Lecture 10:
MS Interpretation – Part 4
Postulation of Molecular Structures

CU- Boulder

CHEM 5181

Mass Spectrometry & Chromatography

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Postulation of Molecular Structures

- There are several major kinds of structural information available from the MS
  - The overall appearance of the spectrum and the low mass peaks can give a general indication of the type of compound
  - The neutral fragments lost in forming the high mass peaks can provide info on specific structural features
  - Then, the fragmentation behavior of the molecule is used to postulate structures

General Appearance of the Spectrum

- Mass and relative abundance of the molecular ion indicate the size & general stability of the molecule
- The number of abundant ions in the spectrum and their distribution on the mass scale are indicative of the type of molecule and the functional groups

Example

- E.g., a molecule composed of stable substructures connected by relatively weak bonds should give a spectrum with a few prominent fragment ions:

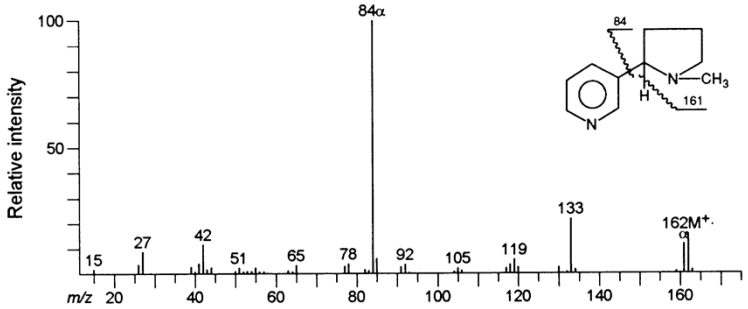
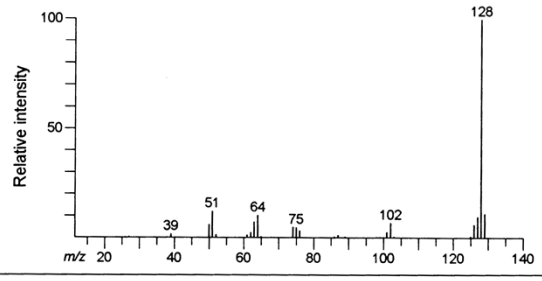


Figure 5.1. Mass spectrum of nicotine.

Unknown 5.1

Unknown 5.1

m/z	Int.	*m/z*	Int.	*m/z*	Int.
38	1.8	64	10.	101	2.7
39	3.9	64.5	1.1	102	7.1
40	0.2	74	4.7	103	0.6
50	6.4	75	4.9	125	0.8
51	12.	76	3.3	126	6.1
52	1.6	77	0.4	127	9.8
61	1.4	87	1.4	128	100.
62	2.7	89	0.7	129	11.
63	7.4			130	0.5
63.5	0.9				

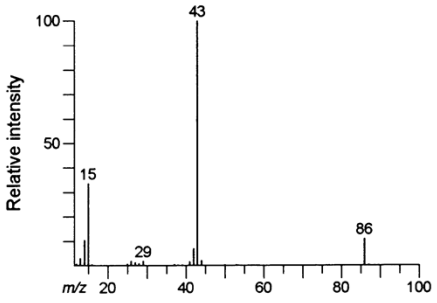


1) A glance should tell you that this is a highly stable molecule
2) Deduce elemental comp. (Should correspond to value of rings + DB consistent with stability)
3) Note that there are no weak bonds on the molecule
4) Apparently the fragmentation pathways are of similar low probability
5) structure?

Unknown 5.2

Unknown 5.2

m/z	Int.
15	34.
16	0.5
27	1.4
28	1.0
29	2.0
41	1.8
42	7.2
43	100.
44	2.1
45	0.2
86	11.
87	0.4

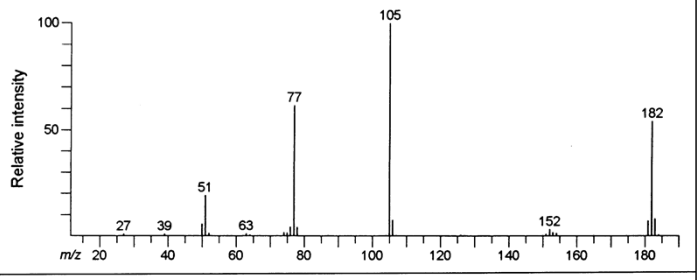


- m/z 43 is by far the most prominent.
  - The bond that is cleaved in the formation of this ion would be expected to be the weakest from its known chemical reactivity

Unknown 5.3

Unknown 5.3

m/z	Int.	*m/z*	Int.	*m/z*	Int.
38	0.4	75	1.7	127	0.4
39	1.1	76	4.3	151	1.1
50	6.2	77	62.	152	3.4
51	19.	78	4.2	153	1.8
52	1.4	104	0.4	154	1.4
53	0.3	105	100.	181	7.4
63	1.3	106	7.8	182	55.
64	0.6	107	0.5	183	8.3
74	2.0	126	0.6	184	0.6



1) Unknowns 5.3 and 5.4 are the spectra of larger molecules producing only a few prominent peaks.

2) In analyzing 5.3, don't forget that the importance of a peak decreases with decreasing mass, as well as decreasing abundance

Example: Unbranched Alkanes

In unbranched alkanes, the most easily cleaved bonds (σ) are nearly equivalent in bond strength. The resulting spectra have many peaks of regularly varying abundance ("picket fence").

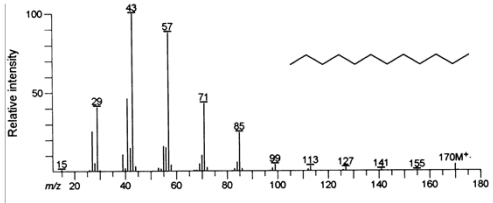


Figure 3.2. (repeated). Mass spectrum of dodecane.

1) Note the striking similarity despite the difference in molecular weight

2) All the peaks except $M^{+\cdot}$ are EE^+

3) Rates of initial fragmentation & of secondary product ion decomposition are similar for different molecules

4) Rearranged products of greater stability are produced by secondary reactions (C_3H_7+ @ m/z 43 and $C_4H_9^+$ @ m/z 57)

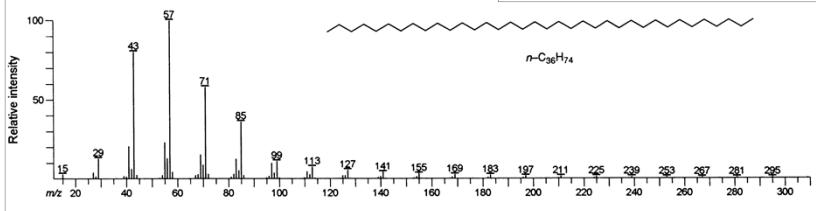


Figure 5.2. Mass spectrum of hexatriacontane. The relative abundances of the m/z 506 and 507 peaks are 0.46% and 0.18%, respectively. The relative abundances of the $C_nH_{2n+1}^+$ peaks decrease regularly from m/z 309 = 0.7% to m/z 505 = 0.1%.

Effect of Substitution

- Substitution of a carbon atom increases the probability of cleaving its bonds
- Compare this to unbranched in previous slide. What are the main differences?

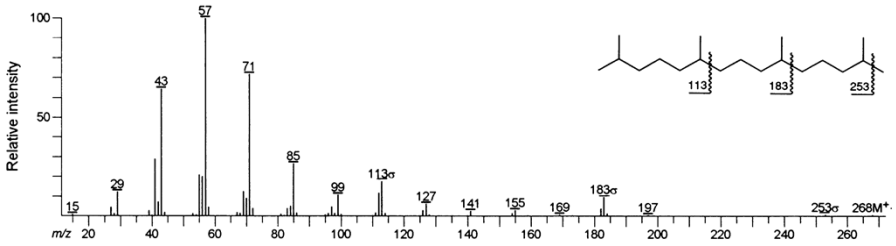
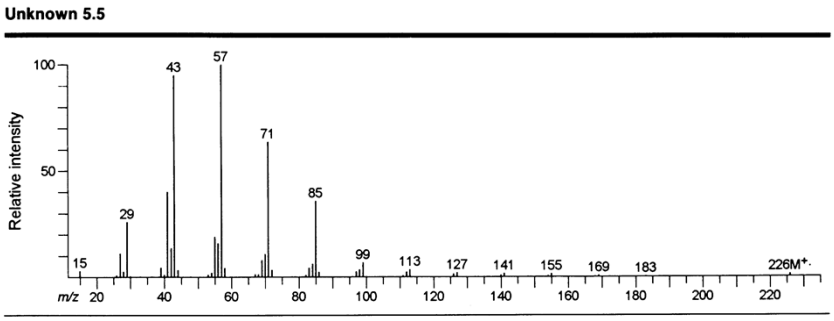


Figure 4.1. Mass spectrum of pristane (2,6,10,14-tetramethylpentadecane).

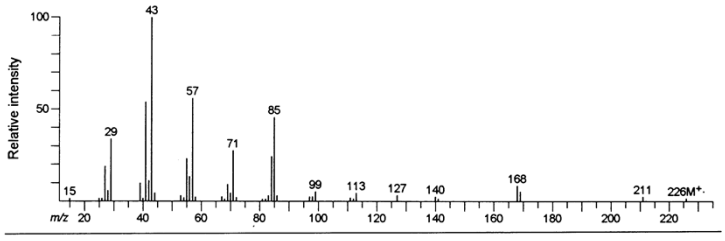
Unknown 5.5



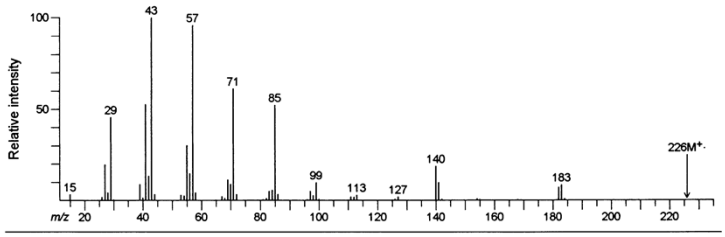
- Remembering σ-bond dissociation, work through unknowns 5.5 to 5.7, which are C16H34 isomers.
- Don't forget that σ-bond cleavage gives EE^+ $C_nH_{2n+1}{}^+$ ions, *not* $OE^{+\cdot}$ $C_nH_{2n}{}^{+\cdot}$ ions. Ignore such important $OE^{+\cdot}$ ions (read 9.2 of McLafferty if interested)

Unknowns 5.6 & 5.7

Unknown 5.6



Unknown 5.7



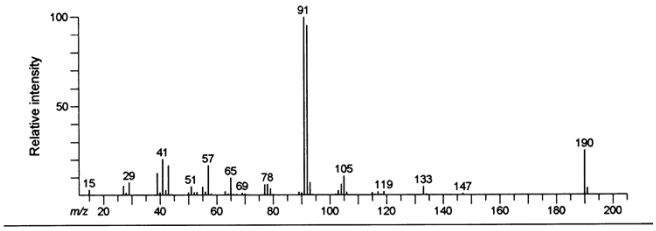
Low-Mass Ion Series

- These are the "picket fence" peak series, separated by 14 amu
  - Sometimes 12 or 13
  - Marked by bar top in Figures 3.2-3.28 (examples on previous lecture)
- Useful for providing general information (heteroatoms, rings-plus-double-bonds) on particular substructures
- The individual peaks at higher masses representing primary fragmentation are more important as indicators of specific structural features.
- The low mass $C_nH_{2n+1}^+$ is a reliable indicator of the presence of an alkyl chain
- Rule: try to identify any low-mass ion series before postulating structures for higher mass peaks.
  - At lower masses there are fewer possible assignments, e.g. *m/z* 29 is usually either $C_2H_5^+$ or CHO^+, while there are hundreds of possibilities for *m/z* 129.

Unknown 5.8

Unknown 5.8

m/z	Int.	m/z	Int.	m/z	Int.
15	3.2	64	0.8	94	0.2
27	5.4	65	10.	98	0.3
29	7.1	66	0.7	103	2.6
39	13.	67	0.6	104	5.9
40	1.7	69	1.4	105	12.
41	21.	70	0.9	106	1.1
42	3.0	71	0.5	117	1.9
43	17.	75	0.4	118	0.6
44	0.6	76	0.5	119	2.2
50	1.5	77	6.1	120	0.2
51	5.1	78	6.5	133	5.1
52	1.6	79	3.8	134	0.6
53	1.9	83	0.3	147	1.1
55	4.7	89	1.8	161	0.3
56	2.0	90	1.4	175	0.1
57	17.	91	100.	190	26.
58	0.8	92	96.	191	4.1
63	2.4	93	7.5	192	0.3



1) Known to contain no oxygen (via previous IR analysis)

2) The high end of the ion series is a good indicator of the size of the alkyl moiety

Common Ion Series

Table 5.1. *Common ion series* (see Tables A.6 and A.7)

Function[a]	Formula	Index, Δ[b]	*m/z* values
Nitriles	$C_nH_{2n-2}N^+$	−1	40 54 68 82
Alkenyl, cycloalkyl	$C_nH_{2n-1}^+$	0	27 41 55 69 83
Alkenes, cycloalkanes, alkyl-Y[c]	$C_nH_{2n}^{+\cdot}$	+1	28 42 56 70 84
Alkyl	$C_nH_{2n+1}^+$	+2	15 29 43 57 71 85
Aldehydes, ketones	$C_nH_{2n-1}O^+$	+2	29 43 57 71 85
Amines	$C_nH_{2n+2}N^+$	+3	30 44 58 72 86
Alcohols, ethers	$C_nH_{2n+1}O^+$	+4	31 45 59 73 87
Acids, esters	$C_nH_{2n-1}O_2^+$	+4	45 59 73 87
Thiols, sulfides	$C_nH_{2n+1}S^+$	+6	33[d] 47 61 75 89
Chloroalkyl	$C_nH_{2n}Cl^+$	−6	35 49 63 77 91
Aromatic	$C_nH_{\leq n}$	−2 to −8	38, 39, 50–52, 63–65, 75–78[e]

[a] Connected to a saturated aliphatic substructure

[b] Δ = mass − 14*x* + 1 (Dromey 1976); an odd number corresponds to an *N*-containing or $OE^{+\cdot}$ series.

[c] For which HY is a molecule of low proton affinity.

[d] HS^+ ion

[e] All of these peaks may not be of significant abundance in a particular spectrum, and neighboring peaks are sometimes observable.

Common Ion Series II

- $C_nH_{2n+1}^+$ gives peaks at *m/z* 15, 29, 43, 57…(Δ = +2)
- $C_nH_{2n+1}O^+$ (31, 45, 59… Δ = +4) is characteristic of saturated alcohols & ethers
  - Figures 3.8 & 3.9
- $C_nH_{2n+2}N^+$ (30, 44, 58… Δ = +3) is characteristic of saturated amines
  - Figures 3.16 to 3.18
  - Note that these EE^+ are at even mass numbers

Common Ion Series III

- Increasing the number of rings plus double bonds by one decreases the mass by two units
- E.g Aliphatic aldehydes & ketones give the $C_nH_{2n-1}O^+$ (31, 45, 59… Δ = +4)
  - This interferes with pure aliphatic
  - Check the elemental composition of the fragments, e.g. if $[44^+]/[43^+]$ is only 2.2%, 43^+ cannot be part of a $C_nH_{2n+1}^+$ series
  - Check for O in molecular ion
- Acids & esters produce $C_nH_{2n-1}O_2^+$ (31, 45, 59… Δ = +4)
  - Interferes with alcohols & ethers
- Ion series by themselves are not conclusive

Peak Importance in Ion Series Analysis

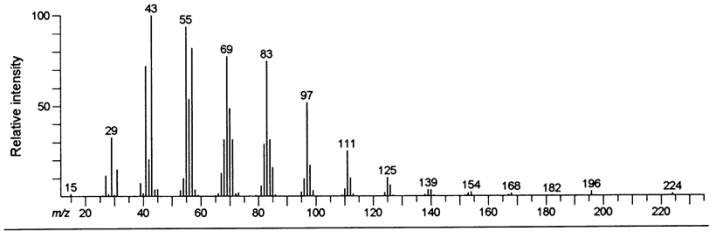
- Use the criteria of peak importance
  - In a "peak group" (compositions differing by H) the peak with the most H is the most important
- Example
  - The spectra of alkanes contain both $C_nH_{2n+1}^+$ and $C_nH_{2n-1}^+$. The former should not be interpreted as an indication of an alkenyl or cycloalkyl group
  - Both of those series also appear in the spectrum of 1-dodecene (Figure 3.5); however $C_nH_{2n-1}^+$ is more important since it can be followed to higher *m/z*

Ion Series at Even Mass Numbers

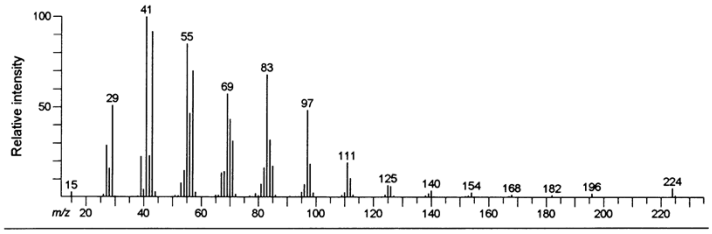
- Note that in the dodecene spectrum (F 3.5) there is also $C_nH_{2n}^{+\cdot}$ ($OE^{+\cdot}$) series, generally larger than $C_nH_{2n+1}^+$
- A series of important low-mass ions at even mass numbers
  - $OE^{+\cdot}$ ions formed in specific cleavages
    - e.g. *m/z* 58 in Fig. 3.10 and 3.11
    - Look carefully to see if there is a series, don't be fouled by isotopic peaks (e.g. *m/z* 30, 44, 72 and 86 in Fig. 3.10-3.11 are entirely due to ^{13}C)
  - EE^+ ions containing one N
    - e.g. *m/z* 30, 44, 58, 72 in Fig. 3.16-3.18
    - Study the rest of the spectrum for signs of N

Unknowns 5.9 & 5.10

Unknown 5.9



Unknown 5.10



1) 5.9 and 5.10 are very similar, with *m/z* 224 shown to be $C_{16}H_{32}^{+}$ via elemental composition

2) However, one is unique in containing an important ion series (note that those are identified best by starting at the low mass end)

3) What possible kinds of molecules are these?

Ions Separated by CH and C

- Compounds with H/C << 2 cannot show a significant series at CH_2 intervals
  - E.g. unknown 5.1, naphtalene $C_{10}H_8$
- A very important ion series is that shown by aromatic hydrocarbons at m/z 38-39, 50-52, and 75-78 (Δ = –2 to –8)
  - $C_nH_{0.5n}$ to C_nH_n
- Heterocyclic compounds with N and O and compounds with N or O near an aromatic ring show peaks at similar, plus an additional series at *m/z* 40, 53, 66, and 79 (Δ = –1, "high" aromatic series)
- Even though they tend to have low abundance, the uniqueness of their m/z makes these series quite recognizable
- Note their absence in U 5.9 & 5.10, compared to 5.3, 5.4, & 5.8
- Using examples 3.2 to 3.27 as unknowns, see if you can decude which contain aromatic moieties

Effect of Halogens on Ion Series

- Replacing H by F, Cl, Br, I changes the homologous series spacings by CHX or CX_2
  - Marked change in the appearance of the spectrum
- Also, the electronegative halogen atoms are more easily lost than H, so that losses of X and HX are found
- Cl and Br give isotope clusters
- F and I have only one natural isotope each, but can be recognized by the very unusal mass differences

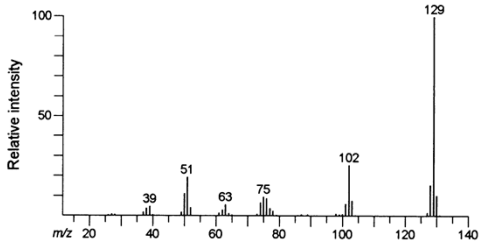
Recognizing Ion Series

- Chemists quickly become able to identify C=O peaks in an IR or CH_3 peaks in proton NMR
- Ion series are the analogous tool in MS
  - "You will feel much more at home" (McLafferty)
  - Use $C_nH_{2n+1}^+$ as your reference scale: *m/z* 15, 29, 43, 57…(Δ = +2)
    - Note that in 100-200 amu, this is only 2 amu lower (113, 127, 141, 155…).
    - The 200-300 amu is 211, 225, 239, 253…
- Since CH_2 can be replaced by NH or O, one can *estimate* the total number of C, N, & O atoms by dividing by 14
- For unsaturation, add twice the *r+db* value before dividing by 14
  - As a rule of thumb, 100 amu ~ $(C+N+O)_7$

Unknown 5.11

Unknown 5.11

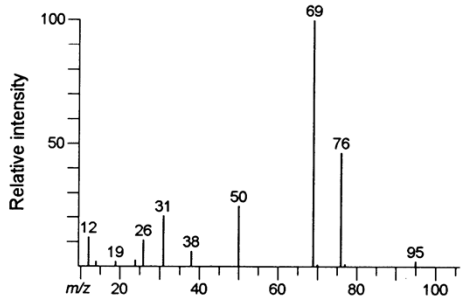
m/z	Int.	*m/z*	Int.	*m/z*	Int.
38	3.7	62	3.2	88	0.3
39	4.8	63	5.8	98	1.2
40	0.6	64	1.5	99	0.9
43	0.4	64.5	3.9	100	0.9
49	2.0	65	0.8	101	5.6
49.5	0.6	74	7.1	102	24.
50	12.	75	9.9	103	7.6
50.5	0.4	76	9.0	104	0.6
51	19.	77	3.8	127	1.8
51.5	1.0	78	2.5	128	16.
52	4.2	79	0.5	129	100.
53	0.4	81	0.4	130	10.
		87	0.9	131	0.5



Unknown 5.12

Unknown 5.12

m/z	Int.
12	13.
14	2.1
19	2.0
24	2.7
26	11.
31	22.
32	0.3
38	6.2
50	25.
51	0.3
69	100.
70	1.1
76	46.
77	1.2
95	2.4



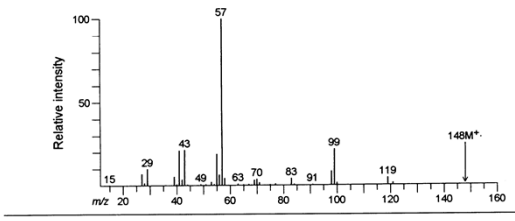
Small Neutral Losses

- The simplest and most specific assignments
  - the small neutral species lost in the fragmentation leading to the formation of high mass ions, especially those formed directly from the molecular ion
  - E.g. important ions at $(M-1)^+$, $(M-15)^+$, $(M-18)^+$, and $(M-20)^+$ almost always represent the losses of H, CH_3, H_2O, and HF
    - Because of low probability of rearrangement, those peaks are of high value for structure determination
  - A large peak at $(M-1)^+$ indicates a labile H (and the absence of other labile substituents)
- If the "logical neutral loss test" indicates that the highest peak is not M, then the difference in the peaks may be the difference in the losses

Unknown 5.13

Unknown 5.13

m/z	Int.	*m/z*	Int.
27	7.0	69	3.3
28	1.5	70	3.9
29	10.	71	1.7
30	0.2	77	1.0
36	0.4	79	0.3
39	5.4	83	4.2
40	0.7	84	0.8
41	21.	91	0.6
42	3.6	93	0.2
43	21.	98	8.4
44	0.7	99	22.
49	0.9	100	1.6
51	0.3	105	0.3
55	19.	112	0.2
56	6.5	119	4.7 ($M - C_2H_5$)
57	100.	120	0.3
58	4.4	121	1.5
63	1.1	148	0.1
65	0.4		



1) CI and exact mass measurements indicate that *m/z* 119 is formed by loss of C_2H_5 from $M^{+\cdot}$

2) Identify *both* important ion series

Characteristic Ions

- Somewhat surprisingly, for many m/z there are only a few structural groupings
  - *m/z* 30 from amines, *m/z* 77 from phenyl, *m/z* 105 from methylbenzyl or benzoyl (U 5.3)
  - Phtalates, *m/z* 149: common contaminant

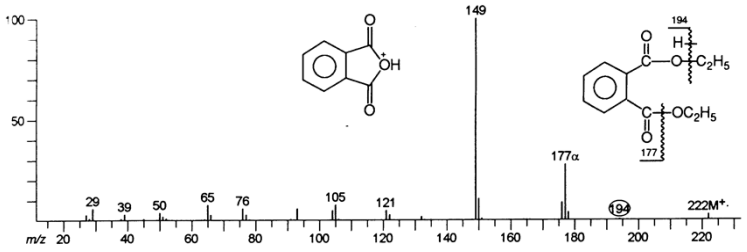


Figure 5.4. Mass spectrum of diethyl phthalate.

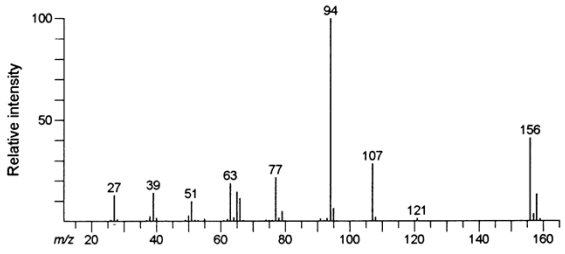
Assignment of the Most Probable Structure

- Use all information
- More complex for bigger molecules
  - Use MS databases
    - If postulated molecule not available, study closely related molecules
    - Abundance values can vary by an order of magnitude between instruments, so you must measure a reference spectra under the same conditions
- "Blind spots" of MS
  - E.g. close similarity of para- and meta-aromatic isomers, or insensitivity to chirality
  - Chapters 8 & 9 of McLafferty

Unknown 5.14

Unknown 5.14

m/z	Int.	m/z	Int.	m/z	Int.
27	14.	64	2.0	92	0.5
28	1.1	65	15.	93	1.6
38	2.2	66	12.	94	100.
39	14.	67	0.7	95	6.6
40	2.1	74	0.9	96	0.4
41	0.3	75	0.6	107	29.
49	0.9	76	0.6	108	2.2
50	3.0	77	22.	121	1.6
51	10.	78	1.8	156	41.
52	0.9	79	5.0	157	3.7
53	0.5	80	0.5	158	13.
55	1.5	91	1.5	159	1.2
63	19.				



Unknown 5.15

Unknown 5.15

m/z	Int.	m/z	Int.	m/z	Int.
15	9.2	54	5.7	82	11.
26	1.3	55	74.	83	46.
27	24.	56	100.	84	51.
28	6.1	57	38.	85	4.9
29	32.	58	2.9	87	1.0
30	0.8	59	3.0	88	0.7
33	0.4	60	4.9	89	11.
34	1.1	61	18.	90	0.6
35	2.8	62	1.6	91	0.5
39	19.	63	0.9	97	4.3
40	4.0	67	4.9	98	0.3
41	76.	68	18.	103	0.9
42	47.	69	59.	112	23.
43	74.	70	70.	113	2.0
44	3.3	71	15.	145	1.7
45	8.2	72	0.8	146	37.
46	3.6	73	0.9	147	3.7
47	29.	74	0.6	148	1.8
48	1.6	75	1.1		
53	4.7