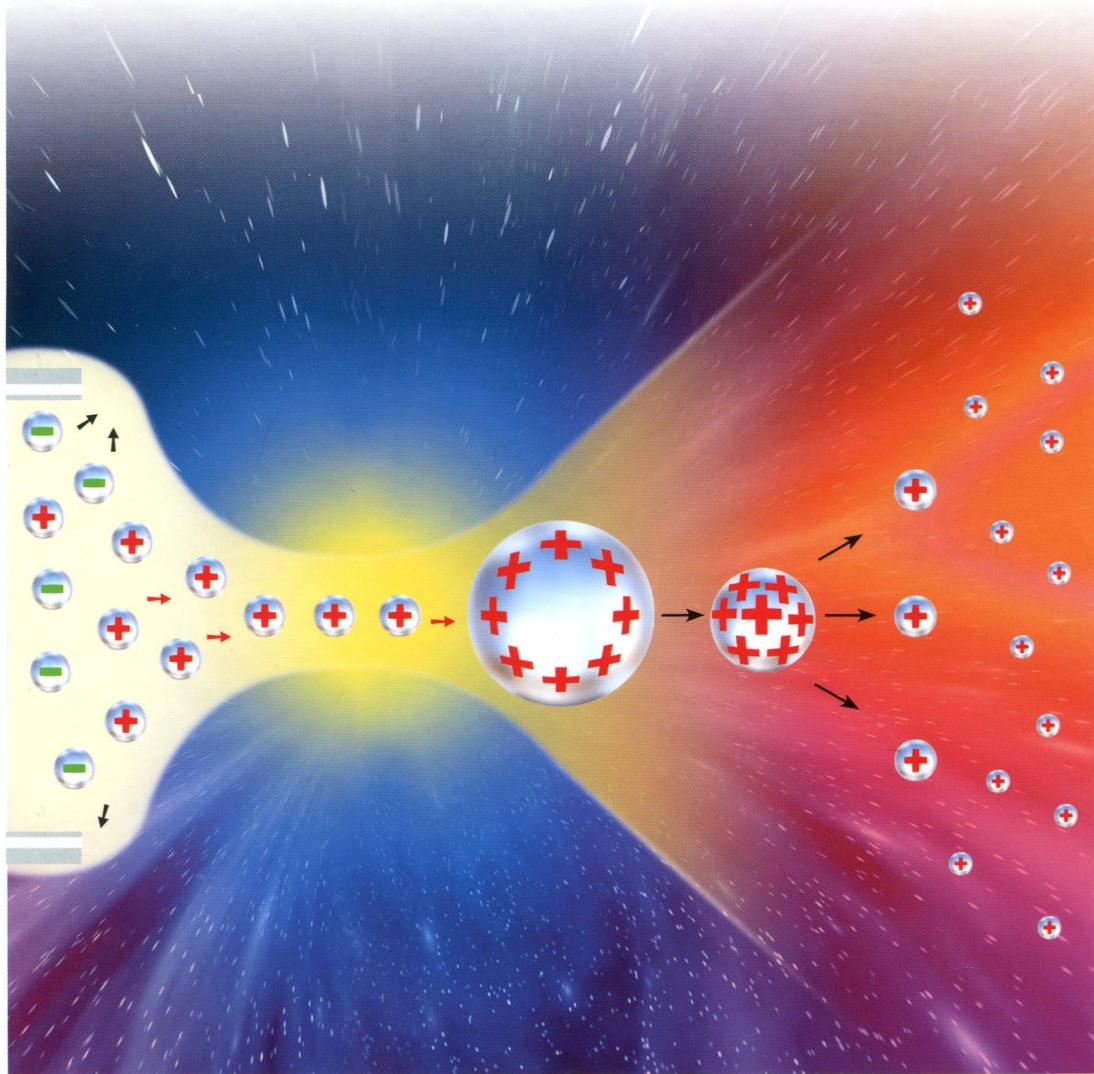


Edited by Christoph A. Schalley

 WILEY-VCH

# Analytical Methods in Supramolecular Chemistry

Second, Completely Revised and Enlarged Edition  
Volume 2



**The Editor**

**Prof. Dr. Christoph Schalley**

Freie Universität Berlin  
Institut für Chemie und Biochemie  
Takustr. 3  
14195 Berlin  
Germany

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

**Library of Congress Card No.:** applied for

**British Library Cataloguing-in-Publication****Data**

A catalogue record for this book is available from the British Library.

**Bibliographic information published by the  
Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2012 Wiley-VCH Verlag & Co. KGaA,  
Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photopyting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

**Composition** Laserwords Private Ltd.,  
Chennai

**Printing and Binding** betz-druck GmbH,  
Darmstadt

**Cover Design** Adam Design, Weinheim

Printed in the Federal Republic of Germany  
Printed on acid-free paper

**Print ISBN:** 978-3-527-32982-3

**ePDF ISBN:** 978-3-527-64415-5

**eBook ISBN:** 978-3-527-64413-1

**ePub ISBN:** 978-3-527-64414-8

**Mobi ISBN:** 978-3-527-64416-2

## Contents to Volume 1

Preface XIII

List of Contributors XV

- 1 **Introduction** 1  
*Lena Kaufmann and Christoph A. Schalley*
- 2 **Quantitative Analysis of Binding Properties** 27  
*Keiji Hirose*
- 3 **Isothermal Titration Calorimetry in Supramolecular Chemistry** 67  
*Franz P. Schmidtchen*
- 4 **Extraction Methods** 105  
*Holger Stephan, Manja Kubeil, Kerstin Gloe, and Karsten Gloe*
- 5 **Mass Spectrometry and Gas Phase Chemistry of Supramolecules** 129  
*Dominik P. Weimann, Michael Kogej, and Christoph A. Schalley*
- 6 **Diffusion NMR in Supramolecular Chemistry and Complexed Systems** 197  
*Yoram Cohen, Liat Avram, Tamar Evan-Salem, Sarit Slovak, Noam Shemesh, and Limor Frish*
- 7 **Photophysics and Photochemistry of Supramolecular Systems** 287  
*Bernard Valeur, Mário Nuno Berberan-Santos, Monique M. Martin, and Pascal Plaza*
- 8 **Circular Dichroism Spectroscopy** 337  
*Marie Urbanová and Petr Maloň*

## Contents to Volume 2

**Preface XIII**

**List of Contributors XV**

|          |  |     |
|----------|--|-----|
| <b>9</b> | <b>Electrochemical Methods</b>                             | 371 |
|          | <i>Paola Ceroni, Alberto Credi, and Margherita Venturi</i> |     |
| 9.1      | Introduction   | 371 |
| 9.2      | Basic Principles of Electrochemistry                       | 372 |
| 9.2.1    | Electric Current and Potential                             | 375 |
| 9.2.2    | Thermodynamics and Kinetics of Electrode Reactions         | 376 |
| 9.3      | Overview of Electrochemical Techniques                     | 378 |
| 9.3.1    | Linear Sweep Voltammetry and Cyclic Voltammetry            | 379 |
| 9.3.2    | Pulsed Voltammetric Techniques                             | 385 |
| 9.3.3    | Chronoamperometry and Chronocoulometry                     | 387 |
| 9.3.4    | Bulk Electrolysis  | 389 |
| 9.3.5    | Spectroelectrochemistry                                    | 390 |
| 9.3.6    | Electrochemiluminescence                                   | 391 |
| 9.4      | Electrochemical Analysis of Supramolecular Systems         | 393 |
| 9.4.1    | Intermolecular Interactions                                | 393 |
| 9.4.2    | Molecular Encapsulation of Electroactive Units             | 394 |
| 9.4.3    | Systems Containing Multiple Redox Sites                    | 394 |
| 9.4.4    | Redox-Controlled Supramolecular Switching                  | 395 |
| 9.5      | Selected Examples  | 396 |
| 9.5.1    | Host–Guest Systems   | 397 |
| 9.5.1.1  | Hydrogen-Bonding Interaction                               | 397 |
| 9.5.1.2  | Metal Ion Coordination                                     | 398 |
| 9.5.1.3  | Hydrophobic Interactions                                   | 403 |
| 9.5.1.4  | Charge-Transfer Interactions                               | 406 |
| 9.5.2    | Dendrimers   | 409 |
| 9.5.2.1  | Artificial Enzymes and Biomimetic Models                   | 411 |
| 9.5.2.2  | Molecular Batteries  | 413 |
| 9.5.2.3  | Sensors with Signal Amplification                          | 420 |
| 9.5.3    | Molecular Machines based on Rotaxanes and Catenanes        | 422 |
| 9.5.3.1  | Systems Based on Rotaxanes                                 | 422 |
| 9.5.3.2  | Systems Based on Catenanes                                 | 429 |
| 9.5.3.3  | Heterogeneous Systems                                      | 435 |
| 9.5.4    | Systems Based on Fullerenes and Carbon Nanotubes           | 438 |
| 9.5.4.1  | Donor–Acceptor Photoactive Dyads Based on Fullerenes       | 440 |
| 9.5.4.2  | Interlocked Architectures Equipped with C <sub>60</sub>    | 442 |
| 9.5.4.3  | Carbon Nanotubes   | 444 |

|           |   |            |
|-----------|---|------------|
| 9.6       | Concluding Remarks  | 448        |
|           | Acknowledgments   | 449        |
|           | References  | 449        |
| <b>10</b> | <b>Crystallography and Crystal Engineering</b>                        | <b>459</b> |
|           | <i>Kari Rissanen</i>  |            |
| 10.1      | Introduction  | 459        |
| 10.2      | Crystallography   | 460        |
| 10.2.1    | Introduction  | 460        |
| 10.2.2    | A Walk Through a Single Crystal Structural Determination              | 462        |
| 10.2.2.1  | The (Single) Crystal  | 463        |
| 10.2.2.2  | Mounting of the Crystal   | 465        |
| 10.2.2.3  | Unit Cell Determination and Preliminary Space Group Selection         | 466        |
| 10.2.2.4  | Data Collection, Data Processing, and Final Space Group Determination | 472        |
| 10.2.2.5  | Data Reduction, Structure Solution, and Refinement                    | 475        |
| 10.2.2.6  | Analysis of Structure   | 480        |
| 10.3      | Crystal Engineering   | 484        |
| 10.3.1    | Introduction  | 484        |
| 10.3.2    | Definition  | 484        |
| 10.4      | Methyl-Resorcinarene as a Crystal Engineering Target                  | 487        |
| 10.4.1    | Crystal Structures of Methyl-Resorcinarene                            | 487        |
| 10.5      | Concluding Remarks  | 495        |
|           | Acknowledgments   | 497        |
|           | References  | 497        |
| <b>11</b> | <b>Scanning Probe Microscopy</b>                                      | <b>499</b> |
|           | <i>Bianca A. Hermann and Regina Hoffmann-Vogel</i>                    |            |
| 11.1      | Introduction: What Is the Strength of Scanning Probe Techniques?      | 499        |
| 11.2      | How Do Scanning Probe Microscopes Work?                               | 501        |
| 11.2.1    | Scanning Tunneling Microscopy (STM)                                   | 503        |
| 11.2.1.1  | Working Principle of STM  | 504        |
| 11.2.1.2  | Operation Modes of STM  | 507        |
| 11.2.1.3  | Imaging with STM  | 509        |
| 11.2.1.4  | Tunneling Spectroscopy  | 513        |
| 11.2.1.5  | Manipulating Atoms and Molecules with STM                             | 520        |
| 11.2.2    | Atomic Force Microscopy   | 524        |
| 11.2.2.1  | Function Principle of AFM   | 524        |
| 11.2.2.2  | Various Operation Modes of AFM  | 525        |
| 11.2.2.3  | Single Molecule Force Spectroscopy –Force–Distance Measurements       | 528        |
| 11.2.2.4  | Manipulating Atoms and Molecules with AFM                             | 531        |
| 11.3      | Which Molecules Can Be Studied?                                       | 533        |
| 11.3.1    | Differences between STM and AFM                                       | 533        |

|           |   |            |
|-----------|---|------------|
| 11.3.2    | Exemplary Results on Smaller Molecules  | 534        |
| 11.4      | What Results Have Been Obtained in the Field of Supramolecular Chemistry?   | 538        |
| 11.4.1    | Coronenes, Crown Ethers, Cryptands, Macrocycles, Squares, Rectangles  | 538        |
| 11.4.2    | Calixarenes, Cyclodextrins, Molecular Sieves, and Boxes   | 540        |
| 11.4.3    | Porphyrins and Porphyrin Oligomers  | 544        |
| 11.4.4    | Complex Interconnected Supermolecules: Rotaxanes and Catenanes  | 545        |
| 11.4.5    | Supramolecular Assemblies, Grids, Arrays, Chains  | 546        |
| 11.4.6    | Bicomponent Supramolecular Assemblies, Surface Reactions, Two-, and One-Dimensional Polymers                      | 547        |
| 11.4.7    | Supramolecular Assemblies on Bulk Insulators  | 548        |
|           | Acknowledgments   | 549        |
|           | References  | 550        |
| <b>12</b> | <b>Single-Molecule Force Spectroscopy of Supramolecular Complexes</b>   | <b>559</b> |
|           | <i>Tobias Schroeder, Volker Walhorn, Jochen Mattay, and Dario Anselmetti</i>                                      |            |
| 12.1      | Introduction and Motivation   | 559        |
| 12.2      | Functionally Immobilizing Supramolecules  | 561        |
| 12.3      | Supramolecular Interactions Investigated by AFM-SMFS  | 565        |
| 12.3.1    | Host–Guest Systems: Cyclodextrins   | 566        |
| 12.3.2    | Host–Guest Systems: Calixarenes   | 571        |
| 12.3.3    | Host–Guest Systems: Photoswitchable Calixarene Systems  | 574        |
| 12.3.4    | Hydrogen-Bonded Supramolecular Structures   | 578        |
| 12.3.5    | $\pi-\pi$ -Interactions in Supramolecular Chemistry   | 581        |
| 12.3.6    | Metal–Ligand Interactions   | 589        |
| 12.3.7    | Supramolecular Mesoscale Systems: Reversible Polymers   | 592        |
| 12.3.8    | Supramolecular Mesoscale Systems: Capsules  | 596        |
| 12.3.9    | Supramolecular Mesoscale Systems: Calixarene-Catenane Polymers  | 599        |
| 12.4      | Summary and Outlook   | 603        |
|           | Acknowledgments   | 604        |
|           | References  | 604        |
| <b>13</b> | <b>Confocal Laser Scanning Microscopy: a Versatile Spectroscopic Tool for the Investigation of Molecular Gels</b> | <b>607</b> |
|           | <i>Anthony D’Aléo, André Del Guerzo, and Frédéric Fages</i>   |            |
| 13.1      | Introduction: Molecular Gels  | 607        |
| 13.2      | Methods Classically Used for the Characterization of Molecular Gels   | 608        |
| 13.3      | Confocal Laser Scanning Microscopy (CLSM)   | 611        |
| 13.4      | Applications of CLSM to the Study of Molecular Gels   | 613        |

|           |   |            |
|-----------|---|------------|
| 13.4.1    | Fiber Imaging and Visualization of the Three-Dimensional Structure of the Self-Assembled Network of Fibrous Aggregates  | 614        |
| 13.4.2    | Single-Fiber Spectroscopy Using CLSM  | 614        |
| 13.4.3    | Investigation of Gelation Mechanism Using CLSM  | 618        |
| 13.4.4    | 3D Monitoring of Interactions between Gel Fibers and Molecular and Macromolecular Species   | 619        |
| 13.4.5    | Miscellaneous Materials Properties  | 622        |
| 13.5      | Conclusion  | 624        |
|           | References  | 624        |
| <b>14</b> | <b>Transmission Electron Microscopy (TEM) of Radiation Sensitive Supramolecular Architectures –Strategies for a Comprehensive Structure Characterization</b>                | <b>629</b> |
|           | <i>Christoph Böttcher</i>   |            |
| 14.1      | Introduction  | 629        |
| 14.2      | Instrumentation   | 631        |
| 14.2.1    | The Microscope  | 632        |
| 14.2.2    | Electron–Specimen Interactions  | 635        |
| 14.2.3    | Radiation Damage  | 638        |
| 14.3      | Contrast in TEM   | 640        |
| 14.3.1    | Absorption Contrast   | 641        |
| 14.3.2    | Scattering Absorption Contrast  | 641        |
| 14.3.3    | Phase Contrast  | 642        |
| 14.3.4    | Amplitude Contrast  | 649        |
| 14.4      | Sample Preparation  | 650        |
| 14.4.1    | Negative Staining Preparation   | 651        |
| 14.4.2    | Cryo-Techniques   | 654        |
| 14.5      | Strategies and Examples to Characterize Supramolecular Structures by Complementary TEM Methods  | 660        |
| 14.5.1    | Characterization of Structural Intermediates in a Complex Self-Assembly Process of a Chiral Amphiphilic Hexonamide Including an Image-Based, 3D Helix-Reconstruction Method | 661        |
| 14.5.2    | The Three-Dimensional Characterization of <i>Structurally Persistent</i> Micellar Assemblies by the <i>Single-Particle</i> Reconstruction Method                            | 675        |
| 14.5.3    | Exemplified Principles of the <i>Single-Particle</i> 3D Reconstruction Method   | 680        |
| 14.5.4    | Cryogenic Electron Tomography (Cryo-ET)   | 693        |
| 14.5.4.1  | Cryo-ET of Mixed Micellar Lipid–Surfactant Assemblies   | 694        |
| 14.5.4.2  | Micellar Triblock Copolymer Domain Architecture   | 697        |
|           | Acknowledgment  | 698        |
|           | References  | 699        |
|           | Further Reading   | 709        |

|           |  |     |
|-----------|--|-----|
| <b>15</b> | <b>The Characterization of Synthetic Ion Channels and Pores</b>          | 711 |
|           | <i>Stefan Matile and Naomi Sakai</i>                                     |     |
| 15.1      | Introduction   | 711 |
| 15.2      | Methods  | 713 |
| 15.2.1    | Planar Bilayer Conductance   | 713 |
| 15.2.2    | Fluorescence Spectroscopy with Labeled Vesicles                          | 716 |
| 15.2.3    | Miscellaneous  | 718 |
| 15.3      | Characteristics  | 719 |
| 15.3.1    | pH Gating  | 721 |
| 15.3.2    | Concentration Dependence   | 722 |
| 15.3.3    | Size Selectivity   | 724 |
| 15.3.4    | Voltage Gating   | 725 |
| 15.3.5    | Ion Selectivity  | 727 |
| 15.3.6    | Blockage and Ligand Gating   | 730 |
| 15.3.7    | Miscellaneous  | 733 |
| 15.4      | Structural Studies   | 734 |
| 15.4.1    | Binding to the Bilayer   | 736 |
| 15.4.2    | Location in the Bilayer  | 737 |
| 15.4.3    | Self-Assembly  | 737 |
| 15.4.4    | Molecular Recognition  | 738 |
| 15.5      | Concluding Remarks   | 738 |
|           | Acknowledgment   | 739 |
|           | References   | 739 |
| <b>16</b> | <b>Theoretical Methods for Supramolecular Chemistry</b>                  | 743 |
|           | <i>Barbara Kirchner and Markus Reiher</i>                                |     |
| 16.1      | Introduction   | 743 |
| 16.2      | A Survey of Theoretical Methods  | 746 |
| 16.2.1    | First-Principles Methods   | 748 |
| 16.2.2    | The Supramolecular Approach and Total Interaction Energies               | 754 |
| 16.2.3    | The Time Dimension: Molecular Dynamics                                   | 756 |
| 16.2.4    | A Technical Note: Linear Scaling and Multiscale Modeling                 | 760 |
| 16.2.5    | How to Make the Connection to Experiment?                                | 762 |
| 16.3      | Standard Classification of Intermolecular Interactions                   | 766 |
| 16.3.1    | A Complication: Cooperative Effects                                      | 768 |
| 16.3.2    | Distributed Multipoles and Polarizabilities                              | 769 |
| 16.3.3    | Local Multipole Expansions in MD Simulations                             | 770 |
| 16.4      | Qualitative Understanding and Decomposition Schemes                      | 772 |
| 16.4.1    | Interaction Energy Decomposition   | 774 |
| 16.4.2    | A Core-Electron Probe for Hydrogen Bond Interactions                     | 774 |
| 16.4.3    | The SEN Approach to Hydrogen Bond Energies                               | 775 |
| 16.5      | General Mechanism for a Static, Step-Wise View on Host–Guest Recognition | 777 |
| 16.5.1    | Template-Free Pre-orientation Processes                                  | 780 |
| 16.5.2    | Rearrangement Reactions  | 781 |

|        |   |     |
|--------|---|-----|
| 16.5.3 | The Host-Controlled Association Reaction                | 781 |
| 16.5.4 | The Transformation Step                                 | 782 |
| 16.5.5 | Inclusion of Environmental Effects                      | 783 |
| 16.5.6 | General Aspects of Template Thermodynamics and Kinetics | 783 |
| 16.6   | Conclusions and Perspective                             | 785 |
|        | Acknowledgments   | 786 |
|        | References  | 786 |

|              |     |
|--------------|-----|
| <b>Index</b> | 795 |
|--------------|-----|