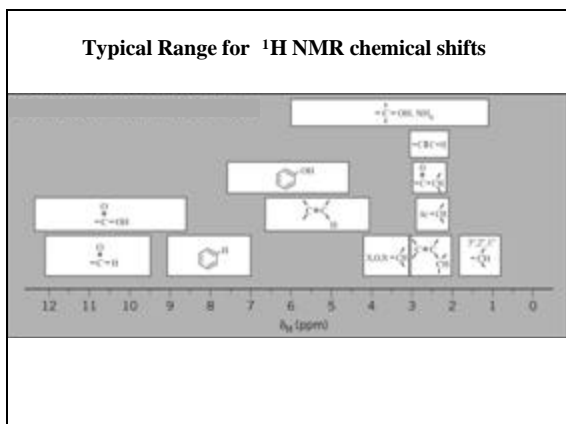
- ◆ The induced field can reinforce or diminish the external field sensed by a proton (depending on the location of the proton), causing deshielding or shielding, respectively
- ◆ Alkene and aromatic ring hydrogens are deshielded by the circulation of p electrons.
- ◆ A terminal alkyne hydrogen is shielded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

Shielding by an Aromatic Ring

- ◆ Aromatic ring electrons also circulate in strong magnetic field
- ◆ Ring current deshield protons outside the ring

Position of signal – the Chemical Shift

- ◆ 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
  - TMS (tetramethylsilane)  $\text{Si}(\text{CH}_3)_4$
- ◆ The  $\delta$  scale for chemical shifts is independent of the magnetic field strength of the instrument (whereas the absolute frequency depends on field strength)
 
$$\delta = \frac{(\text{observed shift from TMS in hertz}) \times 10^6}{(\text{operating frequency of the instrument in hertz})}$$
- ◆ Thus, the chemical shift in  $\delta$  units for protons on benzene is the same whether a 60 MHz or 300 MHz instrument is used

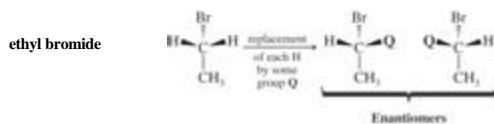


Closer Look at Equivalent and Nonequivalent Protons

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

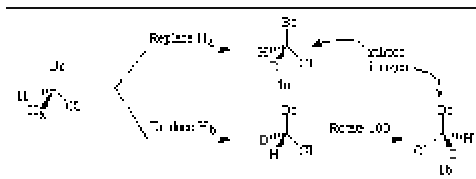
### Enantiotopic Hydrogens

If replacement of each of two hydrogens by some group leads to enantiomers, those hydrogens are enantiotopic



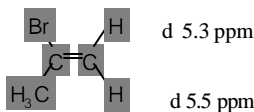
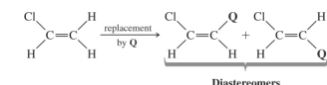
In the absence of a chiral influence, enantiotopic hydrogens have the same chemical shift and appear as the same signal

### Enantiotopic Hydrogens

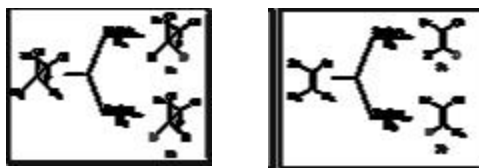


### Diastereotopic Hydrogens

- ◆ 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

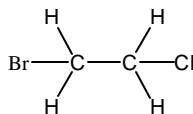


### Common types of Diastereotopic H's



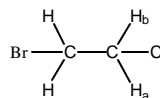
Unsymmetrical CH<sub>2</sub> + chiral center

### How many 1H signals?

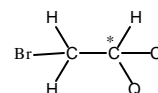
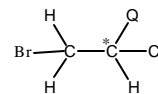


- A. 1      B. 2      C. 3      D. 4

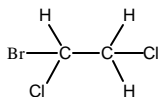
### What is relationship of H<sub>a</sub> and H<sub>b</sub>?



Enantiotopic

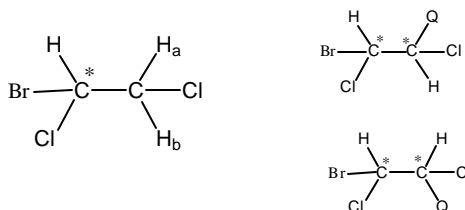


### How many 1H signals?



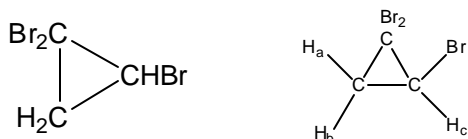
- A. 1      B. 2      C. 3      D. 4

### $H_a$ and $H_b$ are diastereotopic



$H_a$  and  $H_b$  will show separate signals, with similar but different chemical shifts

### How many 1H signals?



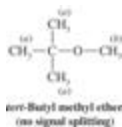
- A. 1      B. 2      C. 3      D. 4

### The protons on a $CH_2$ group are usually diastereotopic if:

- ◆ On an unsymmetrical double bond
- ◆ On opposite sides of a substituted ring
- ◆ There is a chiral center in the molecule

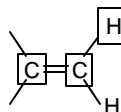
### Signal Splitting: Spin-Spin Coupling

- ◆ Much additional information comes from the influence of one nuclear spin on others nearby
- ◆ The signal from a given proton will be split by the effect of magnetic fields associated with protons on an adjacent carbon
- ◆ 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  $s$  bonds

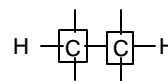


### Signal Splitting: Spin-Spin Coupling

The effect of signal splitting is normally observed only between atoms separated by 3 or fewer  $s$  bonds



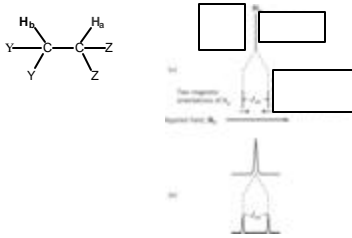
protons separated by  
two bonds  
(geminal relationship)



protons separated by  
three bonds  
(vicinal relationship)

Coupling only when not chemically equivalent or enantiotopic

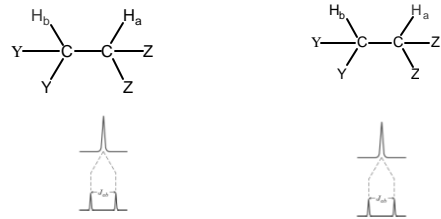
- ◆ The magnetic field sensed by the proton ( $H_a$ ) being observed is affected by the magnetic moment of an adjacent proton ( $H_b$ )
  - A proton ( $H_b$ ) can be aligned with the magnetic field or against the magnetic field, resulting in two energy states for  $H_b$
  - The observed proton ( $H_a$ ) senses the two different magnetic moments of  $H_b$



The signal for  $H_a$  is split into a doublet with a 1:1 ratio of peak areas

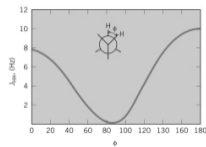
The magnitude of the splitting is called the coupling constant  $J_{ab}$  and is measured in Hertz (Hz)

The signal for  $H_b$  is likewise split into a doublet for same reason and with the same coupling constant

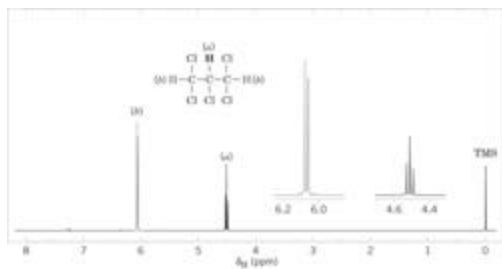
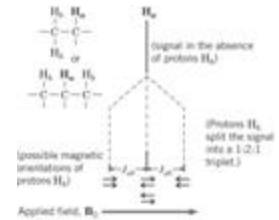


### Karplus equation for vicinal H coupling

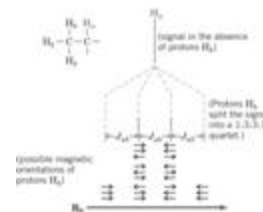
Coupling constant is a function of dihedral bond angle. In freely rotating system,  $J = 6-7$  Hz

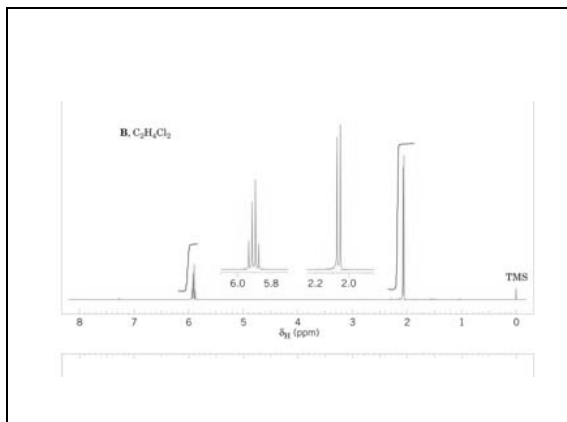


- ◆ When two adjacent protons  $H_b$  are coupled to  $H_a$ , there are 3 possible combinations of the magnetic moments for the two  $H_b$ s
  - Both with the field
  - Both opposed to the field
  - One with and one opposed (with twice the probability)
- $H_a$  is split into a triplet having a 1:2:1 ratio of signal areas



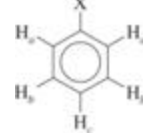
- ◆ When three adjacent protons are coupled to  $H_a$ , there are 4 net combinations of the magnetic moments for the  $H_b$ s
  - Probability of these orientations results in a quartet with intensity ratios of 1:3:3:1



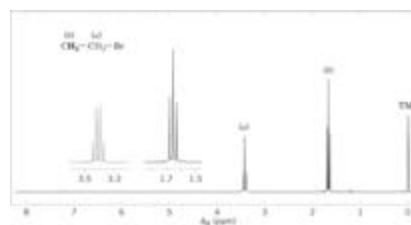


- ◆ General rule for splitting: if there are  $n$  equivalent protons on adjacent atoms, these will split a signal into  $n + 1$  peaks
- ◆ Intensities follow binomial probabilities (Pascal's triangle)
- ◆ Coupled peaks have the same coupling constants  $J$
  
- ◆ Several factors complicate analysis of NMR spectra
  - Peaks may overlap
  - Spin-spin coupling can be long-range (i.e., more than 3 bonds)
- ◆ Splitting patterns in aromatic groups can be confusing

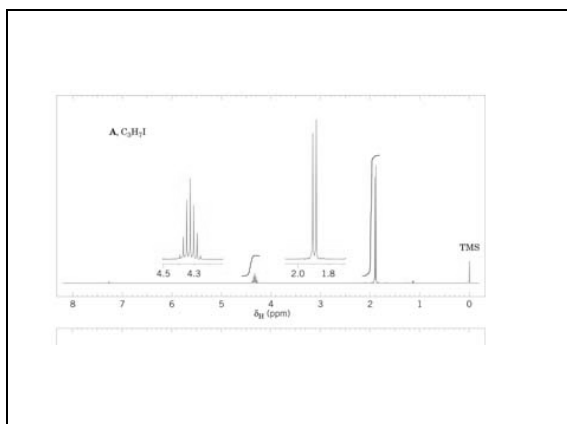
A monosubstituted aromatic ring often appears as an apparent singlet or a complex pattern of peaks of close peaks



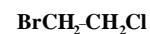
### Pascal's Triangle



Characteristic ethyl pattern:  
triplet at higher field, quartet at lower field

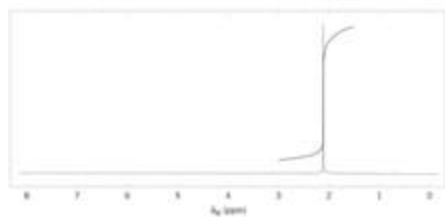


**Predict the  $^1\text{H}$  spectrum of 1-bromo-2-chloroethane**



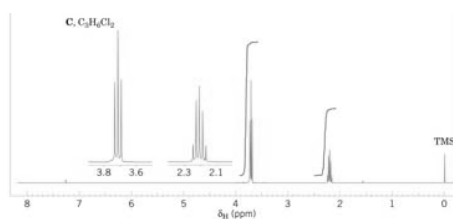
- ◆ A = two singlets
- ◆ B = a doublet and a singlet
- ◆ B = two doublets
- ◆ C = two triplets

Where are the chlorines in this isomer of  $C_3H_6Cl_2$ ?



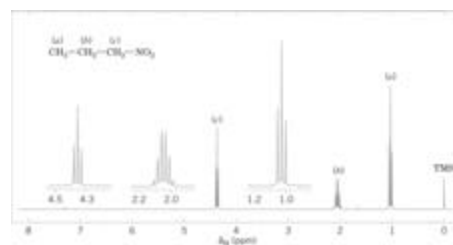
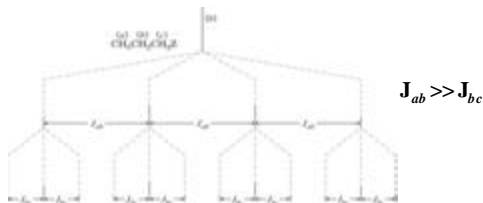
- A. 1,1    B. 1,2    C. 1,3    D. 2,2

Where are the chlorines in this isomer of  $C_3H_6Cl_2$ ?



- A. 1,1    B. 1,2    C. 1,3    D. 2,2

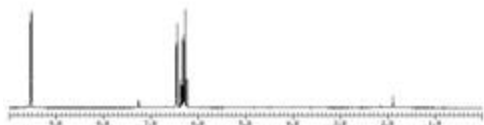
- ◆ Much more complex splitting can occur when two sets of adjacent protons split a particular set of protons
- ◆ In the system below,  $H_b$  is split by two different sets of hydrogens:  $H_a$  and  $H_c$ 
  - Theoretically  $H_b$  could be split into a triplet of quartets (12 peaks) but this complexity is rarely seen



$$J_{ab} = J_{bc}$$

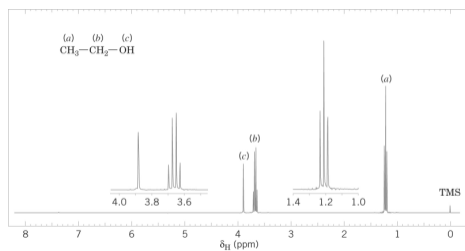
### NMR of $C_3H_4O$

Sometimes can't fully analyze the splitting



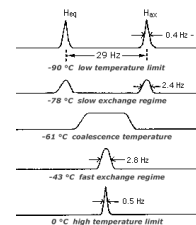
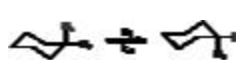
### Proton NMR Spectra and Rate Processes

- ◆ 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 is seen
- ◆ When a  $^1H$  NMR spectrum of 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  $^1\text{H}$  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

### NMR shutter speed about $1/50$ sec



Used D-11 so could look at a single proton – equatorial or axial

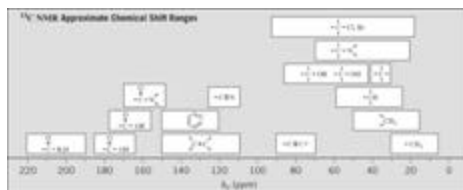
$$? E = 45 \text{ kJ/mol}$$

### Carbon-13 NMR Spectroscopy

- $^{13}\text{C}$  is only 1.1% of naturally occurring carbon
  - $^{12}\text{C}$  has no magnetic spin and produces no NMR signal
- One Peak for Each Unique Carbon Atom
  - Probability of adjacent  $^{13}\text{C}$  atoms is low, so there is no detectable carbon-carbon splitting
  - $^1\text{H}$  and  $^{13}\text{C}$  do split each other, but this splitting can be eliminated by adjusting the instrument.
  - The technique of removing the coupling of  $^1\text{H}$  to an attached carbon is called broadband (BB) proton decoupling
  - Most  $^{13}\text{C}$  NMR, therefore, consist of a single peak for each unique carbon

### $^{13}\text{C}$ Chemical Shifts

- Just as in  $^1\text{H}$  NMR spectroscopy, chemical shifts in  $^{13}\text{C}$  NMR depend on the electron density around the carbon nucleus
  - Decreased electron density causes the signal to move downfield (*deshielding*)
  - Increased electron density causes the signal to move upfield (*shielding*)



- Because of the wide range of chemical shifts, it is rare to have two  $^{13}\text{C}$  peaks coincidentally overlap
- A group of 3 peaks at  $\delta$  77 comes from the common NMR solvent deuteriochloroform and can be ignored

### Off-Resonance Decoupled Spectra

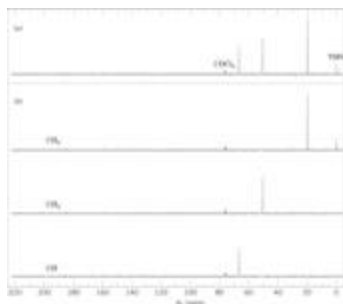
- Broad-band decoupling removes all information about the number of hydrogens attached to each carbon
- Off-resonance decoupling removes longer range C-H coupling, but leaves that of direct C-H bonds
- Thus quaternary carbons would be singlets, but other C would have n+1 signals where n is number of H attached.
- Thus a methyl group would be quartet
- Use of off-resonance decoupled spectra has been largely replaced by use of DEPT  $^{13}\text{C}$  NMR

### DEPT $^{13}\text{C}$ 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,  $\text{CH}_2$ , and  $\text{CH}_3$  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,  $\text{CH}_2$  and  $\text{CH}_3$  above the appropriate peaks

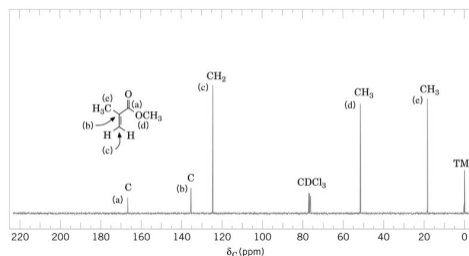
**Example: 1-chloro-2-propanol**  $\text{ClCH}_2\text{-CHOH-CH}_3$

Broadband decoupled spectrum



A set of DEPT spectra showing the separate  $\text{CH}_3$ ,  $\text{CH}_2$ , and  $\text{CH}$  signals

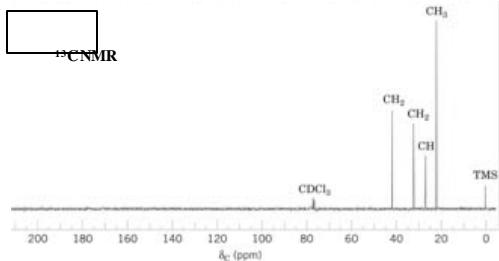
**$^{13}\text{C}$  of methyl methacrylate**



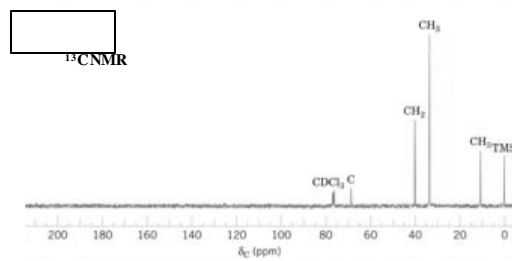
Shown as a single broad-band decoupled spectrum with DEPT information included

Intensities not reliable  
Note solvent and TMS

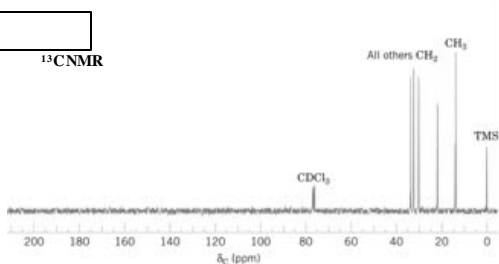
**Which isomer of  $\text{C}_5\text{H}_{11}\text{Br}$ ?**



**Which isomer of  $\text{C}_5\text{H}_{11}\text{Br}$ ?**



**Which isomer of  $\text{C}_5\text{H}_{11}\text{Br}$ ?**



**Introduction to Mass Spectrometry**

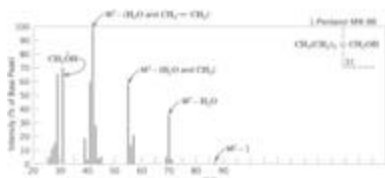
Different principles – not based on absorption of electromagnetic radiation

Creates and detects cations in gas phase:

1. Molecular weight
2. Molecular formula
3. Some information about molecular structure
4. Possible matching to known compounds via fingerprinting
5. Requires only a tiny amount of sample, usefully coupled with separation techniques (GC-MS)

## Introduction to Mass Spectrometry (MS)

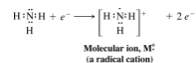
- ◆ A mass spectrometer produces a spectrum of masses for a molecule based on its structure.
- ◆ The mass spectrum is a plot of the mass to charge ratio of the molecular ion and fragments derived from it.
- ◆ The pattern of ions obtained and their abundance is characteristic of the structure of a particular molecule



## The Mass Spectrometer

### 1. Ionization (the formation of ions)

- Molecule is bombarded with a beam of high energy electrons
- An electron is knocked out of the molecule by the impact, leaving a positively charged ion with an unpaired electron



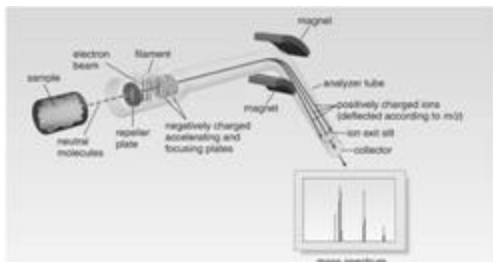
### 2. Fragmentation

- Excess vibrational energy imparted to the molecular ion by collision with the electron beam may cause fragmentation
- ◆ Fragmentation pattern is characteristic of the structure of the molecule

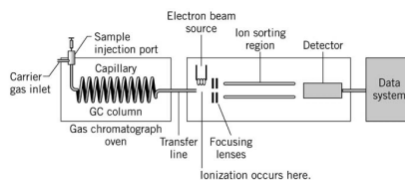


### 3. Ion Sorting

- The fragments are sorted by their mass to charge ratio, (m/z)
- Most of the fragments detected have charge +1; the net effect is sorting of the ions by mass (m/z, where z = +1)
- Sorted by a variable magnetic field and recorded

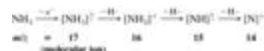
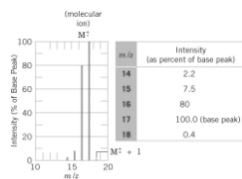


## Simplified Schematic of a gas chromatograph in tandem with mass spectrometry - gcms



## 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 masses are based on rounding of atom masses to the nearest whole number (in low resolution mass spectroscopy)
- ◆ The data and fragmentation patterns for ammonia are as follows



The molecular ion is also the base peak for ammonia, but this is usually not the case

## M+1 and M+2 peaks

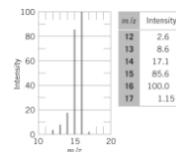
- ◆ The small peak at m/z 18 comes from the small amount of <sup>15</sup>NH<sub>3</sub> because of the small natural abundance of <sup>15</sup>N compared to <sup>14</sup>N
- This peak is called an M+1 peak
- ◆ The highest m/z peak in the mass spectrum is usually the molecular ion, M+
- M+1 and M+2 peaks can often be seen, due to heavier isotopes.
- Mass spectrometry counts individual molecules, not an average

$$C = 1.11\% \text{ } ^{13}\text{C}$$

$$H = 0.016\% \text{ } ^2\text{H}$$

Predict M+1 for methane

$$1.11 + 4(0.016) \approx 1.17\%$$



## M+1 and M+2 peaks

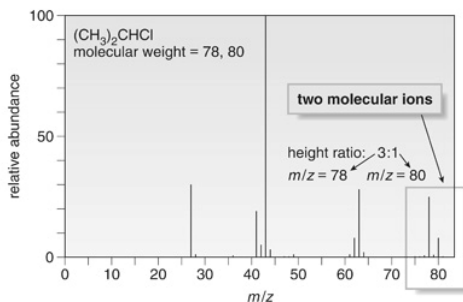
Element	Most Common Isotope	Natural Abundance of Other Isotopes (Based on 100 Atoms of Most Common Isotope)
Carbon	<sup>12</sup> C	<sup>13</sup> C 1.11
Hydrogen	<sup>1</sup> H	<sup>2</sup> H 0.016
Nitrogen	<sup>14</sup> N	<sup>15</sup> N 0.38
Oxygen	<sup>16</sup> O	<sup>17</sup> O 0.04 <sup>18</sup> O 0.20
Fluorine	<sup>19</sup> F	
Silicon	<sup>28</sup> Si	<sup>29</sup> Si 5.10 <sup>30</sup> Si 3.35
Phosphorus	<sup>31</sup> P	
Sulfur	<sup>32</sup> S	<sup>33</sup> S 0.78 <sup>34</sup> S 4.40
Chlorine	<sup>35</sup> Cl	<sup>37</sup> Cl 32.5
Bromine	<sup>79</sup> Br	<sup>81</sup> Br 98.0
Iodine	<sup>127</sup> I	

$$\frac{M+1}{M} * 1.1 = \text{\# Carbon atoms}$$

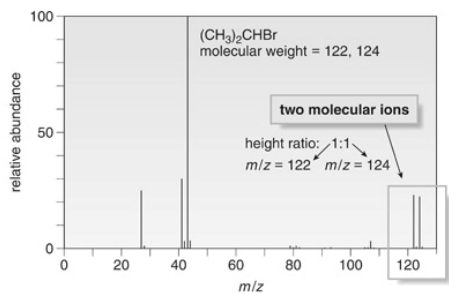
Cl has MW = 35.45  
Made of about 3 parts Cl-35 to 1 part Cl-37

Br has MW 79.90  
Made of about 1 part Br-79 to 1 part Br-81

## Alkyl Halides and the M + 2 Peak



## Alkyl Halides and the M + 2 Peak



## 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

$$\begin{aligned} \text{O}_2 &= 2(15.9949) = 31.9898 \\ \text{N}_2\text{H}_4 &= 2(14.0031) + 4(1.00783) + 32.0375 \\ \text{CH}_2\text{O} &= 12.00000 + 4(1.00783) + 15.9949 = 32.0262 \end{aligned}$$

- The exact mass of certain nuclides is shown below

isotope	Mass	isotope	Mass
<sup>1</sup> H	1.00783	<sup>19</sup> F	18.9984
<sup>2</sup> H	2.01410	<sup>35</sup> S	31.9721
<sup>12</sup> C	12.00000 (std)	<sup>36</sup> S	32.9715
<sup>13</sup> C	13.00336	<sup>37</sup> Cl	34.9689
<sup>14</sup> N	14.0031	<sup>39</sup> K	38.9637
<sup>15</sup> N	15.0001	<sup>79</sup> Br	78.9183
<sup>16</sup> O	15.9949	<sup>81</sup> Br	80.9163
<sup>17</sup> O	16.9991	<sup>127</sup> I	126.9045
<sup>18</sup> O	17.9992		

## 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

## Predicting the Fragmentation Patterns

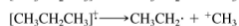
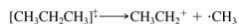
The  $M^+$  ion is usually formed by loss of its most loosely held electron

- Nonbonding electrons on nitrogen and oxygen, and  $\pi$  electrons in double bonds are common locations for an electron to be lost

TABLE 9.3 Ionization Potentials of Selected Molecules

Compound	Ionization Potential (eV)
$\text{CH}_3(\text{CH}_2)_3\text{NH}_2$	8.7
$\text{C}_6\text{H}_6$ (benzene)	9.2
$\text{C}_2\text{H}_4$	10.5
$\text{CH}_3\text{OH}$	10.8
$\text{C}_2\text{H}_6$	11.5
$\text{CH}_4$	12.7

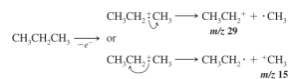
- In molecules with only C-C and C-H bonds, the location of the lone electron cannot be predicted and the formula is written to reflect this using brackets



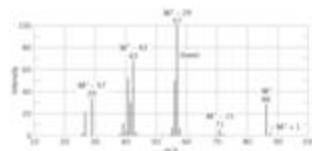
## Fragmentation

### 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%

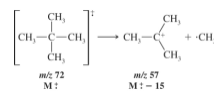
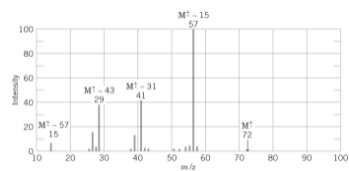


### The spectrum of hexane



### Spectrum of neopentane

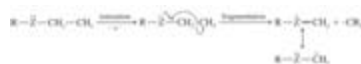
- The formation of the  $3^\circ$  carbocation is so favored that almost no molecular ion is detected



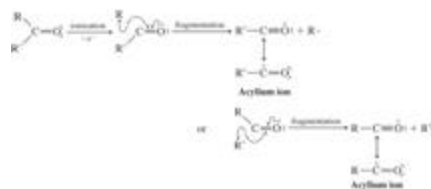
- Carbocations stabilized by resonance are also formed preferentially
  - Alkenes fragment to give resonance-stabilized allylic carbocations



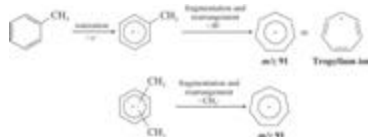
- Carbon-carbon bonds next to an atom with an unshared electron pair break readily to yield a resonance stabilized carbocation
  - Z=N, O, or S R may be H



- Carbon-carbon bonds next to carbonyl groups fragment readily to yield resonance stabilized acylium ions



- ◆ 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



### 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



Cycloalkenes can undergo a retro-Diels Alder reaction (section 13.11) to yield an alkadienyl radical cation



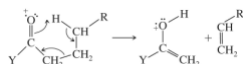
### Six electron cyclic cleavages are common

Cycloalkenes can undergo a retro-Diels Alder reaction (chapter 13) to yield an alkadienyl radical cation



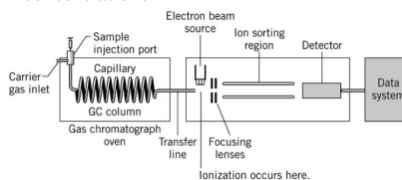
Carbonyl compounds can undergo a *McLafferty Rearrangement*

- Y may be R, H, OH, OR etc.



### The major uses of mass spectrometry

1. Molecular formulas for new compounds
2. With gc-ms, together with data banks, identify components of complex mixtures at low concentrations



### Expectations for mass spectrometry

1. Understand basic principles of instrument
    1. Including basic fragmentation principle
  2. Identify molecular weight from  $M^+$ .
  3. Use structure formula principles, plus  $M+1$  and  $M+2$  data to determine molecular formulas.
  4. Use with other data – NMR and/or IR to identify molecules
- 
1. Will not use detailed fragmentation patterns
  2. Will not use high resolution mass spec.

Problem – what is the molecular formula of a compound whose Molecular Ion is 86?

- ◆ Max number of carbons?? (mass 12)
- ◆ If 7 C, how many H?? (mass 1)
  - Option =  $C_7H_2$
- ◆ If 6 C, how many H??
  - Option =  $C_6H_{14}$
- ◆ If 1 O, max C=??
  - Option =  $C_5H_6O$
  - »  $C_5H_{10}O$
- ◆ If 2 O,
  - »  $C_4H_6O$
- ◆ If compound has N, must have an even number