

## Contents

|   |                |
|---|----------------|
| <i>Preface</i>  | <i>page xv</i> |
| <i>Acknowledgements</i>   | <i>xviii</i>   |
| <b>Part I Bulk water</b>  | <b>1</b>       |
| 1. Uniqueness of water  | 3              |
| 1.1 Introduction  | 3              |
| 1.2 Molecular structure   | 4              |
| 1.3 Six unique features   | 7              |
| 1.4 Modeling of water   | 9              |
| 1.5 Conclusion  | 10             |
| 2. Anomalies of water   | 13             |
| 2.1 Anomalous properties  | 13             |
| 2.1.1 Density maximum   | 13             |
| 2.1.2 Isobaric specific heat ( $C_p$ )  | 15             |
| 2.1.3 Isothermal compressibility ( $\kappa_T$ )   | 15             |
| 2.1.4 Coefficient of thermal expansion ( $\alpha_p$ )   | 16             |
| 2.1.5 Dynamic anomalies present at low temperature  | 17             |
| 2.2 Translational and orientational order   | 19             |
| 2.3 Temperature–density range of water anomalies  | 21             |
| 2.4 Conclusion  | 22             |
| Appendix 2.A Microscopic expressions of specific heat, isothermal compressibility, and coefficient of thermal expansion | 23             |
| Appendix 2.B Quantification of spatial order in water   | 24             |
| 3. Dynamics of water: molecular motions and hydrogen-bond-breaking kinetics   | 27             |
| 3.1 Introduction  | 27             |
| 3.2 Timescales of translational and rotational motion   | 28             |
|   | vii            |

|                |                 |  |
|----------------|-----------------|--|
| viii           | <i>Contents</i> |  |
|                | 3.3             | Jump reorientation motion in water 30  |
|                | 3.4             | Effects of temperature on water motion 33  |
|                | 3.5             | Translational diffusion 35   |
|                | 3.6             | Hydrogen-bond lifetime dynamics 36   |
|                | 3.7             | Vibrational dynamics of the O–H bond 39  |
|                | 3.8             | Dielectric relaxation 40   |
|                | 3.9             | Solvation dynamics 42  |
|                | 3.10            | Ionic conductivity of rigid ions in water 45   |
|                | 3.11            | Electron transfer reactions in water 47  |
|                | 3.12            | Motion becomes collective at low temperature 49  |
|                | 3.13            | Conclusion 50  |
|                | Appendix 3.A    | Rotational time correlation functions 51   |
|                | Appendix 3.B    | Quantification of hydrogen-bond lifetime dynamics 58   |
| 4.             |                 | Inherent structures of liquid water 61   |
|                | 4.1             | Introduction 61  |
|                | 4.2             | Transition between inherent structures of water 66   |
|                | 4.3             | Connected water cluster moves during transition 67   |
|                | 4.4             | HB network restructuring 67  |
|                | 4.5             | Coordination number fluctuation in inherent structure and corresponding dynamics in parent liquid 68 |
|                | 4.6             | Low-energy excitations in liquid water 69  |
|                | 4.7             | Conclusion 69  |
| 5.             |                 | The pH of water 71   |
|                | 5.1             | Introduction 71  |
|                | 5.2             | Temperature and pressure dependence of pH 73   |
|                | 5.3             | Mechanism of autoionization 74   |
|                | 5.4             | pH of blood 75   |
|                | 5.5             | Food and blood pH 76   |
|                | 5.6             | pH of seawater 77  |
|                | 5.7             | Conclusion 77  |
| <b>Part II</b> |                 | <b>Water in biology 79</b>   |
| 6.             |                 | Biological water 81  |
|                | 6.1             | Introduction 81  |
|                | 6.2             | Relaxation measurements 83   |
|                | 6.3             | Unique characteristics of biological water 83  |
|                | 6.4             | Phenomenological models and simple theories 84   |
|                | 6.5             | Protein–glass transition and hydration-layer dynamics 88   |

| <i>Contents</i>   | ix  |
|---|-----|
| 6.6 Protein aggregation and biological water                                    | 90  |
| 6.7 Conclusion  | 90  |
| Appendix 6.A The dynamic exchange model   | 91  |
| 7. An essential chemical for life processes: water in biological functions      | 97  |
| 7.1 Introduction  | 97  |
| 7.2 Role of water in enzyme kinetics  | 99  |
| 7.3 Role of water in drug–DNA intercalation                                     | 101 |
| 7.4 Role of water in the biological function of RNA                             | 105 |
| 7.5 Water-mediated molecular recognition  | 107 |
| 7.6 Protein folding and protein association: role of biological water           | 109 |
| 7.7 Role of water in beta-amyloid aggregation in Alzheimer disease              | 109 |
| 7.7.1 Role of water in the early stages of oligomer formation                   | 110 |
| 7.7.2 Role of water in the late stages of fibril growth                         | 111 |
| 7.8 Role of water in photosynthesis   | 112 |
| 7.9 Conclusion  | 114 |
| 8. Hydration of proteins  | 117 |
| 8.1 Introduction  | 117 |
| 8.2 What is the thickness of the hydration shell?                               | 118 |
| 8.3 How structured is the water in the hydration shell of a protein?            | 121 |
| 8.4 Orientational arrangement of water molecules at the surface                 | 123 |
| 8.5 Dynamics of the protein hydration shell: experimental studies               | 124 |
| 8.5.1 Dielectric spectrum   | 124 |
| 8.5.2 Nuclear magnetic resonance studies  | 126 |
| 8.5.3 Quasi-elastic neutron-scattering experiments                              | 127 |
| 8.5.4 Vibrational spectroscopy  | 128 |
| 8.5.5 Solvation dynamics  | 129 |
| 8.6 Conclusion  | 131 |
| Appendix 8.A Orientation of water molecules in the hydration layer              | 132 |
| 9. Understanding the protein hydration layer: lessons from computer simulations | 135 |
| 9.1 Introduction  | 135 |
| 9.2 Molecular motion in the hydration layer                                     | 136 |
| 9.3 Hydrogen-bond lifetime dynamics   | 140 |
| 9.4 Computer simulation of solvation dynamics                                   | 142 |
| 9.5 Dielectric relaxation   | 143 |
| 9.6 Explanation of anomalous dynamics in the hydration layer                    | 144 |
| 9.7 Protein–glass transition at 200 K: role of water dynamics                   | 144 |

|     |  |     |
|-----|--|-----|
| x   | <i>Contents</i>  |     |
|     | 9.8 Free-energy barrier for escape of water molecules from protein hydration layer | 146 |
|     | 9.9 Conclusion   | 146 |
| 10. | Water in and around DNA and RNA  | 151 |
|     | 10.1 Introduction: the unique role of water in stabilizing DNA and RNA             | 151 |
|     | 10.2 Hydration of different constituents   | 152 |
|     | 10.3 Groove structure and water dynamics   | 153 |
|     | 10.4 Translational and rotational dynamics of water molecules in the grooves       | 153 |
|     | 10.5 Solvation dynamics  | 155 |
|     | 10.6 Entropy of groove water and dynamics  | 156 |
|     | 10.7 Correlation between diffusion and entropy: Adam–Gibbs relation                | 157 |
|     | 10.8 Sequence dependence of DNA hydration: spine of hydration in AT minor groove   | 159 |
|     | 10.9 Effects of nanoconfinement and surface-specific interactions                  | 161 |
|     | 10.10 Water around RNA   | 161 |
|     | 10.10.1 Structure of water around RNA  | 162 |
|     | 10.10.2 Dynamics of water around RNA   | 162 |
|     | 10.11 Conclusion   | 162 |
|     | Appendix 10.A Hydrogen-bonding pattern around DNA                                  | 163 |
| 11. | Protein–DNA interaction: the role of water as a facilitator                        | 167 |
|     | 11.1 Introduction  | 167 |
|     | 11.2 Structural analysis of protein–DNA complex: classification of hydration water | 168 |
|     | 11.3 Dynamics of water around a protein–DNA complex                                | 169 |
|     | 11.4 Role of water in thermodynamics of protein–DNA interactions                   | 170 |
|     | 11.5 Protein diffusion along DNA   | 174 |
|     | 11.6 Conclusion  | 174 |
| 12. | Water surrounding lipid bilayers: its role as a lubricant                          | 177 |
|     | 12.1 Introduction  | 177 |
|     | 12.2 Hydration of different constituents: phospholipids and buried proteins        | 179 |
|     | 12.3 Rugged energy landscape for water motion                                      | 179 |
|     | 12.4 Translational and rotational dynamics of water                                | 180 |
|     | 12.5 Solvation dynamics  | 181 |
|     | 12.6 Transport of small molecules across the bilayer                               | 182 |

|                 | <i>Contents</i>  |            |
|-----------------|--|------------|
|                 |  | xi         |
| 12.7            | Transport of large molecules across the bilayer                                  | 184        |
| 12.8            | Electrostatic potential across the membrane                                      | 184        |
| 12.9            | Conclusion   | 185        |
| 13.             | The role of water in biochemical selection and protein synthesis                 | 187        |
| 13.1            | Introduction   | 187        |
| 13.2            | Role of water in kinetic proofreading  | 188        |
| 13.2.1          | Brief analysis of the Hopfield–Ninio approach to kinetic proofreading            | 190        |
| 13.2.2          | Analysis of experimental results in the light of the Hopfield–Ninio formulation  | 190        |
| 13.2.3          | Aminoacylation of tRNA during protein synthesis                                  | 192        |
| 13.2.4          | tRNA selection in ribosome   | 194        |
| 13.2.5          | DNA replication  | 196        |
| 13.3            | Water as a lubricant of life   | 196        |
| 13.4            | Conclusion   | 197        |
| <b>Part III</b> | <b>Water in complex chemical systems</b>   | <b>199</b> |
| 14.             | The hydrophilic effect   | 201        |
| 14.1            | Introduction   | 201        |
| 14.2            | Water near ions  | 202        |
| 14.3            | Water near an extended hydrophilic surface                                       | 204        |
| 14.4            | Aqueous hydrophilic binary mixtures  | 207        |
| 14.4.1          | Water–urea binary mixture  | 208        |
| 14.4.2          | Water–guanidinium hydrochloride binary mixture                                   | 209        |
| 14.5            | Aqueous salt solutions   | 209        |
| 14.5.1          | Ionic conductivity   | 209        |
| 14.5.2          | Viscosity  | 211        |
| 14.6            | Conclusion   | 212        |
| 15.             | The hydrophobic effect   | 215        |
| 15.1            | Introduction   | 215        |
| 15.2            | Hydrophobic hydration  | 217        |
| 15.3            | Temperature dependence of hydrophobicity: enthalpy versus entropy stabilizations | 219        |
| 15.4            | Hydropathy scale   | 220        |
| 15.5            | Pair hydrophobicity and potential of mean force between two hydrophobic solutes  | 221        |
| 15.6            | Biological applications of potential of mean force                               | 223        |
| 15.6.1          | Protein folding  | 224        |

|     |   |     |
|-----|---|-----|
| xii | <i>Contents</i>   |     |
|     | 15.6.2 Hydrophobic association  | 227 |
|     | 15.6.3 Pattern formation in chiral molecules  | 227 |
|     | 15.7 Hydrophobic collapse of polymers   | 227 |
|     | 15.7.1 The Flory–Huggins theory   | 228 |
|     | 15.8 Molecular-level understanding of hydrophobic interaction   | 230 |
|     | 15.9 Hydrophobic force law  | 234 |
|     | 15.10 Hydrophobicity at different length scales   | 234 |
|     | 15.11 Conclusion  | 235 |
|     | Appendix 15.A Pratt–Chandler theory   | 236 |
|     | 15.A.1 Cavity distribution functions  | 237 |
|     | 15.A.2 Theory for A–W and A–A pair correlations   | 239 |
| 16. | The amphiphilic effect: the diverse but intimate world of aqueous binary mixtures                                     | 243 |
|     | 16.1 Introduction: the role of aqueous mixtures in chemistry and biology  | 243 |
|     | 16.2 Non-ideality of amphiphilic binary mixtures  | 245 |
|     | 16.3 Water–DMSO binary mixture  | 245 |
|     | 16.4 Water–alcohol binary mixture   | 249 |
|     | 16.4.1 Aqueous methanol solution  | 250 |
|     | 16.4.2 Aqueous ethanol solution   | 250 |
|     | 16.4.3 Water–tertiary butyl alcohol   | 250 |
|     | 16.5 Water–acetone binary mixture   | 252 |
|     | 16.6 Water–dioxane binary mixture   | 252 |
|     | 16.7 Liquid–liquid structural transformation in aqueous binary mixtures: a generic phenomenon for amphiphilic solutes | 253 |
|     | 16.8 Theoretical development  | 254 |
|     | 16.9 Biological applications  | 256 |
|     | 16.10 Conclusion  | 258 |
| 17. | Water in and around micelles, reverse micelles, and microemulsions  | 261 |
|     | 17.1 Introduction: different self-assemblies in water   | 261 |
|     | 17.2 Structure of micelles and reverse micelles   | 262 |
|     | 17.2.1 Micelles   | 262 |
|     | 17.2.2 Reverse micelles   | 263 |
|     | 17.3 Dynamics of water surrounding micelles   | 265 |
|     | 17.4 Free-energy landscape of hydrogen-bond arrangements at the surface   | 266 |
|     | 17.5 Reverse micelles and microemulsions: dynamics of water   | 268 |
|     | 17.6 Orientational dynamics   | 269 |
|     | 17.7 Core–shell model   | 270 |

| <i>Contents</i>                         |  | xiii       |
|---|--|------------|
| 17.8                                    | Distance-dependent relaxation near the core of the reverse micelle: propagation of surface-induced frustration | 273        |
| 17.9                                    | Ising model description of the dynamics  | 273        |
| 17.10                                   | Conclusion   | 274        |
| 18.                                     | Water in a carbon nanotube: nature abhors a vacuum   | 277        |
| 18.1                                    | Introduction   | 277        |
| 18.2                                    | Type and structures of carbon nanotubes  | 277        |
| 18.3                                    | Structure of water inside a carbon nanotube  | 278        |
| 18.4                                    | Dynamics and transport of water  | 279        |
| 18.4.1                                  | Translational motion of water inside a CNT   | 279        |
| 18.4.2                                  | Rotation of water molecules within a CNT   | 280        |
| 18.5                                    | Nanotubes as a filtration device   | 282        |
| 18.6                                    | Conclusion   | 283        |
| <b>Part IV Advanced topics on water</b> |  | <b>285</b> |
| 19.                                     | The entropy of water   | 287        |
| 19.1                                    | Introduction   | 287        |
| 19.2                                    | Relation between entropy and diffusion   | 291        |
| 19.2.1                                  | Diffusion–entropy scaling relation: the Rosenfeld relation   | 291        |
| 19.2.2                                  | The Adam–Gibbs relation  | 293        |
| 19.3                                    | Calculation of the entropy of water  | 295        |
| 19.3.1                                  | From structure   | 296        |
| 19.3.2                                  | From dynamics  | 297        |
| 19.4                                    | Entropy from cell theory   | 298        |
| 19.5                                    | Entropy of water in confined systems (reverse micelles, carbon nanotubes, grooves of DNA)                      | 299        |
| 19.6                                    | Conclusion   | 300        |
| Appendix 19.A                           | Entropy for translational degree of freedom of an ideal gas (Sackur–Terode equation)                           | 301        |
| Appendix 19.B                           | Entropy for vibrational degree of freedom  | 302        |
| Appendix 19.C                           | Entropy for rotational degree of freedom   | 303        |
| 20.                                     | The freezing of water into ice   | 305        |
| 20.1                                    | Introduction   | 305        |
| 20.2                                    | Phase diagram of water and ice   | 306        |
| 20.3                                    | Ice formation in micro-droplets  | 307        |
| 20.4                                    | A lesson from the freezing of interacting spheres and the difference from water                                | 308        |
| 20.5                                    | The freezing of water  | 308        |

|     |   |     |
|-----|---|-----|
| xiv | <i>Contents</i>   |     |
|     | 20.6 Nucleation of an embryo  | 309 |
|     | 20.7 The freezing of water in computer simulations                      | 310 |
|     | 20.8 Mechanism of ice formation   | 311 |
|     | 20.9 Freezing inside nanotubes  | 314 |
|     | 20.10 Conclusion  | 315 |
| 21. | Supercritical water   | 317 |
|     | 21.1 Introduction   | 317 |
|     | 21.2 Inhomogeneous density fluctuation in supercritical fluids          | 318 |
|     | 21.3 Crossing the Widom line  | 320 |
|     | 21.4 Spectroscopic studies of supercritical fluids                      | 320 |
|     | 21.5 Conclusion   | 322 |
| 22. | Approaches to understand water anomalies                                | 323 |
|     | 22.1 Introduction   | 323 |
|     | 22.2 Reason for density maximum   | 327 |
|     | 22.3 Reason for large isobaric specific heat of water                   | 327 |
|     | 22.4 Percolation model of water   | 327 |
|     | 22.5 Hydrogen-bond network rearrangement dynamics                       | 330 |
|     | 22.5.1 Energy landscape view of hydrogen-bond<br>rearrangement dynamics | 331 |
|     | 22.5.2 Depolarized Raman scattering profile                             | 333 |
|     | 22.6 Low-temperature anomalies  | 334 |
|     | 22.7 Conclusion   | 341 |
|     | <i>Epilog</i>   | 345 |
|     | <i>Index</i>  | 349 |

The color plates will be found between pages 78 and 79.