



CONTENTS

CHAPTER 1

MOLECULAR FORMULAS AND WHAT CAN BE LEARNED FROM THEM 1

1.1	Elemental Analysis and Calculations	1
1.2	Determination of Molecular Mass	5
1.3	Molecular Formulas	5
1.4	Index of Hydrogen Deficiency	6
1.5	The Rule of Thirteen	9
1.6	The Nitrogen Rule	12
	Problems	12
	References	13

CHAPTER 2

INFRARED SPECTROSCOPY 14

2.1	The Infrared Absorption Process	15
2.2	Uses of the Infrared Spectrum	16
2.3	The Modes of Stretching and Bending	17
2.4	Bond Properties and Absorption Trends	19
2.5	The Infrared Spectrometer	22
	A. Dispersive Infrared Spectrometers	22
	B. Fourier Transform Spectrometers	24
2.6	Preparation of Samples for Infrared Spectroscopy	25
2.7	What to Look for When Examining Infrared Spectra	26
2.8	Correlation Charts and Tables	28
2.9	How to Approach the Analysis of a Spectrum (Or What You Can Tell at a Glance)	30

Contents

2.10	Hydrocarbons: Alkanes, Alkenes, and Alkynes	31
	A. Alkanes	31
	B. Alkenes	33
	C. Alkynes	35
2.11	Aromatic Rings	43
2.12	Alcohols and Phenols	47
2.13	Ethers	50
2.14	Carbonyl Compounds	52
	A. Factors That Influence the C=O Stretching Vibration	54
	B. Aldehydes	56
	C. Ketones	58
	D. Carboxylic Acids	62
	E. Esters	64
	F. Amides	70
	G. Acid Chlorides	72
	H. Anhydrides	73
2.15	Amines	74
2.16	Nitriles, Isocyanates, Isothiocyanates, and Imines	77
2.17	Nitro Compounds	79
2.18	Carboxylate Salts, Amine Salts, and Amino Acids	80
2.19	Sulfur Compounds	81
2.20	Phosphorus Compounds	84
2.21	Alkyl and Aryl Halides	84
2.22	The Background Spectrum	86
2.23	How to Solve Infrared Spectral Problems	87
	Problems	92
	References	106

CHAPTER 3

MASS SPECTROMETRY

PART ONE: BASIC THEORY, INSTRUMENTATION, AND SAMPLING TECHNIQUES 107

3.1	The Mass Spectrometer: Overview	107
3.2	Sample Introduction	108
3.3	Ionization Methods	109
	A. Electron Ionization (EI)	109
	B. Chemical Ionization (CI)	110
	C. Desorption Ionization Techniques (SIMS, FAB, and MALDI)	115
	D. Electrospray Ionization (ESI)	117

3.4	Mass Analysis	119
	A. The Magnetic Sector Mass Analyzer	119
	B. Double-Focusing Mass Analyzers	120
	C. Quadrupole Mass Analyzers	120
	D. Time-of-Flight Mass Analyzers	124
3.5	Detection and Quantitation: The Mass Spectrum	125
3.6	Determination of Molecular Weight	129
3.7	Determination of Molecular Formulas	131
	A. Precise Mass Determination	131
	B. Isotope Ratio Data	132
	Problems	137
	References	137

CHAPTER 4

MASS SPECTROMETRY

PART TWO: FRAGMENTATION AND STRUCTURAL ANALYSIS 139

4.1	The Initial Ionization Event	139
4.2	Fundamental Fragmentation Processes	140
	A. Stevenson's Rule	141
	B. Radical-Site Initiated Cleavage: α -Cleavage	141
	C. Charge-Site Initiated Cleavage: Inductive Cleavage	141
	D. Two-Bond Cleavage	142
	E. Retro Diels-Alder Cleavage	143
	F. McLafferty Rearrangements	143
	G. Other Cleavage Types	144
4.3	Fragmentation Patterns of Hydrocarbons	144
	A. Alkanes	144
	B. Cycloalkanes	147
	C. Alkenes	148
	D. Alkynes	150
	E. Aromatic Hydrocarbons	151
4.4	Fragmentation Patterns of Alcohols, Phenols, and Thiols	156
4.5	Fragmentation Patterns of Ethers and Sulfides	163
4.6	Fragmentation Patterns of Carbonyl-Containing Compounds	166
	A. Aldehydes	166
	B. Ketones	169
	C. Esters	172
	D. Carboxylic Acids	175
4.7	Fragmentation Patterns of Amines	178

Contents

4.8	Fragmentation Patterns of Other Nitrogen Compounds	182
4.9	Fragmentation Patterns of Alkyl Chlorides and Alkyl Bromides	184
4.10	Computerized Matching of Spectra with Spectral Libraries	189
4.11	Strategic Approach to Analyzing Mass Spectra and Solving Problems	191
4.12	How to Solve Mass Spectral Problems	192
	References	214

CHAPTER 5

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

PART ONE: BASIC CONCEPTS 215

5.1	Nuclear Spin States	215
5.2	Nuclear Magnetic Moments	216
5.3	Absorption of Energy	217
5.4	The Mechanism of Absorption (Resonance)	219
5.5	Population Densities of Nuclear Spin States	221
5.6	The Chemical Shift and Shielding	222
5.7	The Nuclear Magnetic Resonance Spectrometer	224
	A. The Continuous-Wave (CW) Instrument	224
	B. The Pulsed Fourier Transform (FT) Instrument	226
5.8	Chemical Equivalence—A Brief Overview	230
5.9	Integrals and Integration	231
5.10	Chemical Environment and Chemical Shift	233
5.11	Local Diamagnetic Shielding	234
	A. Electronegativity Effects	234
	B. Hybridization Effects	236
	C. Acidic and Exchangeable Protons; Hydrogen Bonding	237
5.12	Magnetic Anisotropy	238
5.13	Spin–Spin Splitting ($n + 1$) Rule	241
5.14	The Origin of Spin–Spin Splitting	244
5.15	The Ethyl Group (CH_3CH_2-)	246
5.16	Pascal's Triangle	247
5.17	The Coupling Constant	248
5.18	A Comparison of NMR Spectra at Low- and High-Field Strengths	251
5.19	Survey of Typical ^1H NMR Absorptions by Type of Compound	252
	A. Alkanes	252
	B. Alkenes	254
	C. Aromatic Compounds	255
	D. Alkynes	256
	E. Alkyl Halides	258
	F. Alcohols	259

G. Ethers	261
H. Amines	262
I. Nitriles	263
J. Aldehydes	264
K. Ketones	265
L. Esters	267
M. Carboxylic Acids	268
N. Amides	269
O. Nitroalkanes	270
5.20 How to Solve NMR Spectra Problems	271
Problems	276
References	288

CHAPTER 6

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

PART TWO: CARBON-13 SPECTRA, INCLUDING HETERONUCLEAR COUPLING WITH OTHER NUCLEI 290

6.1 The Carbon-13 Nucleus	290
6.2 Carbon-13 Chemical Shifts	291
A. Correlation Charts	291
B. Calculation of ^{13}C Chemical Shifts	293
6.3 Proton-Coupled ^{13}C Spectra—Spin–Spin Splitting of Carbon-13 Signals	294
6.4 Proton-Decoupled ^{13}C Spectra	296
6.5 Nuclear Overhauser Enhancement (NOE)	297
6.6 Cross-Polarization: Origin of the Nuclear Overhauser Effect	299
6.7 Problems with Integration in ^{13}C Spectra	302
6.8 Molecular Relaxation Processes	303
6.9 Off-Resonance Decoupling	305
6.10 A Quick Dip into DEPT	305
6.11 Some Sample Spectra—Equivalent Carbons	308
6.12 Non-Equivalent Carbon Atoms	310
6.13 Compounds with Aromatic Rings	311
6.14 Carbon-13 NMR Solvents—Heteronuclear Coupling of Carbon to Deuterium	313
6.15 Heteronuclear Coupling of Carbon-13 to Fluorine-19	316
6.16 Heteronuclear Coupling of Carbon-13 to Phosphorus-31	318
6.17 Carbon and Proton NMR: How to Solve a Structure Problem	319
Problems	323
References	347

CHAPTER 7

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

PART THREE: SPIN-SPIN COUPLING 349

7.1	Coupling Constants: Symbols	349
7.2	Coupling Constants: The Mechanism of Coupling	350
	A. One-Bond Couplings (1J)	351
	B. Two-Bond Couplings (2J)	352
	C. Three-Bond Couplings (3J)	355
	D. Long-Range Couplings (4J – nJ)	360
7.3	Magnetic Equivalence	363
7.4	Spectra of Diastereotopic Systems	368
	A. Diastereotopic Hydrogens: Ethyl 3-Hydroxybutanoate	368
	B. Diastereotopic Hydrogens: The Diels-Alder Adduct of Anthracene-9-methanol and <i>N</i> -Methylmaleimide	372
	C. Diastereotopic Hydrogens: 4-Methyl-2-pentanol	374
	D. Diastereotopic Methyl Groups: 4-Methyl-2-pentanol	376
7.5	Nonequivalence within a Group—The Use of Tree Diagrams when the $n + 1$ Rule Fails	377
7.6	Measuring Coupling Constants from First-Order Spectra	380
	A. Simple Multiplets—One Value of J (One Coupling)	380
	B. Is the $n + 1$ Rule Ever <i>Really</i> Obeyed?	382
	C. More Complex Multiplets—More Than One Value of J	384
7.7	Second-Order Spectra—Strong Coupling	388
	A. First-Order and Second-Order Spectra	388
	B. Spin System Notation	389
	C. The A_2 , AB , and AX Spin Systems	390
	D. The $AB_2 \dots AX_2$ and $A_2B_2 \dots A_2X_2$ Spin Systems	390
	E. Simulation of Spectra	392
	F. The Absence of Second-Order Effects at Higher Field	392
	G. Deceptively Simple Spectra	393
7.8	Alkenes	397
7.9	Measuring Coupling Constants—Analysis of an Allylic System	401
7.10	Aromatic Compounds—Substituted Benzene Rings	405
	A. Monosubstituted Rings	405
	B. <i>para</i> -Disubstituted Rings	408
	C. Other Substitution	410
7.11	Coupling in Heteroaromatic Systems	414
7.12	Heteronuclear Coupling of ^1H to ^{19}F and ^{31}P	416
	A. ^1H to ^{19}F Couplings	416
	B. ^1H to ^{31}P Couplings	418

7.13	How to Solve Problems Involving Coupling Constant Analysis	420
	Problems	424
	References	455

CHAPTER 8

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

PART FOUR: OTHER TOPICS IN ONE-DIMENSIONAL NMR 457

8.1	Protons on Oxygen: Alcohols	457
8.2	Exchange in Water and D ₂ O	460
	A. Acid/Water and Alcohol/Water Mixtures	460
	B. Deuterium Exchange	461
	C. Peak Broadening Due to Exchange	463
8.3	Other Types of Exchange: Tautomerism	464
8.4	Protons on Nitrogen: Amines	466
8.5	Protons on Nitrogen: Quadrupole Broadening and Decoupling	470
8.6	Amides	471
8.7	Solvent Effects	475
8.8	Chemical Shift Reagents	479
8.9	Chiral Resolving Agents	481
8.10	Determining Absolute and Relative Configuration via NMR	484
	A. Determining Absolute Configuration	484
	B. Determining Relative Configuration	486
8.11	Nuclear Overhauser Effect Difference Spectra	487
8.12	How to Solve Problems Involving Advanced 1-D Methods	489
	Problems	490
	References	509

CHAPTER 9

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

PART FIVE: ADVANCED NMR TECHNIQUES 511

9.1	Pulse Sequences	511
9.2	Pulse Widths, Spins, and Magnetization Vectors	513
9.3	Pulsed Field Gradients	517
9.4	The DEPT Experiment: Number of Protons Attached to ¹³ C Atoms	519
9.5	Determining the Number of Attached Hydrogens	522
	A. Methine Carbons (CH)	522
	B. Methylene Carbons (CH ₂)	523
	C. Methyl Carbons (CH ₃)	525
	D. Quaternary Carbons (C)	525
	E. The Final Result	526

Contents

9.6	Introduction to Two-Dimensional Spectroscopic Methods	526
9.7	The COSY Technique: ^1H - ^1H Correlations	526
	A. An Overview of the COSY Experiment	527
	B. How to Read COSY Spectra	528
9.8	The HETCOR Technique: ^1H - ^{13}C Correlations	534
	A. An Overview of the HETCOR Experiment	535
	B. How to Read HETCOR Spectra	535
9.9	Inverse Detection Methods	539
9.10	The NOESY Experiment	539
9.11	Magnetic Resonance Imaging	541
9.12	Solving a Structural Problem Using Combined 1-D and 2-D Techniques	542
	A. Index of Hydrogen Deficiency and Infrared Spectrum	543
	B. Carbon-13 NMR Spectrum	543
	C. DEPT Spectrum	544
	D. Proton NMR Spectrum	545
	E. COSY NMR Spectrum	547
	F. HETCOR (HSQC) NMR Spectrum	548
	Problems	549
	References	576

CHAPTER 10

ULTRAVIOLET SPECTROSCOPY 577

10.1	The Nature of Electronic Excitations	577
10.2	The Origin of UV Band Structure	579
10.3	Principles of Absorption Spectroscopy	579
10.4	Instrumentation	580
10.5	Presentation of Spectra	581
10.6	Solvents	582
10.7	What Is a Chromophore?	583
10.8	The Effect of Conjugation	586
10.9	The Effect of Conjugation on Alkenes	587
10.10	The Woodward-Fieser Rules for Dienes	590
10.11	Carbonyl Compounds; Enones	593
10.12	Woodward's Rules for Enones	596
10.13	α , β -Unsaturated Aldehydes, Acids, and Esters	598
10.14	Aromatic Compounds	598
	A. Substituents with Unshared Electrons	600
	B. Substituents Capable of π -Conjugation	602
	C. Electron-Releasing and Electron-Withdrawing Effects	602
	D. Disubstituted Benzene Derivatives	602
	E. Polynuclear Aromatic Hydrocarbons and Heterocyclic Compounds	605

10.15	Model Compound Studies	607
10.16	Visible Spectra: Color in Compounds	608
10.17	What to Look for in an Ultraviolet Spectrum: A Practical Guide	609
	Problems	611
	References	613

CHAPTER 11

COMBINED STRUCTURE PROBLEMS 614

Example 1	616
Example 2	618
Example 3	620
Example 4	623
Problems	624
Sources of Additional Problems	689

ANSWERS TO SELECTED PROBLEMS ANS-1

APPENDICES A-1

Appendix 1	Infrared Absorption Frequencies of Functional Groups	A-1
Appendix 2	Approximate ^1H Chemical Shift Ranges (ppm) for Selected Types of Protons	A-8
Appendix 3	Some Representative ^1H Chemical Shift Values for Various Types of Protons	A-9
Appendix 4	^1H Chemical Shifts of Selected Heterocyclic and Polycyclic Aromatic Compounds	A-12
Appendix 5	Typical Proton Coupling Constants	A-13
Appendix 6	Calculation of Proton (^1H) Chemical Shifts	A-18
Appendix 7	Approximate ^{13}C Chemical-Shift Values (ppm) for Selected Types of Carbon	A-22
Appendix 8	Calculation of ^{13}C Chemical Shifts	A-23
Appendix 9	^{13}C Coupling Constants to Proton, Deuterium, Fluorine, and Phosphorus	A-33
Appendix 10	^1H and ^{13}C Chemical Shifts for Common NMR Solvents	A-36
Appendix 11	Common Fragment Ions under Mass 105	A-37
Appendix 12	A Handy-Dandy Guide to Mass Spectral Fragmentation Patterns	A-40
Appendix 13	Index of Spectra	A-43

INDEX I-1