

Volume Editors C.A.Schalley · F.Vögtle · K.H.Dötz

Templates in Chemistry II



Springer

0621.3
7284
V.2

333 31

Templates in Chemistry II

Volume Editors:

Christoph A. Schalley, Fritz Vögtle, Karl Heinz Dötz

With contributions by

F. Aricó · J. D. Badjic · P. Bäuerle · D. H. Busch · S. J. Cantrill

M. G. J. ten Cate · B. X. Colasson · M. Crego-Calama

C. Dietrich-Buchecker · M. Emgenbroich · A. H. Flood · B. C. Gibb

A. J. Hall · A. Kaiser · Z. R. Laughrey · K. C.-F. Leung · Y. Liu

D. N. Reinhoudt · J.-P. Sauvage · B. Sellergren · J. F. Stoddart



E200501670



Springer

The series *Topics in Current Chemistry* presents critical reviews of the present and future trends in modern chemical research. The scope of coverage includes all areas of chemical science including the interfaces with related disciplines such as biology, medicine and materials science. The goal of each thematic volume is to give the nonspecialist reader, whether at the university or in industry, a comprehensive overview of an area where new insights are emerging that are of interest to a larger scientific audience.

As a rule, contributions are specially commissioned. The editors and publishers will, however, always be pleased to receive suggestions and supplementary information. Papers are accepted for *Topics in Current Chemistry* in English.

In references *Topics in Current Chemistry* is abbreviated Top Curr Chem and is cited as a journal.

Visit the TCC content at springerlink.com

Library of Congress Control Number: 2004108949

ISSN 0340-1022

ISBN-10 3-540-23087-4 Springer Berlin Heidelberg New York

ISBN-13 978-3-540-23087-8 Springer Berlin Heidelberg New York

DOI 10.1007/b98632

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other ways, and storage in data banks. Duplication of this publication or parts thereof is only permitted under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media

springeronline.com

© Springer-Verlag Berlin Heidelberg 2005

Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: KünkelLopka, Heidelberg/design & production GmbH, Heidelberg
Typesetting: Fotosatz-Service Köhler GmbH, Würzburg

Printed on acid-free paper 02/3141/xv – 5 4 3 2 1 0

249

Topics in Current Chemistry

Editorial Board:

**A. de Meijere · K. N. Houk · H. Kessler · J.-M. Lehn · S.V. Ley
S. L. Schreiber · J. Thiem · B. M. Trost · F. Vögtle · H. Yamamoto**

Topics in Current Chemistry

Recently Published and Forthcoming Volumes

Anion Sensing

Volume Editor: Stibor, I.
Vol. 255, 2005

Organic Solid State Reactions

Volume Editor: Toda, E.
Vol. 254, 2005

DNA Binders and Related Subjects

Volume Editors: Waring, M.J., Chaires, J.B.
Vol. 253, 2005

Contrast Agents III

Volume Editor: Krause, W.
Vol. 252, 2005

Chalcogenocarboxylic Acid Derivatives

Volume Editor: Kato, S.
Vol. 251, 2005

New Aspects in Phosphorus Chemistry V

Volume Editor: Majoral, J.-P.
Vol. 250, 2005

Templates in Chemistry II

Volume Editors: Schalley, C.A.,
Vögtle, F., Dötz, K.H.
Vol. 249, 2005

Templates in Chemistry I

Volume Editors: Schalley, C.A.,
Vögtle, F., Dötz, K.H.
Vol. 248, 2004

Collagen

Volume Editors: Brinckmann, J.,
Notbohm, H., Müller, P.K.
Vol. 247, 2005

New Techniques in Solid-State NMR

Volume Editor: Klinowski, J.
Vol. 246, 2005

Functional Molecular Nanostructures

Volume Editor: Schlüter, A.D.
Vol. 245, 2005

Natural Product Synthesis II

Volume Editor: Mulzer, J.
Vol. 244, 2005

Natural Product Synthesis I

Volume Editor: Mulzer, J.
Vol. 243, 2005

Immobilized Catalysts

Volume Editor: Kirschning, A.
Vol. 242, 2004

Transition Metal and Rare Earth Compounds III

Volume Editor: Yersin, H.
Vol. 241, 2004

The Chemistry of Pheromones and Other Semiochemicals II

Volume Editor: Schulz, S.
Vol. 240, 2005

The Chemistry of Pheromones and Other Semiochemicals I

Volume Editor: Schulz, S.
Vol. 239, 2004

Orotidine Monophosphate Decarboxylase

Volume Editors: Lee, J.K., Tantillo, D.J.
Vol. 238, 2004

Long-Range Charge Transfer in DNA II

Volume Editor: Schuster, G.B.
Vol. 237, 2004

Long-Range Charge Transfer in DNA I

Volume Editor: Schuster, G.B.
Vol. 236, 2004

Spin Crossover in Transition Metal Compounds III

Volume Editors: Gülich, P., Goodwin, H.A.
Vol. 235, 2004

Spin Crossover in Transition Metal Compounds II

Volume Editors: Gülich, P., Goodwin, H.A.
Vol. 234, 2004

Spin Crossover in Transition Metal Compounds I

Volume Editors: Gülich, P., Goodwin, H.A.
Vol. 233, 2004

Volume Editors

Priv-Doz. Dr. Christoph A. Schalley
c.schalley@uni-bonn.de

Prof. Dr. Fritz Vögtle
voegtle@uni-bonn.de

Prof. Dr. Karl H. Dötz
doetz@uni-bonn.de

Kekulé-Institut für Organische
Chemie und Biochemie
Gerhard-Domagk-Str. 1
53121 Bonn, Germany

Editorial Board

Prof. Dr. Armin de Meijere
Institut für Organische Chemie
der Georg-August-Universität
Tammannstraße 2
37077 Göttingen, Germany
ameijer1@uni-goettingen.de

Prof. Dr. Horst Kessler
Institut für Organische Chemie
TU München
Lichtenbergstraße 4
85747 Garching, Germany
kessler@ch.tum.de

Prof. Steven V. Ley
University Chemical Laboratory
Lensfield Road
Cambridge CB2 1EW, Great Britain
svl1000@cus.cam.ac.uk

Prof. Dr. Joachim Thiem
Institut für Organische Chemie
Universität Hamburg
Martin-Luther-King-Platz 6
20146 Hamburg, Germany
thiem@chemie.uni-hamburg.de

Prof. Dr. Fritz Vögtle
Kekulé-Institut für Organische Chemie
und Biochemie der Universität Bonn
Gerhard-Domagk-Straße 1
53121 Bonn, Germany
voegtle@uni-bonn.de

Prof. Kendall N. Houk
Department of Chemistry and Biochemistry
University of California
405 Hilgard Avenue
Los Angeles, CA 90024-1589, USA
houk@chem.ucla.edu

Prof. Jean-Marie Lehn
Institut de Chimie
Université de Strasbourg
1 rue Blaise Pascal, B.P.Z 296/R8
67008 Strasbourg Cedex, France
lehn@chimie.u-strasbg.fr

Prof. Stuart L. Schreiber
Chemical Laboratories
Harvard University
12 Oxford Street
Cambridge, MA 02138-2902, USA
sls@slsiris.harvard.edu

Prof. Barry M. Trost
Department of Chemistry
Stanford University
Stanford, CA 94305-5080, USA
bmtrost@leland.stanford.edu

Prof. Hisashi Yamamoto
Arthur Holly Compton Distinguished
Professor
Department of Chemistry
The University of Chicago
5735 South Ellis Avenue
Chicago, IL 60637
773-702-5059, USA
yamamoto@uchicago.edu

Topics in Current Chemistry also Available Electronically

For all customers who have a standing order to Topics in Current Chemistry, we offer the electronic version via SpringerLink free of charge. Please contact your librarian who can receive a password for free access to the full articles by registration at:

springerlink.com

If you do not have a subscription, you can still view the tables of contents of the volumes and the abstract of each article by going to the SpringerLink Homepage, clicking on "Browse by Online Libraries", then "Chemical Sciences", and finally choose Topics in Current Chemistry.

You will find information about the

- Editorial Board
- Aims and Scope
- Instructions for Authors
- Sample Contribution

at springeronline.com using the search function.

Preface

When we invited authors to contribute to the first Topics in Current Chemistry volume on “Templates in Chemistry”, the resonance was overwhelming and encouraged us to edit a second volume which together with the first one provides an even broader overview of and a deeper insight into the template topic adding new aspects and new views.

The present volume begins with a chapter by Daryle H. Busch, the pioneer in the field, who puts molecular templates into the context of their 40 years’ history. In view of the many different new aspects appearing in the current chemistry literature, we sometimes tend to lose sight of the long and successful history of templates. Therefore, this chapter may well serve as a reminder of the wealth of chemistry that developed from the template strategy even several decades ago.

The other contributions to the present volume are organized roughly in order of the decreasing bond strengths involved and the increasing complexity of the systems under study. Zachary Laughrey and Bruce Gibb review templated macrocycle formation starting with covalent templates and proceeding to other, weaker interactions involving coordinative and hydrogen bonds. The third chapter by Achim Kaiser and Peter B  uerle is devoted to macrocycle formation through coordination to Pt(II). Then, Fraser Stoddart and his colleagues describe the templated synthesis of interlocked molecules, followed by an overview on molecular knots by Jean-Pierre Sauvage and his coworkers. The two latter chapters thus continue a theme which was already touched on in the first volume on templates in this series of monographs. David Reinhoudt et al. show how templation can assist the hierarchical self-assembly of complex hydrogen-bonded rosette-type aggregates. Finally, imprinted polymers which form around a template and – after its removal – can recognize guest molecules or even accelerate reactions, form the topic of the last chapter by B  rje Sellergren and his colleagues. These two final chapters thus deal with increasingly complex and structurally rich systems which were not possible without the use of templates. This nicely illustrates how templates help to tame complexity by a suitable design of smaller and simpler building blocks.

We believe that this volume not only provides excellent and comprehensive overviews for expert readers, but also certainly shows that there are many new aspects of templates still to be discovered for readers not so familiar with the chemistry presented here.

Contents of Volume 248

Templates in Chemistry II

Volume Editors: Christoph A. Schalley · Fritz Vögtle · Karl Heinz Dötz
ISBN 3-540-22547-1

Spacer-Controlled Multiple Functionalization of Fullerenes

C. Thilgen · S. Sergeyev · F. Diederich

Chromium-Templated Benzannulation and Haptotropic Metal Migration

K. H. Dötz · B. Wenzel · H. C. Jahr

Supramolecular Templating in the Formation of Helicates

M. Albrecht

Hydrogen-Bond-Mediated Template Synthesis of Rotaxanes, Catenanes, and Knotanes

C. A. Schalley · T. Weilandt · J. Brüggemann · F. Vögtle

Template-Controlled Synthesis in the Solid State

L. R. MacGillivray · G. S. Papaefstathiou · T. Friščić · D. B. Varshney ·
T. D. Hamilton

Gels as Templates for Nanotubes

J. H. Jung · S. Shinkai

Contents

First Considerations: Principles, Classification, and History

D. H. Busch 1

Macrocycle Synthesis Through Templatation

Z. R. Laughrey · B. C. Gibb 67

Macrocycles and Complex Three-Dimensional Structures Comprising Pt(II) Building Blocks

A. Kaiser · P. Bäuerle 127

Templated Synthesis of Interlocked Molecules

F. Aricó · J. D. Badjic · S. J. Cantrill · A. H. Flood · K. C.-F. Leung · Y. Liu ·
J. F. Stoddart 203

Molecular Knots

C. Dietrich-Buchecker · B. X. Colasson · J.-P. Sauvage 261

Templatation in Noncovalent Synthesis of Hydrogen-Bonded Rosettes

M. Crego-Calama · D. N. Reinhoudt · M. G. J. ten Cate 285

Imprinted Polymers

A. J. Hall · M. Emgenbroich · B. Sellergren 317

Author Index Volumes 201–249 351

Subject Index 369

First Considerations: Principles, Classification, and History

Daryle H. Busch (✉)

University of Kansas, Department of Chemistry and Center for Environmentally Beneficial Catalysis, 1501 Wakarusa Drive, Bldg A, Lawrence Kansas 66047, USA
busch@ku.edu

1	Introduction	2
1.1	The Borromean Link	4
2	Elements that Compose Templates	6
3	Kinds of Templates	11
3.1	Metal Ion Anchored Templates	11
3.2	π - π Templates	12
3.3	Hydrogen Bond Anchored Templates	13
3.4	Hydrophobically Enhanced Templates	15
4	History	17
4.1	The Template Route to Macrocyclic Ligands	17
4.1.1	The Quest and Discovery	17
4.1.2	Concept Development and Missed Opportunities to Recognize Templates	21
4.2	The Template Route to Molecular Cage Ligands	22
4.2.1	The Quest and Discovery	22
4.2.2	Concept Development and Missed Opportunities	26
4.3	The Template Route to Catenanes	26
4.3.1	The Quest and Discovery	26
4.3.2	Concept Development and Missed Opportunities	35
4.4	The Template Route to Rotaxanes	35
4.4.1	The Quest and Discovery	35
4.4.2	Concept Development and Missed Opportunities	50
4.5	The Template Route to Knots	50
4.5.1	The Quest and Discovery	50
4.5.2	Concept Development and Missed Opportunities	57
5	Molecular Templates – a Limited Field with an Unlimited Future	58
	References	59

1

Introduction

Despite a 40 year history, molecular templates continue to open new frontiers in chemistry. They greatly facilitated the availability, study, and exploitation of macrocyclic molecules and the many chemical developments associated with macrocyclic ligands and receptor chemistry. The use of molecular templates to optimize catanane and rotaxane formation (in their many small molecule, dendritic, and polymeric manifestations) and the yielding by templates of both simple and composite molecular knots has opened the universe constituted by the orderly entanglement of molecules of various topologies. Chemists stand at the border of that new land of great promise and toy with the simplest of examples while coveting the ultimate, for example, template-generated molecular scale computer elements or new kinds of materials such as 3-dimensional substances woven at the molecular level. As is typical of true frontiers of knowledge, each unique advance opens the way for myriads of other advances. One example of a new interlocked form of matter constitutes the creation of a new molecular species of unknown and, perhaps, unexpected properties. We now recognize the parallel nature of synthetic chemical templates (which we have called molecular templates) and DNA, the marvelous template of nature that implements genetic information and directs the construction of whole organisms, molecule by molecule. Remarkably, it has been shown that DNA can produce a most extensive and astounding list of topological motifs in its multitude of molecular entanglements [1]. Here we deal with the orderly molecular entanglements and interlocked structures that chemists have managed to make from small molecules.

Chemists and physicists have long been the pico- and nanoscientists, but popular literature and public fascination with extremes of all kind have made words like nanoscience and nanotechnology common language. The molecular scientists and the public equally expect new marvels from these realms, at least in molecular electronics and molecular machines. Chemical templates will provide guiding principles for many advances as these ambitions are realized. A clear point of application for molecular templates is the building of nanostructures in the direction proceeding from the smallest of atomic and molecular components to the nanoscale final product. The new fields of dynamic organic chemistry [2] and dynamic combinatorial chemistry [3] exemplify exciting chemical frontiers that have a less than universally recognized, but undeniable, relationship to molecular templates. In fact, the equilibrium molecular template described at a later point in this discussion is a very early recognized example making use of dynamic organic chemistry.

Along with the concept of complementarity, the principles of molecular templates provide the foundations for understanding the vast array of scenarios in which interactions occur between individual atomic or molecular entities, regardless of the complexity of the examples involved. In a templated process, molecular entities, or their components, actively organize complementary

entities, resulting in selected results that would be highly improbable in the absence of the templating interaction. A second feature of template processes is the common, but not essential, use of molecular/atomic entities as anchors that facilitate the selected result but which, post reaction, can be removed, leaving the highly improbable structure as a stable entity.

A simple example, the formation of a rotaxane, dramatizes the essential relationships (Fig. 1). A rotaxane is a molecularly interlocked molecule in which a relatively linear molecule occupies a threaded position through a cyclic molecule; bulky groups at both ends of the linear molecule prevent it from slipping out of the ring. Over 40 years ago, Frisch and Wasserman wrote about molecular topology and the formation of such simple interlocked structures as interlocked rings (catenanes) and knots in molecules [4]. As part of their investigations, they considered the probability that linear molecules might thread through appropriately sized cyclic molecules, as required for rotaxane or catenane formation (by certain mechanisms), and concluded that it would be a tiny fraction. Harrison and Harrison [5] performed elaborate experiments in which threadings were repeated some 70 times with a result indicating that the likelihood of threading linear molecules through molecular rings is something like 10^{-3} . Experimenters confront numbers of this magnitude with varied reactions ranging from “this is so improbable it doesn’t deserve attention” to “it happens; maybe we can make it happen more often – maybe much more often”. In fact, if the random result is unfavorable then it is appropriate to find ways

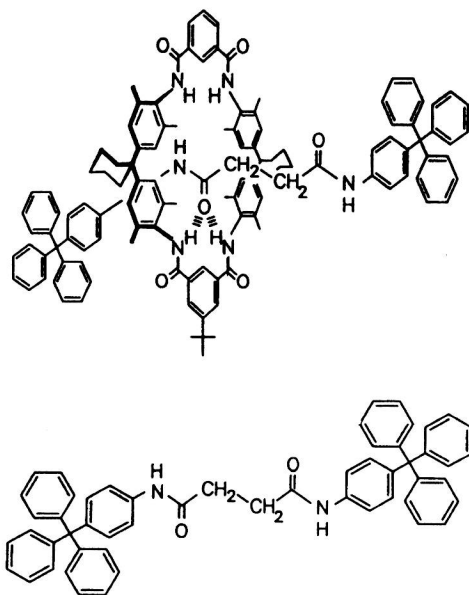


Fig. 1 Example of a rotaxane [140]. Reprinted with permission from Wiley-VCH. Copyright 1997

to exert control in order to create a favorable result, and that is what molecular templates do.

Many researchers have demonstrated the impact of templates on the yields of such threading reactions with strongly contrasting results. At the limit, one can anticipate quantitative formation of the pseudo-rotaxane, made possible by a template interaction between complementary linear and cyclic molecules. A pseudo-rotaxane involves the threading of the axle into the ring but without the blocking groups at the ends of the linear molecule. Removable anchors, employed to hold the parts together while rotaxanes are formed, have most commonly been protons, cationic metal ions (such as Cu^+ , Ru^{2+} , Zn^{2+} , or Fe^{2+}), or π - π stacking. It must be emphasized that many of the ultimate applications of designed orderly molecular entanglements, be they interlocked or the product of an open topology, require enormous numbers of identical repetitive events, e.g., the weaving of linear molecules, or the construction of a computer chip based on millions of molecular sites. Achieving these goals will require an essentially complete reaction at each step. Otherwise the cumulative error, or incompleteness, may produce a useless product.

Before becoming immersed in the total content of this subject let us enjoy the beauty, excitement, and immensity of what is probably the most elegant success, to date, of the synthetic molecular template.

1.1

The Borromean Link

Adopting, for the moment, one of many histories of this famous image – an ancient Italian family logo has attracted the attention of chemists interested in stereochemistry since the beginning of discussions on subjects that may be called chemical topology. The motif is usefully perceived as three oval rings, each in its own plane, which is orthogonal to the planes of the other two rings, and all three rings have a common center of gravity (Fig. 2). The rings are collectively inseparable, but once one ring is broken, the other two are liberated – an intriguing topological parody of a demanding social scenario. A nicely planned strategy by Siegel et al. provided the template synthesis of a motif that correctly positioned two of the three rings, linked by two templating ions [6]. Molecular turns of the octahedral Sauvage type (based on a Cu^+ anchor, vide infra) were used for one of the rings, while the other ring used a modification that focused the reactive centers away from its copper(I) anchor. The success of that work boded well for synthesis by these seekers of the first Borromean motif. However, history interceded. To quote Dr. Siegel from his review on chemical topology in *Science* [7] “Chichak et al. report on page 1308 that they combined the equilibrium-based methods of imine formation with the templation power of zinc ions to effect an elegant one-step total synthesis of a Borromean link from 18 precursors. Their strategy uses a set of endo- and exo-oriented ligands designed to form an oriented trigonal bipyramidal unit around zinc ions, six of which assemble into the Borromean link.” The X-ray

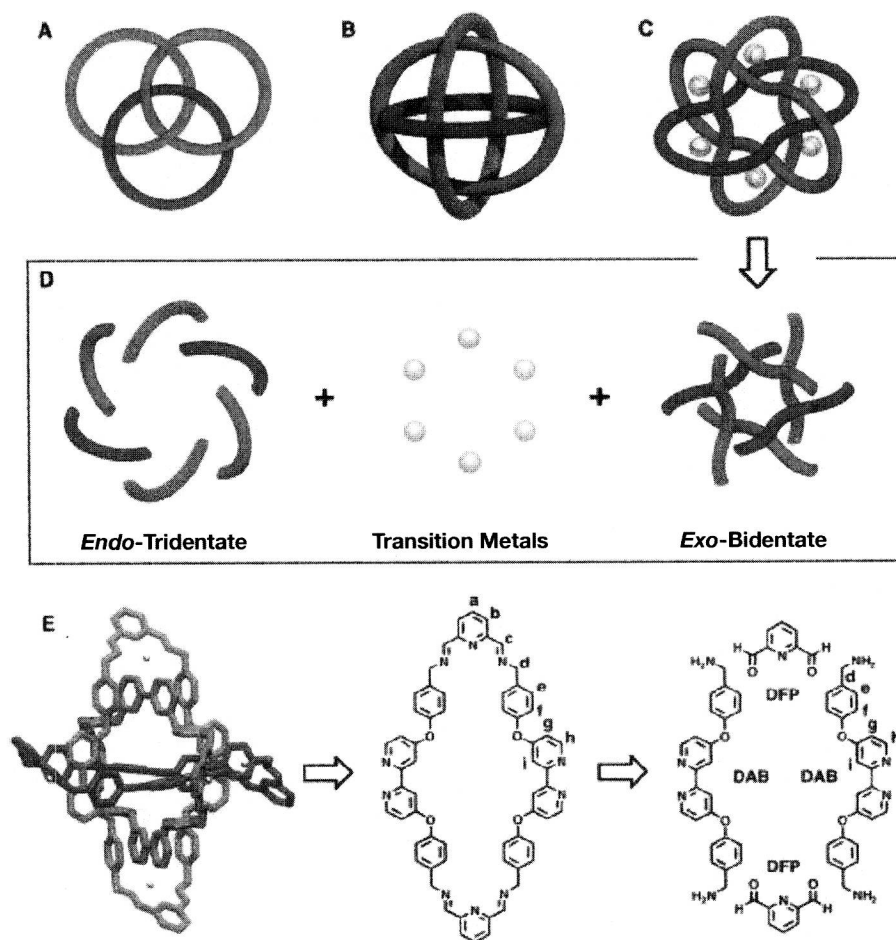


Fig. 2 Three representations of the Borromean link (Venn rings, orthogonal rings and template). Excerpted with permission from [8]. Copyright 2004 AAAS

structure determination confirmed the achievement of Stoddart and his colleagues [8].

The achievement was remarkable in a number of ways. It involved what is probably the most complicated template in the chemical literature, based on six zinc(II) ions and both convergent (or endo-directed) and divergent (or exo-directed) molecular turns (Fig. 2). In contrast to the overall complexity of the templating system, the reactants were relatively simple. The divergent component was a dipyridyl while the convergent component was an α, α' -diiminopyridyl unit formed by a thermodynamic, or equilibrium, templating process. Top of the outstanding characteristics of the template is the fact that it involves both kinetic and thermodynamic template components, a combination that should

become common. Both of these distinctive template types were used in their fully modern contexts. The combination is extremely powerful; the components of the kinetic template hold the subjugated components in place while the thermodynamic components find their final disposition at equilibrium. In the classic equilibrium template [9] the reactants form their normal distribution of products and the anchoring/selecting factor (often a metal ion) selects the product that binds best, combines with it and shifts the equilibrium accordingly. Only the authors know the extent to which alternative components were selected and rejected in failure, but their final choices contain still another special feature.

The choice of zinc as the template anchor provided a second opportunity for flexibility in the reacting system because zinc, being a spherical ion, is adaptable when it comes to coordination numbers and coordination geometries. So, this template system allowed the chemistry to determine critical features both in the Schiff base reaction steps and in the basic stereochemistry of the metal ion anchor. Further, the yield in this scientific triumph was 90%. The success over the enormous challenge of synthesizing the molecular embodiment of the Borromean link suggests that the science of using the molecular template has reached a level of maturity from which scientists may be expected to produce new molecular entanglements and interlocked structures of profound significance, despite the equally profound challenges they represent.

2

Elements that Compose Templates

The history of templates is most readily appreciated with an understanding of the most basic underlying relationships. These elements make molecular templates very special and, from the standpoint of controlling matter, extremely powerful. After having worked with templates, off and on, for close to 40 years, the author offered a definition for a molecular template [10] “a chemical template organizes an assembly of atoms, with respect to one or more geometric loci, in order to achieve a particular linking of atoms.” That simple statement does capture the essence of a molecular template, but it fails to consider the complexity of a templating process. Missing are several levels of complexity, including:

1. The general kind of template, whether it is a kinetic or equilibrium template
2. The essential elements that must be present in a template and how they depend on the specific purpose of the template
3. The centricity of the template, i.e., whether it involves a single center or two or more such centers, and whether those centers are independent or cooperative
4. Complementarity

From the time when they were first reported and given their universally accepted name, it has been clear that there are two kinds of molecular templates:

Kinetic templates. The template affects the sequence of events that determine the structural changes during the course of the reacting process [9b, 11].

Equilibrium (or thermodynamic) templates. The reaction between organic components produces a variety of products but one, or more, of those products is/are sequestered in the course of the template process, shifting the equilibrium in favor of that product(s) [9a, 12].

The kinetic and equilibrium template processes are illustrated in Figs. 3 and 4. The most common molecular templates control processes that create topological or other related effects: ring closure, cage formation, catenane (interlocking rings) formation, tying of molecular knots, creating the Borromean link. Consequences dependent on size relationships are also significant in the case of real molecules, as in rotaxane formation and entrapping of ions or molecules in

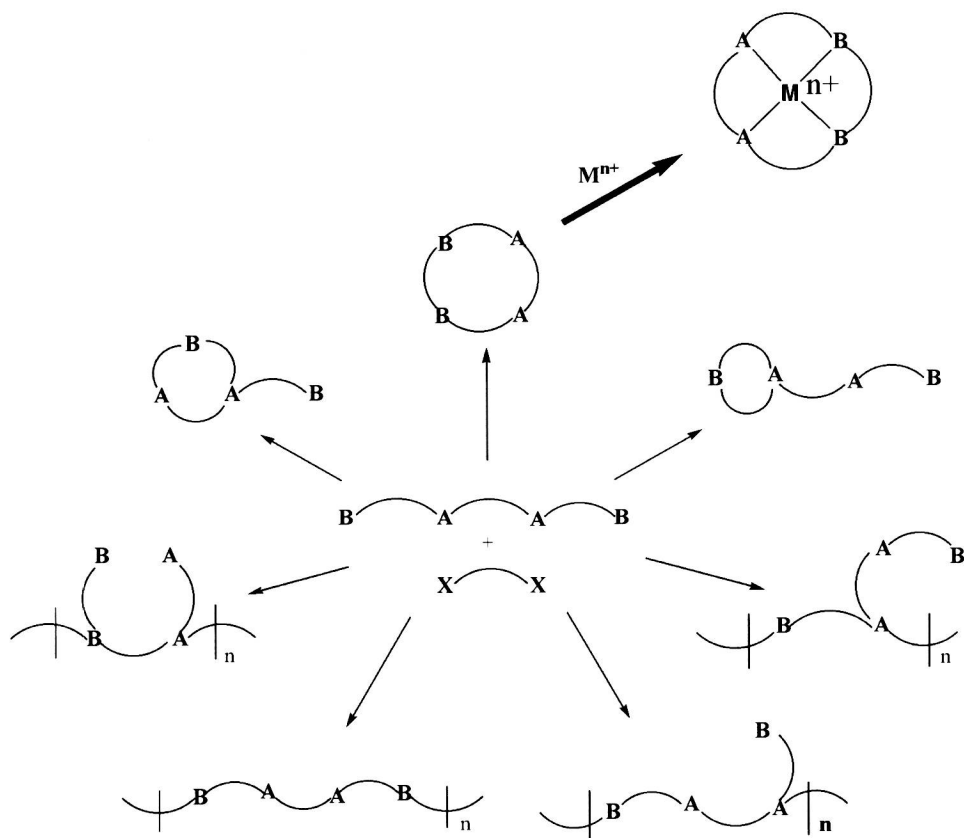


Fig. 3 Equilibrium molecular template. At equilibrium the organic reactants form multiple products. A metal ion binds to a single product and sequesters that product. The equilibrium shifts to generate more of that product