

CONTENTS

CHAPTER 1 *Introduction* 1

CHAPTER 2 *Mass Spectrometry* 2

2.1 *Introduction* 2

2.2 *Instrumentation* 2

- 2.2.1 Magnetic Field Only (A.1) 3
- 2.2.2 Double Focusing (Electrostatic and Magnetic Fields) (A.2) 4
- 2.2.3 Quadrupole Mass Filter (B.1) 4
- 2.2.4 Quadrupole Ion Storage (Ion Trap) (B.2) 5
- 2.2.5 Time of Flight (C) 5
- 2.2.6 FT-ICR (Fourier Transform-Ion Cyclotron Resonance) (D) (Also termed FT-MS) 6
- 2.2.7 MS/MS (Tandem Mass Spectrometry) (E) 6

2.3 *The Mass Spectrum* 6

2.4 *Determination of a Molecular Formula* 7

- 2.4.1 Unit-Mass Molecular Ion and Isotope Peaks 7
- 2.4.2 High-Resolution Molecular Ion 8

2.5 *Recognition of the Molecular Ion Peak* 8

- 2.5.1 Other Useful Ionization Techniques 9
 - 2.5.1.1 Chemical Ionization (CI) 9
 - 2.5.1.2 Field Desorption (FD) 10
 - 2.5.1.3 Fast Ion Bombardment (FAB) 10
 - 2.5.1.4 Electrospray Ionization (ESI) 11
 - 2.5.1.5 Matrix Assisted Laser Desorption/Ionization (MALDI) 11

2.6 *Use of the Molecular Formula. Index of Hydrogen Deficiency* 11

2.7 *Fragmentation* 12

2.8 *Rearrangements* 14

2.9 *Derivatives* 15

2.10 *Mass Spectra of Some Chemical Classes* 15

- 2.10.1 Hydrocarbons 15
 - 2.10.1.1 Saturated Hydrocarbons 15
 - 2.10.1.2 Alkenes (Olefins) 17
 - 2.10.1.3 Aromatic and Alkyl Hydrocarbons 17
- 2.10.2 Hydroxy Compounds 18
 - 2.10.2.1 Alcohols 18
 - 2.10.2.2 Phenols 20
- 2.10.3 Ethers 20
 - 2.10.3.1 Aliphatic Ethers (and Acetals) 20
 - 2.10.3.2 Aromatic Ethers 22
- 2.10.4 Ketones 22
 - 2.10.4.1 Aliphatic Ketones 22
 - 2.10.4.2 Cyclic Ketones 23
 - 2.10.4.3 Aromatic Ketones 23
- 2.10.5 Aldehydes 24
 - 2.10.5.1 Aliphatic Aldehydes 24
 - 2.10.5.2 Aromatic Aldehydes 24
- 2.10.6 Carboxylic Acids 26
 - 2.10.6.1 Aliphatic Acids 26
 - 2.10.6.2 Aromatic Acids 26

- 2.10.7 Carboxylic Esters 27
 - 2.10.7.1 Aliphatic Esters 27
 - 2.10.7.2 Benzyl and Phenyl Esters 28
 - 2.10.7.3 Esters of Aromatic Acids 28
- 2.10.8 Lactones 29
- 2.10.9 Amines 29
 - 2.10.9.1 Aliphatic Amines 29
 - 2.10.9.2 Cyclic Amines 30
 - 2.10.9.3 Aromatic Amines (Anilines) 30
- 2.10.10 Amides 30
 - 2.10.10.1 Aliphatic Amides 30
 - 2.10.10.2 Aromatic Amides 31
- 2.10.11 Aliphatic Nitriles 31
- 2.10.12 Nitro Compounds 31
 - 2.10.12.1 Aliphatic Nitro Compounds 31
 - 2.10.12.2 Aromatic Nitro Compounds 31
- 2.10.13 Aliphatic Nitrites 32
- 2.10.14 Aliphatic Nitrates 32
- 2.10.15 Sulfur Compounds 32
 - 2.10.15.1 Aliphatic Mercaptans (Thiols) 32
 - 2.10.15.2 Aliphatic Sulfides 33
 - 2.10.15.3 Aliphatic Disulfides 34
- 2.10.16 Halogen Compounds 34
 - 2.10.16.1 Aliphatic Chlorides 34
 - 2.10.16.2 Aliphatic Bromides 35
 - 2.10.16.3 Aliphatic Iodides 35
 - 2.10.16.4 Aliphatic Fluorides 35
 - 2.10.16.5 Benzyl Halides 36
 - 2.10.16.6 Aromatic Halides 36
- 2.10.17 Heteroaromatic Compounds 36
- 2.10.18 Natural Products 37
 - 2.10.18.1 Amino Acids 37
 - 2.10.18.2 Steroids 38
 - 2.10.18.3 Triglycerides 38
- 2.10.19 Miscellaneous Classes 39

References 39

Problems 40

Appendices 45

- A. Formula Masses 45
- B. Common Fragment Ions 66
- C. Common Fragments Lost 69

CHAPTER 3 *Infrared Spectrometry* 71

3.1 *Introduction* 71

3.2 *Theory* 71

- 3.2.1 Coupled Interactions 74
- 3.2.2 Hydrogen Bonding 75

3.3 *Instrumentation* 76

- 3.3.1 Dispersion IR Spectrometer 76
- 3.3.2 Fourier Transform Infrared Spectrometer (Interferometer) 76

3.4 *Sample Handling* 77

3.5 Interpretation of Spectra 79

3.6 Characteristic Group Absorptions of Organic Molecules 81

- 3.6.1 Normal Alkanes (Paraffins) 81
 3.6.1.1 C—H Stretching Vibrations 82
 3.6.1.2 C—H Bending Vibrations 82
- 3.6.2 Branched-Chain Alkanes 83
 3.6.2.1 C—H Stretching Vibrations 83
 3.6.2.2 C—H Bending Vibrations 83
- 3.6.3 Cyclic Alkanes 83
 3.6.3.1 C—H Stretching Vibrations 83
 3.6.3.2 C—H Bending Vibrations 84
- 3.6.4 Alkenes 84
 3.6.4.1 C=C Stretching Vibrations 84
 3.6.4.2 Alkene C—H Stretching Vibrations 85
 3.6.4.3 Alkene C—H Bending Vibrations 85
- 3.6.5 Alkynes 85
 3.6.5.1 C≡C Stretching Vibrations 85
 3.6.5.2 C—H Stretching Vibrations 86
 3.6.5.3 C—H Bending Vibrations 86
- 3.6.6 Mononuclear Aromatic Hydrocarbons 86
 3.6.6.1 Out-of-Plane C—H Bending Vibrations 86
- 3.6.7 Polynuclear Aromatic Hydrocarbons 87
- 3.6.8 Alcohols and Phenols 87
 3.6.8.1 O—H Stretching Vibrations 87
 3.6.8.2 C—O Stretching Vibrations 90
 3.6.8.3 O—H Bending Vibrations 90
- 3.6.9 Ethers, Epoxides, and Peroxides 90
 3.6.9.1 C—O Stretching Vibrations 90
- 3.6.10 Ketones 92
 3.6.10.1 C=O Stretching Vibrations 92

$$\begin{array}{c} \text{O} \\ \parallel \\ \text{C} \end{array}$$

 3.6.10.2 C—C Stretching and Bending Vibrations 94
- 3.6.11 Aldehydes 94
 3.6.11.1 C=O Stretching Vibrations 94
 3.6.11.2 C—H Stretching Vibrations 94
- 3.6.12 Carboxylic Acids 95
 3.6.12.1 O—H Stretching Vibrations 95
 3.6.12.2 C=O Stretching Vibrations 96
 3.6.12.3 C—O Stretching and O—H Bending Vibrations 96
- 3.6.13 Carboxylate Anion 96
- 3.6.14 Esters and Lactones 97
 3.6.14.1 C=O Stretching Vibrations 97
 3.6.14.2 C—O Stretching Vibrations 98
- 3.6.15 Acid Halides 99
 3.6.15.1 C=O Stretching Vibrations 99
- 3.6.16 Carboxylic Acid Anhydrides 99
 3.6.16.1 C=O Stretching Vibrations 99
 3.6.16.2 C—O Stretching Vibrations 99
- 3.6.17 Amides and Lactams 99
 3.6.17.1 N—H Stretching Vibrations 101
 3.6.17.2 C=O Stretching Vibrations (Amide I Band) 101
 3.6.17.3 N—H Bending Vibrations (Amide II Band) 101
 3.6.17.4 Other Vibration Bands 101
 3.6.17.5 C=O Stretching Vibrations of Lactams 101
- 3.6.18 Amines 102
 3.6.18.1 N—H Stretching Vibrations 102
 3.6.18.2 N—H Bending Vibrations 102

- 3.6.18.3 C—N Stretching Vibrations 102
- 3.6.19 Amine Salts 103
 3.6.19.1 N—H Stretching Vibrations 103
 3.6.19.2 N—H Bending Vibrations 103
- 3.6.20 Amino Acids and Salts of Amino Acids 103
- 3.6.21 Nitriles 104
- 3.6.22 Isonitriles ($\text{R}-\text{N}^+\equiv\text{C}^-$), Cyanates ($\text{R}-\text{O}-\text{C}\equiv\text{N}$), Isocyanates ($\text{R}-\text{N}=\text{C}=\text{O}$), Thiocyanates ($\text{R}-\text{S}-\text{C}\equiv\text{N}$), and Isothiocyanates ($\text{R}-\text{N}=\text{C}=\text{S}$) 104
- 3.6.23 Compounds Containing —N=N—Group 104
- 3.6.24 Covalent Compounds Containing Nitrogen—Oxygen Bonds 104
 3.6.24.1 $\text{N}\equiv\text{O}$ Stretching Vibrations 105
- 3.6.25 Organic Sulfur Compounds 106
 3.6.25.1 S—H Stretching Vibrations 106
 3.6.25.2 C—S and C=S Stretching Vibrations 106
- 3.6.26 Compounds Containing Sulfur—Oxygen Bonds 107
 3.6.26.1 S=O Stretching Vibrations 107
- 3.6.27 Organic Halogen Compounds 108
- 3.6.28 Silicon Compounds 108
 3.6.28.1 Si—H Vibrations 108
 3.6.28.2 SiO—H and Si—O Vibrations 108
 3.6.28.3 Silicon—Halogen Stretching Vibrations 108
- 3.6.29 Phosphorus Compounds 109
 3.6.29.1 P=O and P—O Stretching Vibrations 109
- 3.6.30 Heteroaromatic Compounds 109
 3.6.30.1 C—H Stretching Vibrations 109
 3.6.30.2 N—H Stretching Frequencies 109
 3.6.30.3 Ring Stretching Vibrations (Skeletal Bands) 109
 3.6.30.4 C—H Out-of-Plane Bending 109

References 109

Problems 111

Appendices 120

- A. Transparent Regions of Solvent and Mulling Oils 120
- B. Spectra of Common Laboratory Substances 121
- C. Characteristic Group Absorptions 136
- D. Absorptions for Alkenes 141
- E. Absorptions for Phosphorus Compounds 142
- F. Absorptions for Heteroaromatics 143

CHAPTER 4 Proton Magnetic Resonance Spectrometry

144

- 4.1 Introduction 144
- 4.2 Continuous-Wave (CW) NMR Spectrometry 145
- 4.3 Relaxation 146
- 4.4 Pulsed Fourier Transform Spectrometry 148
- 4.5 Rotating Frame of Reference 149
- 4.6 Instrumentation and Sample Handling 149
- 4.7 Chemical Shift 151
- 4.8 Simple Spin Coupling 157
- 4.9 Protons on Oxygen, Nitrogen, and Sulfur Atoms 163

4.9.1 Protons on an Oxygen Atom	163
4.9.1.1 Alcohols	163
4.9.1.2 Water	165
4.9.1.3 Phenols	165
4.9.1.4 Enols	165
4.9.1.5 Carboxylic Acids	166
4.9.2 Protons on Nitrogen	166
4.9.3 Protons on Sulfur	168
4.10 Protons on or Near Chlorine, Bromine, or Iodine Nuclei	168
4.11 Coupling of Protons to Other Important Nuclei (^{19}F , D, ^{31}P , ^{29}Si , and ^{13}C)	168
4.11.1 Coupling of Protons to ^{19}F	168
4.11.2 Coupling of Protons to D	168
4.11.3 Coupling of Protons to ^{31}P	169
4.11.4 Coupling of Protons to ^{29}Si	169
4.11.5 Coupling of Protons to ^{13}C	169
4.12 Chemical Shift Equivalence	170
4.12.1 Determination of Chemical Shift Equivalence by Interchange Through Symmetry Operations	170
4.12.1.1 Interchange by Rotation Around a Simple Axis of Symmetry (C_n)	170
4.12.1.2 Interchange by Reflection Through a Plane of Symmetry (σ)	170
4.12.1.3 Interchange by Inversion Through a Center of Symmetry (i)	170
4.12.1.4 No Interchangeability by a Symmetry Operation	171
4.12.2 Determination of Chemical Shift Equivalence by Tagging (or Substitution)	172
4.12.3 Chemical Shift Equivalence by Rapid Interconversion of Structures	172
4.12.3.1 Keto–Enol Interconversion	172
4.12.3.2 Interconversion Around a “Partial Double Bond” (Restricted Rotation)	173
4.12.3.3 Interconversion Around the Single Bonds of Rings	174
4.12.3.4 Interconversion Around the Single Bonds of Chains	174
4.13 Magnetic Equivalence (Spin–Coupling Equivalence)	174
4.14 AMX, ABX, and ABC Rigid Systems with Three Coupling Constants	178
4.15 Conformationally Mobile, Open-Chain Systems. Virtual Coupling	179
4.15.1 Unsymmetrical Chains	171
4.15.1.1 1-Nitropropane	179
4.15.1.2 1-Hexanol	179
4.15.2 Symmetrical Chains	181
4.15.2.1 Dimethyl Succinate	181
4.15.2.2 Dimethyl Glutarate	181
4.15.2.3 Dimethyl Adipate	181
4.15.3 Less Symmetrical Chains	182
4.15.3.1 3-Methylglutaric Acid	182
4.16 Chirality	183
4.16.1 One Chiral Center	183
4.16.2 Two Chiral Centers	185
4.17 Vicinal and Geminal Coupling	185

4.18 Long-Range Coupling	187
4.19 Spin Decoupling	187
4.20 Nuclear Overhauser Effect Difference Spectrometry, $^1\text{H}/^1\text{H}$ Proximity Through Space	189
4.21 NMR Shift Reagents	191
4.22 Addendum—Analysis of First-Order Patterns	191
References	193
Problems	194
Appendices	200
A. Chart A.1 Chemical Shifts of Protons on a Carbon Atom Adjacent (α Position) to a Functional Group in Aliphatic Compounds (M—Y)	200
Chart A.2 Chemical Shifts of Protons on a Carbon Atom Once Removed (β Position) from a Functional Group in Aliphatic Compounds (M—C—Y)	202
B. Effect on Chemical Shifts by Two or Three Directly Attached Functional Groups	203
C. Chemical Shifts in Alicyclic and Heterocyclic Rings	205
D. Chemical Shifts in Unsaturated and Aromatic Systems	206
E. Protons on Heteroatoms	211
F. Proton Spin-Coupling Constants	212
G. Chemical Shifts and Multiplicities of Residual Protons in Commercially Available Deuterated Solvents (Merck & Co., Inc.)	214
H. Properties of Several Nuclei	216

CHAPTER 5 ^{13}C NMR Spectrometry 217

5.1 Introduction	217
5.2 Peak Assignments	221
5.2.1 Peak Intensity	221
5.2.2 Deuterium Substitution	222
5.2.3 Chemical Shift Equivalence	222
5.3 Chemical Classes and Chemical Shifts	222
5.3.1 Alkanes	223
5.3.1.1 Linear and Branched Alkanes	223
5.3.2 Effects of Substituents on Alkanes	225
5.3.3 Cycloalkanes and Saturated Heterocyclics	225
5.3.4 Alkenes	226
5.3.5 Alkynes	227
5.3.6 Aromatic Compounds	228
5.3.7 Heteroaromatic Compounds	230
5.3.8 Alcohols	230
5.3.9 Ethers, Acetals, and Epoxides	230
5.3.10 Halides	232
5.3.11 Amines	232
5.3.12 Thiols, Sulfides, and Disulfides	232
5.3.13 Functional Groups Containing Carbon	232
5.3.13.1 Ketones and Aldehydes	232
5.3.13.2 Carboxylic Acids, Esters, Chlorides, Anhydrides, Amides, and Nitriles	233
5.3.13.3 Oximes	233

5.4 ^{13}C — ^1H Spin Coupling (*J* values) 223

5.5 DEPT 236

5.6 Quantitative Analysis 236

References 239

Problems 239

Appendices 245

A. The ^{13}C Chemical Shifts, Couplings, and
Multiplicities of Common NMR Solvents 245B. Comparison of ^1H and ^{13}C Chemical Shifts 246C. The ^{13}C Correlation Chart for Chemical
Classes 247D. ^{13}C NMR Data for Several Natural Products
(δ) 249CHAPTER 6 **Correlation NMR
Spectrometry** 250

6.1 Introduction 250

6.2 Theory 250

6.3 Correlation Spectrometry 253

6.4 ^1H — ^1H COSY 2556.5 Double-Quantum Filtered ^1H — ^1H COSY 255

6.5.1 Ipsenol 256

6.5.2 Caryophyllene oxide 258

6.6 ^1H — ^{13}C COSY: HETCOR 259

6.7 Proton-Detected HETCOR: HMQC 262

6.8 Proton-Detected, Long-Range ^1H — ^{13}C
Heteronuclear Correlation: HMBC 2636.9 ^{13}C — ^{13}C Correlations: INADEQUATE 268

6.10 Relayed Coherence Transfer: TOCSY 270

6.11 Gradient Field NMR 273

References 274

Problems 274

CHAPTER 7 **Spectrometry of Other
Important Nuclei** 280

7.1 Introduction 280

7.2 ^{15}N Nuclear Magnetic Resonance 2817.3 ^{19}F Nuclear Magnetic Resonance 2877.4 ^{29}Si Nuclear Magnetic Resonance 2897.5 ^{31}P Nuclear Magnetic Resonance 291

7.6 Conclusions 293

References 295

Problems 296

CHAPTER 8 **A. Introduction** 301
References 302
B. Solved Problems 303CHAPTER 9 **A. Introduction** 325
B. Assigned Problems 326