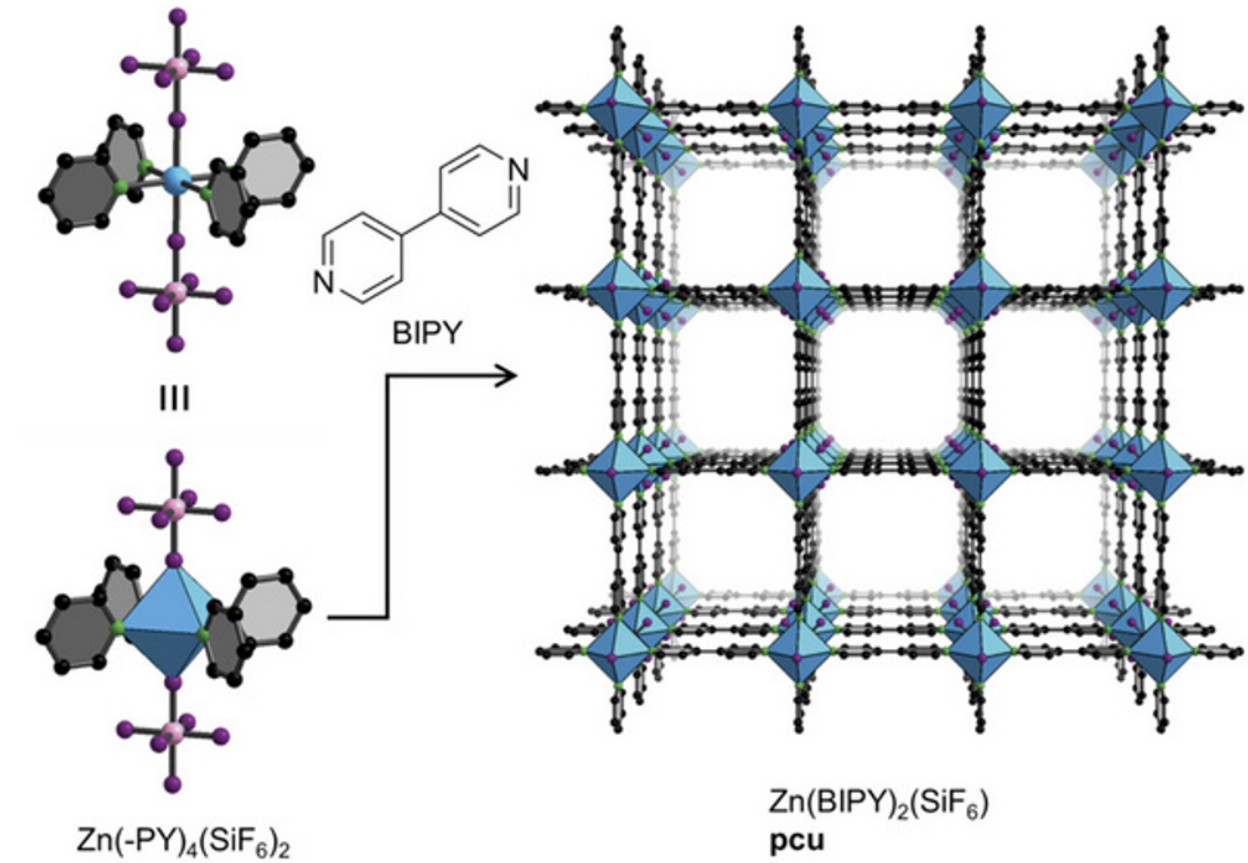
Macrocyclic and Supramolecular Chemistry

How Izatt-Christensen Award Winners Shaped the Field



Editor **Reed M. Izatt**

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Macrocyclic and Supramolecular Chemistry

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How Izatt–Christensen Award Winners Shaped the Field

Edited by

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Preface

The International Izatt–Christensen Award in Macrocyclic and Supramolecular Chemistry was initiated in 1991. It recognizes excellence in these fields of chemistry and is presented annually at the International Symposium on Macrocyclic and Supramolecular Chemistry (ISMSC). Recipients are representative of those who are doing fine work in this vibrant and expanding field of chemistry, which has developed into one of the most active and promising research areas in science.

In 2016, the 25th International Izatt–Christensen Award will be presented at the 11th ISMSC in Seoul, Korea. I conceived the idea of a book featuring chapters from Award recipients in August 2015. Wiley editor Sarah Higginbotham agreed that the idea was sound and 21 recipients of the Award agreed to prepare the chapters found in this volume. In Chapter 1, recipients of the Award from 1991 to 2016 are given, together with titles of their ISMSC presentations.

The work presented in this volume covers a wide range of subject matter. This range reflects the growth of the field during the past half century. Several chapters present historical aspects providing insight into the beginnings of work on macrocyclic and supramolecular chemistry in the 1960s. A recurring theme in the chapters is molecular recognition, which has played an important role from the beginning and has led investigators along many different paths. This diversity is evident in the work presented in the various chapters.

Backgrounds of the award recipients are varied and their contributions to the field are different. Not all authors present up-to-date research results although the book contains many of these. Several of the authors are retired and not as active in research as they once were. However, their contributions were cutting-edge and a review of their work and, perhaps, how their studies added to our present knowledge base is of great interest. I feel that it is important for the younger generation to have an appreciation for origins of the science they now enjoy and of the people who created it. How better can this be obtained than through reading first-hand accounts of the work of those who went before. The material in this book provides an opportunity to convey much useful information to the next generation. It has thrilled me to see the continuing enthusiasm of students and young faculty members in this field. This interest is expressed each year in locations worldwide by the large number of enthusiastic young people who attend the ISMSC meetings where the Izatt–Christensen Award is made. I suspect that most of these individuals have little knowledge of the history behind the chemistry presented at these symposia. This book will fill that void to some degree.

The authors are prominent among those whose contributions have shaped, and continue to shape, macrocyclic and supramolecular chemistry. Prospects for the future in this rapidly developing field are part of many chapters. Coincident with the development in the 1960s and 1970s of the concept of molecular recognition into the current rapidly expanding field of supramolecular chemistry was the following statement by Richard Feynman (*Eng. Sci*. 1960, 23, 22–36; 1965 Physics Nobel Laureate) about rearranging atoms at the molecular level.

> *What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do.*

I believe that this prediction of Feynman's has seen its fulfillment in the demonstrated ability of scientists, including those in supramolecular chemistry, to do exactly what he describes. Design at the molecular level has enabled the production of hosts with impressive selectivity for guest molecules. In the pages of this volume, many examples are given and I predict that the reader will have fun discovering them. One of the chapters is titled "Serendipity." Several authors use the word serendipity to describe some of their findings. Charles J. Pedersen's discovery of crown ethers (Chapter 1) was an example of serendipity. The future of macrocyclic and supramolecular chemistry is bright with opportunity even though we cannot *see exactly what will happen.*

Reed M. Izatt,
Provo, Utah
March 2016

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I appreciate and thank the authors of each chapter who have worked diligently to deliver high-quality content for this volume. I have enjoyed the constant guidance of a terrific set of Wiley editors who have provided help whenever it was needed for me and for the authors. My computer-literate daughter, Anne Marie Izatt, has been of immeasurable assistance throughout this editing experience. Knowing she was there when needed, which was often, brought me great comfort. Finally, I thank my wife, Janet, for her patience, understanding and support throughout the preparation of this book. Janet has been a valuable sounding-board and has made many helpful suggestions.

Reed M. Izatt
March 2016

1

The Izatt–Christensen Award in Macrocyclic and Supramolecular Chemistry: A 25-Year History (1991–2016)

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1.1 Introduction

The Izatt–Christensen Award (I–C Award) recognizes excellence in macrocyclic and supramolecular chemistry. It has been presented annually since 1991 by the International Symposium on Macrocyclic and Supramolecular Chemistry (ISMSC). A common theme to both of these fields is molecular recognition. The search for underlying principles governing molecular recognition or how molecules recognize each other began in earnest in the early 1960s. Working independently, several individuals who later became prominent in the emerging fields of macrocyclic chemistry and supramolecular chemistry, made important early contributions to molecular recognition. Four of these were Charles J. Pedersen (1904–1989), Daryle H. Busch, Jean-Marie Lehn, and Donald J. Cram (1919–2001). Prior to the 1960s, no concentrated effort had been made to investigate chemical selectivity involving macrocyclic compound interactions with metal ions or other guest molecules [1].

Charles Pedersen while employed at du Pont serendipitously discovered the compound that later came to be known as dibenzo-18-crown-6 (DBl8C6). Pedersen isolated DBI8C6 in a 0.4% yield from a "brownish goo" while attempting to prepare a completely different compound [2]. The decision to expend the effort needed to isolate, purify, and characterize the compound that became known as DBl8C6 represents a true example of scientific creativity and luck. The story of Pedersen's discovery, reported in 1967, his identification of the many new cyclic polyether macrocyclic compounds he synthesized, his characterization of their selective complexation with alkali metal ions, and his own account of the events surrounding the discovery make fascinating reading [2, 3].

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Daryle Busch remembers that his first ideas of synthesizing macrocycles occurred while a graduate student with John Bailar at the University of Illinois in the early1950s. His account of these first ideas of forming macrocycles from bidentate amines involved in copper(II) chelation illustrates the workings of a creative mind. It was several years later in 1962, as a Professor of Inorganic Chemistry at Ohio State University, that he reported the first synthesis of a macrocycle using a metal template [1, 5] He received the I–C Award in 1994 and is the author of a chapter in this book [4], in which he gives a first-hand account of his work.

Jean-Marie Lehn reported the synthesis of macrobicyclic polyethers containing three polyether strands joined by two bridgehead nitrogen atoms [6] in 1969, shortly after Pedersen's initial paper. Lehn later coined the term, "supramolecular chemistry," to describe the broadening of the scope of host–guest chemistry which he and his research group had spearheaded [7]. To quote Professor Lehn, "Beyond molecular chemistry, supramolecular chemistry aims at constructing highly complex, functional chemical systems from components held together by intermolecular forces." These components can be visualized as host–guest systems bonded by intermolecular forces, which are much weaker than covalent chemical bonds. The guest systems may include organic guests as well as metal ions. The number and variety of hosts synthesized has expanded far beyond macrocyclic compounds. Lehn has provided an account of his early work [7].

Donald Cram was a prominent organic chemist in the 1960s. John Sherman [8], one of his Ph.D. students, describes him as "definitely old school. Eccentric. Hard driven. Strong-willed. Spirited. Fearless." Cram's accomplishments included a major research program in organic chemistry, co-author of three major organic chemistry textbooks, and instructor at UCLA of several generations of organic chemistry students. His first acquaintance with macrocyclic chemistry was recorded by Roeland Nolte who remembers [9] that during a stay as a visiting scientist in Cram's laboratory at UCLA in 1981, Cram told him "after reading Pedersen's paper he had become so excited that he had made the decision to completely change his research program." Nolte goes on to say, "After having seen the potential of host–guest chemistry and the way it was approached by Cram, i.e., by designing compounds with the help of space-filling (CPK) models, we became fascinated and concluded that we should start a line of research in the Netherlands in which this new type of chemistry was incorporated." This attitude was contagious, and transfer of the excitement to others was responsible for the explosion of interest in macrocyclic chemistry, which characterized the field in the 1970s and 1980s.

As was the case with Nolte, many of the I–C Award winners spent time in the laboratories of Donald Cram, Daryle Busch, or Jean-Marie Lehn. A number of researchers, including one of us (RMI) and James J. Christensen, had close contact with Charles Pedersen, who influenced our early work in macrocyclic chemistry [10]. The influence of these early pioneers on the field through their own work and the work they inspired in others has been remarkable. The list of I–C Award recipients includes many of the early workers in the field who had close association with these individuals.

1.2 International Izatt–Christensen Award in Macrocyclic and Supramolecular Chemistry

In 1991, Jerald S. Bradshaw and Steven R. Izatt, President of IBC Advanced Technologies, Inc. (IBC), conceived the idea that it would be appropriate to initiate an annual award, titled the Izatt–Christensen Award, recognizing the vision of Reed M. Izatt and James J. Christensen in organizing the First Symposium on Macrocyclic Chemistry in 1977. From 1977 to 1991, the field had broadened, resulting in the design, synthesis and characterization of increasingly more complex organic ligands and their application to new fields of chemistry that were scarcely envisioned decades earlier. This trend is illustrated by the titles of the lectures presented by the I–C awardees.

The I–C Award was instituted in 1991 by IBC. This competitive annual award recognizes excellence in macrocyclic chemistry and is given to individuals who have not received a major award in chemistry. The awardee receives a small honorarium and a travel grant, provided by IBC, and is expected to present an invited lecture at the Symposium in the year of the award. The recipients of the I–C Award from 1991 through 2016 are listed in Table 1.1, together with the locations and titles of their Award lectures.

Table 1.1 *Izatt–Christensen Awardees in Macrocyclic and Supramolecular Chemistry 1991–2016*

Year	Awardee	Location	Title of Award Lecture
1991	Jean-Pierre Sauvage	Sheffield, UK	Synthetic Molecular Knots
1992	Eiichi Kimura	Provo, Utah	Role of Zinc(II) in Zinc Enzymes
1993	J. Fraser Stoddart	Enschede, The Netherlands	Self-Assembly in Unnatural Product Synthesis
1994	Daryle H. Busch	Lawrence, Kansas	A Sampling of Multi-receptor Supramolecular Systems
1995	David N. Reinhoudt	Jerusalem, Israel	Synthesis and Self-assembly of Supramolecular Structures for Switches and Sensors
1996	George W. Gokel	Montecatini, Terme, Italy	Synthetic Models for Cation Channel Function
1997	Alan M. Sargeson	Seoul, Korea	Outer-sphere Electron Transfer Reactions of Macro-bicyclic Complexes
1998	Seiji Shinkai	Turtle Bay, Oahu, Hawaii	Dynamic Control of Ion and Molecule Recognition Processes in Macrocyclic Host–guest Systems
1999	Fritz Vögtle	Barcelona, Spain	Rotaxanes, Catenanes, Pretzelanes–Template Synthesis and Chirality
2000	Jerry L. Atwood	St. Andrews, UK	Macrocycles as Building Blocks for Large Supramolecular Assemblies
2001	Jonathan L. Sessler	Fukuoka, Japan	Novel Polypyrrole Macrocycles
2002	C. David Gutsche	Park City, Utah	The Cornucopia of Calixarene Chemistry
2003	Jeremy K. M. Sanders	Gdansk, Poland	The Ins and Outs of Templating: A Dynamic Future for Macrocyclic Chemistry
2004	Makoto Fujita	Cairns, Australia	Self-assembly and Function of Metal-linked Macrocyclic and Cage-like Molecular Frameworks
2005	Kenneth N. Raymond	Dresden, Germany	Chemistry in Chiral, Nanoscale Flasks
2006	Roeland J. M. Nolte	Victoria, Canada	Supramolecular Catalysts and Materials from Macrocyclic Building Blocks
2007	David A. Leigh	Salice Terme, Italy	Exercising Demons: Synthetic Molecular Motors and Machines
2008	Akira Harada	Las Vegas, Nevada	Cyclodextrin-based Supramolecular Architectures, Dynamics, and Functions
2009	Omar M. Yaghi	Maastricht, The Netherlands	Reticular Chemistry and Frameworks Replete with Large Macrocycles
2010	Luigi Fabbrizzi	Nara, Japan	Put the Anion into the Cage–If You Can
2011	Andrew D. Hamilton	Brighton, UK	Protein Surface Recognition: A Supramolecular Approach to Controlling Biological Function
2012	Kimoon Kim	Otago, New Zealand	Cucurbituril-based Functional Materials
2013	Eric V. Anslyn	Arlington, Virginia	Three Short Stories of Analytical Supramolecular Chemistry
2014	Mir Wais Hosseini	Shanghai, China	Perspectives in Molecular Tectonics
2015	Paul D. Beer	Strasbourg, France	Interlocked Host Molecules for Anion Recognition and Sensing
2016	Hanadi Sleiman	Seoul, Korea	Supramolecular Chemistry with DNA: Towards Biological and Materials Applications

1.3 International Symposium on Macrocyclic and Supramolecular Chemistry

The First Symposium on Macrocyclic Compounds was organized by Reed M. Izatt and James J. Christensen and was held August 15–17, 1977 at Brigham Young University (BYU) in Provo, Utah [11]. Seventy-nine persons attended, 13 of them from ten countries outside of the USA. Of those attending from the USA, 23 were from BYU. Sixteen of the attendees came from l3 industrial companies. Twenty-eight universities were represented. The expenses for the symposium totaled $9500. The Provo symposia were held annually through 1981.

Izatt and Christensen envisioned the value of an annual symposium to provide a forum for the presentation and discussion of research activities in the field of macrocyclic chemistry. They saw a need in this new and rapidly evolving field to bring together persons from a variety of chemical and non-chemical fields who had an interest in macrocyclic chemistry, but who were not personally acquainted with each other. It was already apparent that the number of workers in the field was increasing rapidly and that interest spanned chemistry, physics, biology, and pharmacy. It was felt that an annual symposium could be the means to catalyze growth in the field and lead to the exploration of new areas of chemistry. It was visualized that both theoretical and experimental aspects of the properties and behavior of synthetic and naturally occurring macrocyclic compounds would be covered in a series of invited lectures as well as accepted contributed papers.

In 1980, the First European Symposium on Macrocyclic Compounds was held in Basel, Switzerland with Thomas Kaden as Chair. In 1982, the Second European Symposium on Macrocyclic Compounds was held in Strasbourg, France. At this meeting, informal discussions were held on the possibility of combining these two meetings into an annual symposium, which would be international in nature. It was agreed that the 1983 Symposium on Macrocyclic Compounds in Provo and the 1984 European Symposium in Stirling, Scotland would be held as scheduled. The 1985 meeting in Provo would be the first to be held under the new title of International Symposium on Macrocyclic Chemistry (ISMC). The ISMC meetings were held on an annual basis from 1985 until 2005.

In the early 2000s, it was recognized by several individuals that the fields of macrocyclic and supramolecular chemistry were growing together and becoming intertwined. As a result, it was proposed that the conferences in the two areas, the ISMC and the International Symposium on Supramolecular Chemistry (ISSC) be combined. Scientists found themselves attending both conferences to learn of new findings and meet colleagues. Also, it was evident that macrocycles were being used in many supramolecular structures, as can be seen in many of the chapters in this book. The committees for the two conferences decided to join the two conferences into one, to be called the International Symposium on Macrocyclic and Supramolecular Chemistry (ISMSC). Thomas Fyles from the University of Victoria organized the first joint meeting, which was held in June 2006 in Victoria, British Columbia, Canada. The ISMSC meetings continue the tradition of previous meetings of having excellent presenters who present groundbreaking discoveries in the fields of macrocyclic and supramolecular chemistry.

After being held in Canada, the meeting moved to Italy (2007) and was hosted by Luigi Fabbrizzi. Next, the meeting went back to North America and to Las Vegas, Nevada (2008) and was hosted by Jonathan Sessler and Eric Anslyn. Again it returned to Europe to Maastricht, The Netherlands (2009) and was hosted by Roeland Nolte and Alan Rowan. Asia came next with the meeting in Nara, Japan (2010) hosted by Makoto Fujita and Yoshihisa Inoue. Back to Europe the meeting went to Brighton, United Kingdom (2011) under Philip Gale. After the United Kingdom, it went to Otago, New Zealand (2012) where Sally Brooker hosted it. Next it went to Arlington, Virginia (2013), where Lyle Isaacs, Jeffery Davis, and Amar Flood were hosts. After Virginia, it went to Shanghai, China (2014) hosted by Zhanting Li. The 10th meeting was in Strasbourg, France (2015), where it was hosted by Luisa De Cola. The 2016 meeting will be held in Seoul, Korea under the direction of Kimoon Kim, Jong Seung Kim, and Juyoung Yoon. Future meetings are scheduled to be held in the United Kingdom, Canada, and Italy.

Table 1.2 *Symposia involving Macrocyclic and Supramolecular Chemistry (1977–2016). Abbreviations used: ISMC (International Symposium on Macrocyclic Chemistry); ISMSC (International Symposium on Macrocyclic and Supramolecular Chemistry)*

Year	Title	Location	Dates	Chair(s)
1977	First Symposium on Macrocyclic Compounds	Provo, Utah	15–17 August	R.M. Izatt, J.J. Christensen
1978	Second Symposium on Macrocyclic Compounds	Provo, Utah	14–16 August	R.M. Izatt, J.J. Christensen
1979	Third Symposium on Macrocyclic Compounds	Provo, Utah	6–8 August	R.M. Izatt, J.J. Christensen
1980	First European Symposium on Macrocyclic Compounds	Basel, Switzerland	2–4 July	T.A. Kaden
1980	Fourth Symposium on Macrocyclic Compounds	Provo, Utah	11–13 August	R.M. Izatt, J.J. Christensen
1981	Fifth Symposium on Macrocyclic Compounds	Provo, Utah	10–12 August	R.M. Izatt, J.J. Christensen
1982	Second European Symposium on Macrocyclic Compounds	Strasbourg, France	30 August–1 September	M-J. Schwing
1983	Seventh Symposium on Macrocyclic Compounds	Provo, Utah	8–10 August	R.M. Izatt, J.J. Christensen
1984	Third European Symposium on Macrocyclic Compounds	Stirling, UK	29–31August	R.W. Hay, R.M. Clay
1985	X ISMC	Provo, Utah	5–7 August	R.M. Izatt, J.J. Christensen
1986	XI ISMC	Florence, Italy	1–4 September	P. Paoletti L. Fabbrizzi
1987	XII ISMC	Hiroshima, Japan	20–23 July	E. Kimura
1988	XIII ISMC	Hamburg, Germany	4–8 September	A. Knöchel
1989	XIV ISMC	Townsville, Australia	25–28 June	L.F. Lindoy
1990	XV ISMC	Odessa, Ukraine	3–8 September	S.A. Andronati, V.P. Kukhar, N.G. Lukyanenko
1991	XVI ISMC	Sheffield, UK	1–6 September	J.F. Stoddart, D. Fenton
1992	XVII ISMC	Provo, Utah	9–14 August	R.M. Izatt, J.S. Bradshaw
1993	XVIII ISMC	Enschede, The Netherlands	27 June–2 July	D.N. Reinhoudt
1994	XIX ISMC	Lawrence, Kansas	12–17 June	D.H. Busch, K. Bowman-James
1995	XX ISMC	Jerusalem, Israel	2–7 July	A.Shanzer, D. Meyerstein
1996	XXI ISMC	Montecatini Terme, Italy	23–28 June	P. Paoletti, A. Bianchi
1997	XXII ISMC	Seoul, Korea	3–8 August	S.J. Kim
1998	XXIII ISMC	Turtle Bay, Oahu, Hawaii	7–12 June	J.L. Sessler, E.V. Anslyn
1999	XXIV ISMC	Barcelona, Spain	18–23 July	J. Casabo, E. Garcia-España
2000	XXV ISMC	St. Andrews, UK	2–7 July	R.W. Hay (posthumous) M. Schröder

(Continued)

Table 1.2 (*Continued*)

Year	Title	Location	Dates	Chair(s)
2001	XXVI ISMC	Fukuoka, Japan	15–20 July	S. Shinkai
2002	XXVII ISMC	Park City, Utah	23–27 June	J.D. Lamb
2003	XXVIII ISMC	Gdansk, Poland	13–18 July	J.F. Biernat
2004	XXIX ISMC	Cairns, Australia	4–8 July	L.F. Lindoy, F.R. Keene
2005	XXX ISMC	Dresden, Germany	17–21 July	K. Gloe
2006	1st ISMSC	Victoria, Canada	25–30 June	T.M. Fyles
2007	2nd ISMSC	Salice Terme, Italy	24–28 June	L. Fabbrizzi
2008	3rd ISMSC	Las Vegas, Nevada	13–18 July	E.V. Anslyn, J.L. Sessler
2009	4th ISMSC	Maastricht, The Netherlands	21–25 June	R.J.M. Nolte, A.E. Rowan
2010	5th ISMSC	Nara, Japan	6–10 June	M. Fujita, Y. Inoue
2011	6th ISMSC	Brighton, UK	2–7 July	P.A. Gale
2012	7th ISMSC	Otago, New Zealand	29 January–2 February	S.A. Brooker
2013	8th ISMSC	Arlington, Virginia	7–11 July	A.H. Flood, J.T. Davis L.D. Isaacs
2014	9th ISMSC	Shanghai, China	7–11 June	Z. Li
2015	10th ISMSC	Strasbourg, France	28 June–2 July	L. De Cola
2016	11th ISMSC	Seoul, Korea	10–14 July	K. Kim, J.S. Kim, J. Yoon

From the first joint meeting in 2006, the ISMSC has attracted top scientists and many students interested in the fields of macrocyclic and supramolecular chemistry, as was the case in its predecessor meetings. Presentations on molecular machines, metal organic frameworks, and supramolecular polymers as well as traditional topics such as host–guest binding and new macrocycles have been given. The 2015 ISMSC meeting in Strasbourg, France attracted 550 participants, two thirds of whom were students. The number of students attending the Symposium has always been high. For example, at the 8th ISMSC in Virginia, over 50% of the 350 attendees were students. Attendance at the meeting is normally around 350 as it was at the 3rd ISMSC in Las Vegas, Nevada, and at the 6th ISMSC in Brighton, U.K. The attendance at the 5th ISMSC in Nara, Japan was over 420. At the 2015 ISMSC in Strasbourg, the number of speakers was 50 and the number of poster presentations was 200. The large number of students in attendance at the symposia augurs well for the future of the field. The interest that characterized the early development of the field in the 1960s and 1970s continues to stimulate young people today. A summary of the symposia held from 1977 through 2016 is given in Table 1.2. Symposium titles, chairs, locations, and dates are presented.

1.4 Izatt–Christensen award sponsor: IBC Advanced Technologies, Inc.

IBC shares a common interest with the ISMSC in promoting molecular recognition as a guiding principle in developing new chemistry. This interest stems from a strong belief that scientific and engineering excellence in this field should be encouraged and will result in untold benefits for future generations. IBC has made an important contribution to the ISMSC for 25 years by providing financial support for the I–C Award. The chapters in this book provide insight into the way I–C Award winners have influenced progress in the fields of macrocyclic and supramolecular chemistry over this period.

The study of molecular recognition over the past half century has led to important discoveries and many applications, particularly in the medical, pharmacological, metallurgical and radiochemical sciences. The

1987 Nobel Prize in Chemistry was awarded to Charles Pedersen, Donald Cram, and Jean-Marie Lehn for "development and use of molecules with structure-specific interactions of high selectivity [12]." Two of the founders of IBC (Izatt and Bradshaw) received the American Chemical Society National Award in Separations Science and Technology in 1996 [13]. Inscribed on the award plaque were the words: "For advancing the separations science of metals and for new technology to forward industrial-scale recovery of metals from aqueous solutions." Many of the I–C Award recipients have received significant prizes and/or awards for their contributions to understanding and advancing the concepts of molecular recognition.

IBC was founded in 1988 by, and named after, Reed M. lzatt, Jerald S. Bradshaw, and James J. Christensen, three early workers in the field. These professors received much stimulus from contacts in the macrocyclic and supramolecular chemistry community. They made use of the ideas evolving in this scientific community during the 1970s and 1980s to design and prepare ligands with high affinity and high selectivity for specific metal ions in the presence of other competing metal ions that often have chemical properties very similar to those of the target metal ion. The resulting high selectivity of the ligands enabled IBC to develop a series of products (trade named SuperLig® and AnaLig®) using solid-supported ligands that could perform difficult metal ion separations at both the process and analytical scales [14]. The term Molecular Recognition Technology (MRT) was formulated in 1989 by Steven R. Izatt, President and CEO of IBC, to describe the practical application of molecular recognition in engineered systems for which customers receive value (i.e., for which they will pay money). MRT is well known today in extractive metallurgy [15–17] radionuclide separations [18], and chemical analysis [19]. Some early successes of MRT were its adoption by Impala Platinum Limited to process the palladium produced at its Springs Refinery in South Africa; its adoption by Tanaka Kikinzoku, Kogyo K.K. in Japan to recover rhodium from spent precious metal wastes [16, 17]; and the development, by IBC, 3 M and Argonne National Laboratory, of Empore™ Rad Disks [18] marketed worldwide by 3 M for analysis of radionuclides such as Sr and Ra. This development of Rad Disks was recognized by R&D 100 awards in 1996 and 1999 as well as the Federal Laboratory Consortium Award for Excellence in Technology Transfer in 1997 [18]. A hallmark of these processes is that they are based on green chemistry principles [15–17] resulting in significant economic and environmental advantages to the customer. The latest achievement made using MRT has been the demonstrated green chemistry separation in early 2015 of individual rare earth metals at the laboratory scale [20, 21]. Scale-up of the REE separations is underway and a pilot plant is expected to be operational in early 2016 [21, 22] that will be capable of producing individual rare earth metals at >99% recovery and >99% purity, with minimal waste generation.

IBC is committed to the principles of supramolecular chemistry which are central to the development of its highly selective separation systems that operate at the molecular level. Continuing support by IBC of the I–C Award is predicated on the belief that there are individuals in the macrocyclic and supramolecular chemistry community that will visualize and carry to fruition applications that will benefit society. The experience of IBC and the ideas expressed in this volume may be of value in stimulating others to commercialize their findings to the benefit of the larger community.

1.5 Summary

Twenty-five scientists have received the I–C Award since its inception in 1991. These individuals have made remarkable contributions to the fields of macrocyclic and supramolecular chemistry. The generosity of IBC in funding the Award and the willingness of ISMSC to host the Awardees at their annual symposia have made the Award possible. The ISMSC and its predecessor symposia have made significant contributions to the development of the fields of macrocyclic and supramolecular chemistry over the past nearly four decades. These symposia have provided a venue for the presentation of new results, for the discussion of new ideas, and for the development of new collaborations among researchers young and old. As the meetings move from

country to country, opportunity is afforded for younger scientists to meet and interact with senior scientists in the field. The scientific programs of the Symposium have changed over the years and reflect the changing nature of the field. A strength of macrocyclic and supramolecular chemistry that has emerged over the decades has been its use in the hands of creative and skilled scientists to explore new areas of chemistry, as exemplified by the I–C Awardees. For example, the creation of host molecules of predesigned shapes enables one to mimic, on the molecular scale, components of simple machines such as molecular on–off switches, molecular axles, and molecular wires. Macrocycles pre-designed to interact selectively with target inorganic or organic guests have also had an important impact in separations chemistry. The future of the macrocyclic chemistry field is limited only by the imagination and creativity of its practitioners. It is expected that the ISMSC will continue to play an important role in facilitating personal interactions, exchanges of ideas, and the discovery of new chemistry.

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