

CRYSTAL ENGINEERING

A TEXTBOOK

Gautam R Desiraju

Indian Institute of Science

Jagadese J Vittal

National University of Singapore

Arunachalam Ramanan

Indian Institute of Technology Delhi



**IISc
Press**

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Contents

Preface	ix
Acknowledgements	xi
Copyright Permissions	xiii
1. Crystal Engineering	1
1.1 X-ray Crystallography	3
1.2 Organic Solid State Chemistry	5
1.3 The Crystal as a Supramolecular Entity	7
1.4 Modern Crystal Engineering	10
1.4.1 Horizontal and Vertical Divisions of Chemistry	10
1.4.2 Organic Crystal Engineering	11
1.4.3 Metal-Organic Crystal Engineering	15
1.4.4 Properties of Crystals	16
1.5 Summary	17
1.6 Further Reading	21
1.7 Problems	22
2. Intermolecular Interactions	25
2.1 General Properties	26
2.2 van der Waals Interactions	28
2.2.1 Close Packing	29
2.3 Hydrogen Bonds	32
2.3.1 Weak Hydrogen Bonds	36
2.3.2 Hierarchies of Hydrogen Bonds	37
2.4 Halogen Bonds	38
2.5 Other Interactions	40
2.6 Methods of Study of Interactions	41
2.6.1 Crystallography	41
2.6.2 Crystallographic Databases	43
2.6.2.1 Graph Sets	46
2.6.3 Spectroscopy	46
2.6.4 Computational Methods	47
2.6.4.1 Crystal Structure Prediction	48
2.7 Analysis of Typical Crystal Structures	49
2.8 Summary	51
2.9 Further Reading	52
2.10 Problems	53

3. Crystal Design Strategies	55
3.1 Synthesis in Chemistry	55
3.2 Supramolecular Chemistry	57
3.3 The Synthons in Crystal Engineering	59
3.3.1 Some Representative Synthons	60
3.3.2 The Carboxyl Dimer Synthons	62
3.3.3 Structural Insulation in Crystal Engineering	65
3.3.4 Discovery of New Synthons	67
3.3.5 Two-dimensional Patterns	69
3.3.6 Higher Dimensional Control	70
3.3.7 Coordination Polymers as Networks	71
3.3.8 Useful Synthons	72
3.4 Summary	74
3.5 Further Reading	74
3.6 Problems	75
4. Crystallization and Crystal Growth	77
4.1 Crystallization of Organic Solids	78
4.1.1 Solution Crystallization	78
4.1.1.1 Antisolvent Crystallization	78
4.1.2 Melt Crystallization	79
4.1.3 Sublimation	79
4.1.4 Hydrothermal and Solvothermal Crystallization	80
4.1.5 Crystallization from a Solid Phase	81
4.1.5.1 Single Crystal to Single Crystal (SCSC) Transformations	81
4.1.5.2 Mechanochemistry	82
4.1.6 Crystallization of Chiral Solids	83
4.2 Nucleation	84
4.2.1 Nucleation as Distinct from Crystal Growth	84
4.3 Thermodynamics and Kinetics of Crystallization	86
4.4 Crystal Growth	87
4.4.1 The Terrace-Ledge-Kink Model of Crystal Growth	88
4.4.2 Two-dimensional Nucleation versus Growth at Dislocations	89
4.4.3 Ostwald Ripening	90
4.5 Crystal Morphology and Habit	90
4.5.1 Crystal Morphology and Crystal Symmetry	91
4.6 Crystal Morphology Engineering	91
4.6.1 Tailor-made Inhibitors	92
4.7 Why is it that all Compounds don't seem to Crystallize Equally Well or Equally Quickly?	93
4.8 Summary	94
4.9 Further Reading	95
4.10 Problems	96

5. Polymorphism	99
5.1 What is Polymorphism?	99
5.1.1 Polymorphism and the Pharmaceutical Industry	100
5.1.2 Some Simple Definitions	102
5.2 Occurrence of Polymorphism	105
5.2.1 Polymorphism and Intermolecular Interactions	106
5.3 Thermodynamics of Polymorphism	108
5.3.1 Free Energy Diagrams and Stability of Polymorphs	109
5.3.2 Monotropes and Enantiotropes	110
5.3.2.1 Burger-Ramberger Rules	111
5.3.2.2 Distinguishing between Enantiotropes and Monotropes	112
5.4 Thermodynamics versus Kinetics and the Formation of Polymorphs	113
5.5 Methods of Polymorph Characterization	114
5.5.1 Hot Stage Microscopy	114
5.5.2 X-ray Diffraction	114
5.5.3 Thermal Analysis	115
5.6 Properties of Polymorphs	116
5.6.1 Color	116
5.6.2 Mechanical Properties	117
5.6.3 Chemical Reactivity	118
5.6.3.1 Polymorphism in Energetic Materials	119
5.6.3.2 Polymorphism and Reactivity of Drugs	119
5.7 Case Studies from the Pharmaceutical Industry	120
5.7.1 Ranitidine	120
5.7.2 Ritonavir	121
5.7.3 Aspirin	123
5.7.4 Omeprazole	125
5.8 Polymorphism Today	126
5.9 Summary	127
5.10 Further Reading	128
5.11 Problems	129
6. Multi-component Crystals	131
6.1 General Classification and Nomenclature	131
6.2 Solid Solutions	133
6.3 Host-Guest Compounds	134
6.3.1 Design of Hosts	135
6.4 Solvates and Hydrates	140
6.5 Donor-Acceptor Complexes	141
6.6 Co-crystals	143
6.6.1 Hydrogen Bonded Co-crystals	144
6.6.2 Pharmaceutical Co-crystals	147
6.6.2.1 Design of Pharmaceutical Co-crystals	147
6.6.2.2 Properties of Pharmaceutical Co-crystals	148
6.6.2.3 Co-crystals and Salts	149
6.7 Summary	150
6.8 Further Reading	150
6.9 Problems	151

7. Coordination Polymers	155
7.1 What are Coordination Polymers?	155
7.2 Classification Schemes	158
7.3 Crystal Design Strategies	159
7.4 Network Topologies	159
7.4.1 Net Symbols and Nomenclature	160
7.4.2 Topologies of Three-dimensional Structures	161
7.4.2.1 Diamond Topology	161
7.4.2.2 NaCl Topology	162
7.4.2.3 NbO and CdSO ₄ Topologies	163
7.4.2.4 PtS and Related Topologies	164
7.5 Supramolecular Isomerism	165
7.6 Interpenetration	168
7.7 Porous Coordination Polymers	170
7.7.1 Pore Size	171
7.7.2 Gas Sorption and Storage	171
7.8 Properties and Applications	174
7.8.1 Magnetism, Magnetic Ordering and Spin Crossover	174
7.8.2 Luminescence and Sensing	177
7.8.3 Nonlinear Optical Properties	178
7.8.4 Proton Conductivity	179
7.8.5 Ferroelectricity	179
7.8.6 Birefringence	180
7.8.7 Negative Thermal Expansion	181
7.8.8 Processability	181
7.8.9 Chemical Reactivity	183
7.8.9.1 Structural Transformations on Heating	183
7.8.9.2 [2+2] Cycloaddition Reactions	184
7.8.9.3 Structural Transformations due to Loss of Solvents	184
7.8.9.4 Reactivity of Supramolecular Isomers	185
7.9 Building Approach: Influence of Experimental Conditions	186
7.10 Summary	187
7.11 Further Reading	188
7.12 Problems	189
Glossary	193
Some Data on Crystallographic Space Groups	205
List of Useful Web Sites	207
Some Useful Educational References in Crystal Engineering	211
Index	213