

Contents

Foreword V

Preface VII

1	Introduction to Nuclear Magnetic Resonance	1
1.1	Basic Principle of NMR	1
1.1.1	Nuclear Magnetic Momentum	1
1.1.2	Quantization of Angular Momentum and Magnetic Moment	3
1.1.3	Nuclear Magnetic Resonance	4
1.2	Chemical Shift	6
1.2.1	Shielding Constant	6
1.2.2	Chemical Shift δ	7
1.3	Spin-spin Coupling	8
1.3.1	Spin-spin Coupling Produces NMR Signal Splitting	8
1.3.2	Energy Level Diagram	9
1.3.3	Coupling Constant J	10
1.4	Magnetization	11
1.4.1	Magnetization Concept	11
1.4.2	Rotating Frame	12
1.5	Relaxation Process	14
1.5.1	What is a Relaxation Process?	14
1.5.2	Longitudinal and Transverse Relaxation	15
1.5.3	Width of an NMR Signal	17
1.6	Pulse-Fourier Transform NMR Spectrometer	18
1.6.1	Application of Strong and Short RF Pulses	18
1.6.2	Time Domain Signal and Frequency Domain Spectrum, and their Fourier Transform	20
1.6.3	FT-NMR with Respect to the Fourier Decomposition	22
1.6.4	Advantages of an FT-NMR Spectrometer	24
1.7	Recent Developments in NMR Spectroscopy	25
1.8	References	26

2	¹H NMR Spectroscopy	27
2.1	Chemical Shift	28
2.1.1	Reference for Chemical Shift	28
2.1.2	Factors Affecting Chemical Shifts	28
2.1.3	Chemical Shift Values of Common Functional Groups	34
2.2	Coupling Constant J	38
2.2.1	Vector Model for Couplings	38
2.2.2	1J and 2J	39
2.2.3	3J	40
2.2.4	Coupling Constants of Long-range Couplings	43
2.2.5	Couplings in a Phenyl Ring or in a Heteroaromatic Ring	43
2.3	Spin-spin Coupling System and Classification of NMR Spectra	45
2.3.1	Chemical Equivalence	45
2.3.2	Magnetic Equivalence	49
2.3.3	Spin System	50
2.3.4	Classification of NMR Spectra	51
2.4	Common Second-order Spectra	52
2.4.1	AB System	52
2.4.2	AB ₂ System	54
2.4.3	AMX System	55
2.4.4	ABX System	55
2.4.5	AA'BB' System	57
2.5	Spectra of Common Functional Groups	57
2.5.1	Substituted Phenyl Ring	57
2.5.2	Substituted Heteroaromatic Ring	60
2.5.3	Mono-substituted Ethylene	60
2.5.4	Normal Long-chain Alkyl	60
2.6	Methods for Assisting the Spectrum Analysis	61
2.6.1	Using a Spectrometer with a High Frequency	61
2.6.2	Deuterium Exchange	61
2.6.3	Medium Effect	62
2.6.4	Shift Reagents	62
2.6.5	Spectral Simulation by Computer	62
2.7	Double Resonance	62
2.7.1	Spin Decoupling	63
2.7.2	Nuclear Overhauser Effect	67
2.8	Dynamic Nuclear Magnetic Resonance	70
2.8.1	Description of Dynamic Nuclear Magnetic Resonance	70
2.8.2	Spectral Peak of Reactive Hydrogen Atom (OH, NH and SH)	72
2.9	Interpreting ¹ H NMR Spectra	74
2.9.1	Sampling and Measurement	75
2.9.2	Steps for ¹ H Spectrum Interpretation	75
2.9.3	Examples of ¹ H Spectrum Interpretation	78
2.10	References	89

3	^{13}C NMR Spectroscopy	91
3.1	Introduction	91
3.1.1	Advantages of ^{13}C NMR Spectra	91
3.1.2	Difficulties in the Measurement of ^{13}C NMR Spectra	92
3.1.3	^{13}C NMR Spectra	92
3.2	Chemical Shift	92
3.2.1	Paramagnetic Shielding is the Decisive Factor for Chemical Shifts	93
3.2.2	Alkanes and their Derivatives	93
3.2.3	Cycloalkanes and their Derivatives	95
3.2.4	Alkenes and their Derivatives	96
3.2.5	Benzene and its Derivatives	97
3.2.6	Carbonyl Compounds	99
3.2.7	Influences of Hydrogen Bonds and the Medium	101
3.3	Coupling and Decoupling Methods in ^{13}C Spectra	101
3.3.1	Coupling in ^{13}C Spectra	101
3.3.2	Broadband Decoupling	102
3.3.3	Off-resonance Decoupling	104
3.3.4	Selective Decoupling	104
3.3.5	Gated Decoupling	104
3.4	Relaxation	105
3.4.1	Why does the Discussion of Relaxation of ^{13}C Nuclei Require a Whole Section?	105
3.4.2	Basic Concepts of the Relaxation of ^{13}C Nuclei	105
3.4.3	Measurement of Relaxation Time	106
3.4.4	Application of T_1	109
3.5	Interpretation of ^{13}C NMR Spectra	110
3.5.1	Sampling and Plotting	110
3.5.2	Steps for the Interpretation of ^{13}C Spectra	111
3.5.3	Examples of the Interpretation of ^{13}C Spectra	113
3.6	References	126
4	Application of Pulse Sequences and Two-dimensional NMR Spectroscopy	127
4.1	Fundamentals	127
4.1.1	Transverse Magnetization Vector	127
4.1.2	Coherence and Related Topics	130
4.1.3	Spin Echo	132
4.1.4	The Phase of an NMR Signal is Modulated by the Chemical Shift	136
4.1.5	Bilinear Rotational Decoupling, BIRD	137
4.1.6	Spin Locking	138
4.1.7	Isotropic Mixing	141

4.1.8	Selective Population Inversion	143
4.1.9	Pulsed-field Gradient	147
4.1.10	Shaped Pulse	152
4.2	Spectrum Editing	154
4.2.1	<i>J</i> Modulation or APT	154
4.2.2	INEPT (Insensitive Nuclei Enhancement by Polarization Transfer)	157
4.2.3	DEPT (Distortionless Enhancement by Polarization Transfer)	160
4.3	Introduction to 2D NMR	162
4.3.1	What are 2D NMR Spectra?	162
4.3.2	Time Axis of 2D NMR	163
4.3.3	Classification of 2D NMR Spectra	164
4.3.4	Illustration of 2D NMR Spectra	164
4.4	<i>J</i> Resolved Spectra	165
4.4.1	Homonuclear <i>J</i> Resolved Spectra	165
4.4.2	Heteronuclear <i>J</i> Resolved Spectra	168
4.5	Heteronuclear Shift Correlation Spectroscopy	169
4.5.1	H,C-COSY	169
4.5.2	COLOC	172
4.5.3	H,X-COSY	173
4.6	Homonuclear Shift Correlation Spectroscopy	174
4.6.1	COSY	175
4.6.2	Phase-sensitive Homonuclear Shift Correlation Spectroscopy	178
4.6.3	COSY-45 (β -COSY)	182
4.6.4	COSY with Decoupling on the ω_1 Axis	183
4.6.5	COSYLR	184
4.6.6	DQF-COSY	186
4.7	NOESY and its Variations	187
4.7.1	NOESY	188
4.7.2	ROESY	189
4.7.3	HOESY	191
4.8	Relayed Correlation Spectra and Total Correlation Spectra	192
4.8.1	RCOSY	192
4.8.2	Heteronuclear Relayed COSY	193
4.8.3	Total Correlation Spectroscopy (TOCSY)	195
4.9	Multiple Quantum 2D NMR Spectra	198
4.9.1	2D INADEQUATE	198
4.9.2	Two-dimensional Double Quantum Spectra of ^1H	201
4.10	^1H Detected Heteronuclear Correlation Spectra	202
4.10.1	HMQC and HSQC	203
4.10.2	HMBC	206
4.11	Combined 2D NMR Spectra	208
4.12	Three-dimensional NMR Spectra	209
4.12.1	Principle of Three-dimensional NMR Spectra	209
4.12.2	Classification of 3D NMR Spectra	210

4.12.3	Application of 3D NMR Spectra	210
4.13	DOSY	211
4.14	References	213
5	Organic Mass Spectrometry	215
5.1	Fundamentals of Organic Mass Spectrometry	216
5.1.1	Instruments	216
5.1.2	Major Specifications	216
5.1.3	Mass Spectrum	217
5.1.4	Ion Types in Organic Mass Spectrometry	217
5.2	Mass Analyzers	219
5.2.1	Single-focusing or Double-focusing Mass Analyzers	219
5.2.2	Quadrupole Mass Analyzers	221
5.2.3	Ion Trap	223
5.2.4	Fourier Transform Mass Spectrometer	228
5.2.5	Time-of-flight (TOF) MS	231
5.3	Ionization	233
5.3.1	Electron Impact Ionization, EI	233
5.3.2	Chemical Ionization, CI	234
5.3.3	Field Ionization and Field Desorption	235
5.3.4	Fast Atom Bombardment, FAB, and Liquid Secondary Ion Mass Spectrometry, LSIMS	236
5.3.5	Matrix-assisted Laser Desorption-ionization, MALDI	236
5.3.6	Atmospheric Pressure Ionization, API	237
5.4	Metastable Ions and their Measurement	238
5.4.1	Metastable Ions Produced in the Second Field-free Region	240
5.4.2	Metastable Ions Produced in the First Field-free Region	241
5.4.3	Ion Kinetic Energy Spectrum (IKES)	242
5.4.4	Mass-analyzed Ion Kinetic Energy Spectrum (MIKES)	242
5.4.5	Linked Scanning	242
5.4.6	Information Provided by Metastable Ions	245
5.4.7	Peak Shapes of Metastable Ions	246
5.5	Tandem Mass Spectrometry (MS^n)	246
5.5.1	Collision-induced Dissociation (CID)	246
5.5.2	Tandem Mass Spectrometry	248
5.6	Combination of Chromatography and Mass Spectrometry	252
5.6.1	GC-MS	252
5.6.2	LC-MS and LC- MS^n	253
5.7	References	254
6	Interpretation of Mass Spectra	257
6.1	Determination of Molecular Weight and Elemental Composition	257
6.1.1	Determination of Molecular Weight by an EI Spectrum	257

6.1.2	Determination of the Molecular Weight from a Multiply-charged Ion Cluster in an ESI Spectrum	259
6.1.3	Postulation of the Molecular Weight from a Spectrum Obtained Using Soft Ionization Techniques	261
6.1.4	Determination of the Molecular Formula from High Resolution MS Data	261
6.1.5	Peak Matching	262
6.1.6	Postulation of the Molecular Weight from Low Resolution MS Data	262
6.1.7	Measurement of Exact Masses by a TOF or Quadrupole	265
6.2	Reactions and their Mechanisms in Organic Mass Spectrometry	265
6.2.1	Basic Knowledge	265
6.2.2	Simple Cleavage	266
6.2.3	Rearrangements	273
6.2.4	Cleavage of Alicyclic Compounds	279
6.2.5	Consecutive Decompositions of Primary Fragmentation Ions	281
6.2.6	Stevenson-Audier's Rule	281
6.2.7	Methods to Study Reaction Mechanisms of Organic Mass Spectrometry	283
6.3	Mass Spectrum Patterns of Common Functional Groups	284
6.3.1	Alkanes	284
6.3.2	Unsaturated Hydrocarbons	286
6.3.3	Aliphatic Compounds Containing Saturated Heteroatoms	287
6.3.4	Aliphatic Compounds Containing Unsaturated Heteroatoms	290
6.3.5	Alkyl Benzenes	291
6.3.6	Aromatic Compounds with Heteroatom Substitutions	292
6.3.7	Heteroaromatic Compounds and their Derivatives	293
6.4	Interpretation of Mass Spectra	293
6.4.1	Steps of the Interpretation	294
6.4.2	Examples	295
6.5	Library Retrieval of Mass Spectra	305
6.6	Interpretation of the Mass Spectra from Soft Ionization	310
6.6.1	Mass Spectra from CI	310
6.6.2	Mass Spectra from FAB	311
6.6.3	Mass Spectra from MALDI	312
6.6.4	Mass Spectra from ESI	313
6.6.5	Mass Spectra from APCI	314
6.7	References	314
7	Infrared Spectroscopy and Raman Spectroscopy	315
7.1	General Information on Infrared Spectroscopy	315
7.1.1	Wavelength and Wavenumber	315
7.1.2	Near, Medium and Far Infrared Rays	316
7.1.3	The Ordinate of IR Spectra	316

7.2	Basic Theory of IR Spectroscopy	316
7.2.1	IR Absorption Frequencies of a Diatomic Molecule	316
7.2.2	IR Absorption Frequencies of a Polyatomic Molecule	320
7.2.3	IR Absorption Intensities	322
7.3	Characteristic Frequencies of Functional Groups	322
7.3.1	Functional Groups Possessing Characteristic Frequencies	322
7.3.2	Factors Affecting Absorption Frequencies	323
7.3.3	Characteristic Frequencies of Common Functional Groups	324
7.4	Interpretation of IR Spectra	325
7.4.1	Wavenumber Regions of IR Absorption Bands	325
7.4.2	Fingerprint and Functional Group Regions	327
7.4.3	Key Points for the Interpretation of IR Spectra	328
7.4.4	Examples of IR Spectrum Interpretation	329
7.5	Recent Developments in Infrared Spectroscopy	334
7.5.1	Step Scan	334
7.5.2	Photo-acoustic Spectroscopy	337
7.5.3	Time-resolved Spectroscopy	339
7.5.4	Two-dimensional Infrared Spectroscopy	340
7.5.5	Infrared Microscope and Chemical Imaging	343
7.5.6	GC-FT-IR	344
7.6	Principle and Application of Raman Spectroscopy	346
7.6.1	Principle of Raman Spectroscopy	346
7.6.2	Advantages and Applications of Raman Spectroscopy	350
7.6.3	FT Raman Spectrometer	352
7.7	References	354
8	Identification of an Unknown Compound through a Combination of Spectra	355
8.1	Structural Identification of an Unknown Compound by Combination of One-dimensional NMR and Other Spectra	356
8.2	Determination of the Functional Groups (or Structural Units) of an Unknown Compound	358
8.2.1	Substituted Benzene Ring	359
8.2.2	Normal Long-chain Alkyl Groups	360
8.2.3	Alcohols and Phenols	360
8.2.4	Carbonyl Compounds	361
8.3	Deduction of the Structure of an Organic Compound on the Basis of 2D NMR Spectra	361
8.3.1	Shift Correlation Spectra as the Key to Structural Postulation	363
8.3.2	Deduction of the Structure of an Unknown Compound by Using Mainly HMQC-TOCSY	366
8.3.3	Postulating an Unknown Structure by 2D INADEQUATE	368
8.4	Examples of Structural Identification or Assignment	369
8.5	References	398

9	Determination of Configuration and Conformation of Organic Compounds by Spectroscopic Methods	399
9.1	NMR	400
9.1.1	Chemical Shift	400
9.1.2	Coupling Constants	407
9.1.3	NOE	414
9.2	Mass Spectrometry	417
9.2.1	Utilizing Electron Impact Ionization	418
9.2.2	Utilizing Soft Ionization	420
9.2.3	Reaction Mass Spectrometry	421
9.3	Infrared and Raman Spectroscopy	422
9.4	References	425
Appendix 1	Product Operator Formalism for Pulse Sequences	427
Appendix 2	Characteristic Frequencies of Common Functional Groups	437
Index		449