

Self-Assembly, Symmetry, and Molecular Architecture: Coordination as the Motif in the Rational Design of Supramolecular Metallacyclic Polygons and Polyhedra

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"I try in my prints to testify that we live in a beautiful and orderly world, not in a chaos without norms, even though that is how it sometimes appears."

M. C. Escher

Introduction

Since the beginning of science in the ancient world the symmetry of objects has always fascinated the human mind. Over two millennia ago Greek philosophers discovered how symmetry can be expressed in simple mathematical terms and applied in architecture. Since then, the study of the principles of symmetry and their application in architectural design has been an important part of human history. However, only after the birth of modern science and the emergence of chemistry as a discipline did it become possible to apply these principles to objects in the nanoscopic world. Chemical principles in combination with symmetry considerations allow one to design rational strategies necessary for the construction of a variety of nanoscale systems with desirable shapes, sizes, and ultimately function.

The self-assembly process driven by noncovalent interactions, that is now universally recognized to be crucial in the proliferation of all biological organisms, offers considerable advantages over the stepwise bond formation in the construction of large supramolecular assemblies. These include (1) a highly convergent synthetic protocol based on the simultaneous assembly of the predetermined building blocks, whose preparation requires significantly fewer steps than the comparable covalent synthesis, (2)

fast and facile formation of the final product since noncovalent interactions are usually established very rapidly, and (3) inherent defect-free assembly as the equilibria between the constituents and the final products contribute to the self-rearrangement of the components within the assembled structure and thus to the self-correction of defects. These advantages have long been exploited by nature, starting with photobiogenesis and the subsequent evolution of living organisms.

Although modern supramolecular chemistry¹ emerged from the studies of such covalent macrocycles as crown ethers, cyclophanes, calixarenes, cryptands, etc., it is currently dominated by the biomimetic motive of weak interactions such as hydrogen bonding, π - π -stacking, electrostatic and van der Waals forces, hydrophobic and hydrophilic interactions, etc. The power and versatility of this bio-derived motive is illustrated by the elegant recent investigations of the noncovalent synthesis of "rosette" aggregates and the two- and three-dimensional self-assemblies of mesoscale objects by Whitesides and co-workers,² the synthesis of self-organized nanostructures by Stupp and co-workers,³ the preparation of nanoporous molecular sandwiches by Ward et al.,⁴ the self-assembled three-dimensional capsules by Rebek,⁵ and the ordered hydrogen-bonded arrays investigated by Hamilton⁶ and many others.

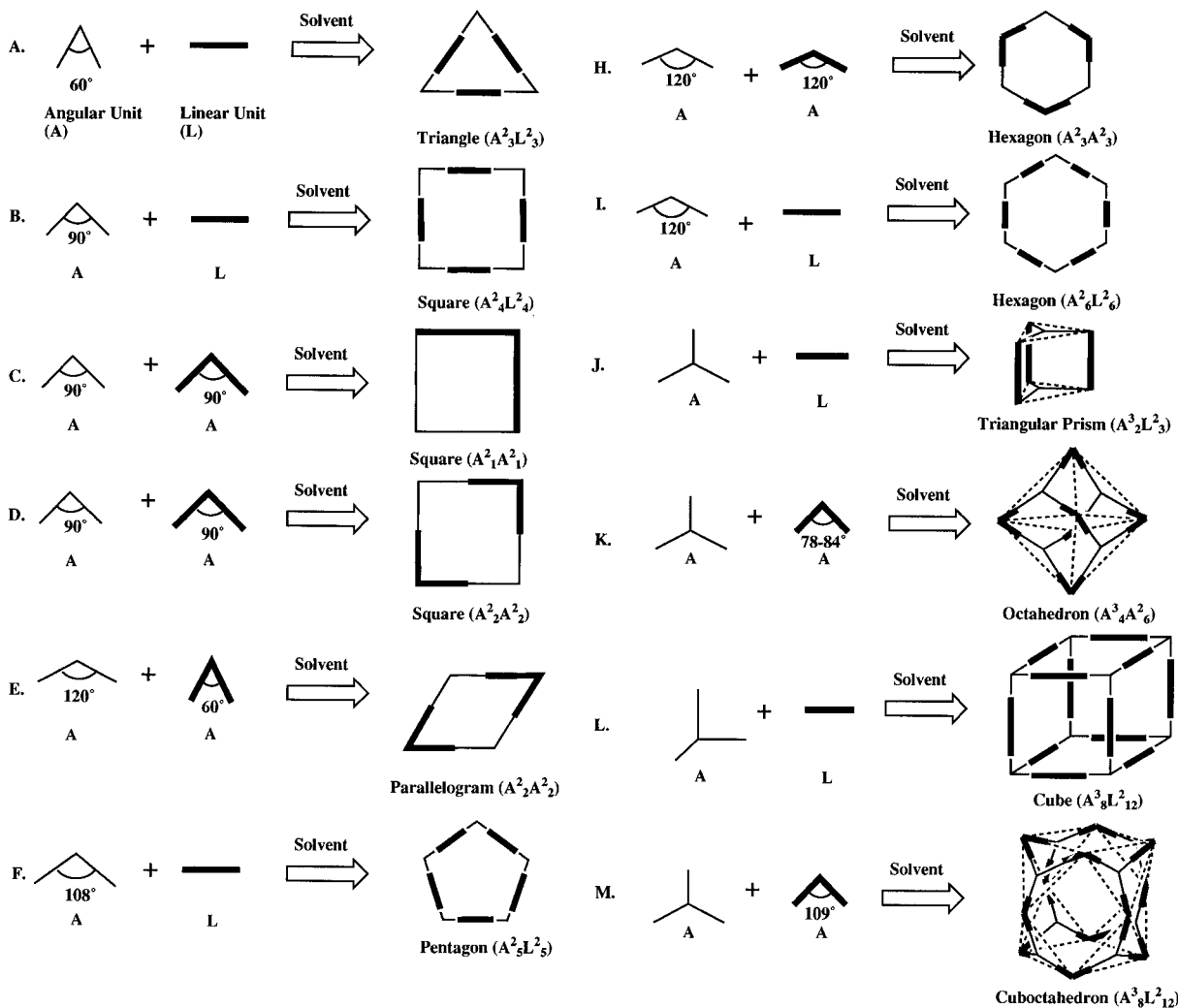
A very different approach for the formation of supramolecular species via spontaneous self-assembly of precursor building blocks is the use of metals and dative bonding via coordination. Although this methodology has been successfully employed in the formation of infinite networks and grids as well as the template-based synthesis of catenanes and molecular knots and discrete helical species,⁷ it has been much less explored in the self-assembly of discrete nanoscopic supramolecular species with predetermined shapes, geometries, and symmetries. In this Account we describe our recent efforts and results in this endeavor. At first we will discuss the general

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Chart 1



concepts, principles, and framework of the coordination motif, then we illustrate the power, depth, and versatility of this methodology via the self-assembly of molecular squares. Finally, we will demonstrate the breadth of this novel method via the spontaneous self-assembly of hexagons and three-dimensional species and conclude with some prognostications in this exciting and rapidly growing area.

Self-Assembly and Symmetry Considerations

The two most important factors to be considered in the rational design of coordination-based discrete nanoscale supramolecular entities are the symmetry and the overall shape of the resulting macrocyclic assembly. This is determined solely by the type and properties of the multidentate building units used in the construction of the assembly. Two types of building blocks are required: linear units (L) of two-fold symmetry, which contain reactive sites with a 180° orientation relative to each other and angular units (A), possessing reactive sites with other desirable angles which may contain either two-fold or higher symmetry axes. With such building units, when the overall assembly process is symmetry-conserved, the final shape of the resulting species will depend upon the type of each individual subunit and their stoichiometry and its symmetry will be the result of the simultaneous

combination and distribution of their main symmetry axes in a closed, spherical-like "Aufbau" order.

Thus, two-dimensional *monocyclic* assemblies (or their projections into the plane perpendicular to the main axis of the molecule in case of nonplanar entities) possessing building subunits of no higher than two-fold symmetry therefore resemble the shapes of convex polygons. Three-dimensional *polycyclic* structures that contain at least one type of subunit with the main symmetry axis greater than two-fold will possess the shapes of canonical polyhedra with the linking subunits serving as either the framework or the sides of these polyhedra. With these simple governing principles and the large diverse number of potential multidentate ligands and transition metals it is possible to assemble all manner of polygons and polyhedra with tremendous variations in geometric features.

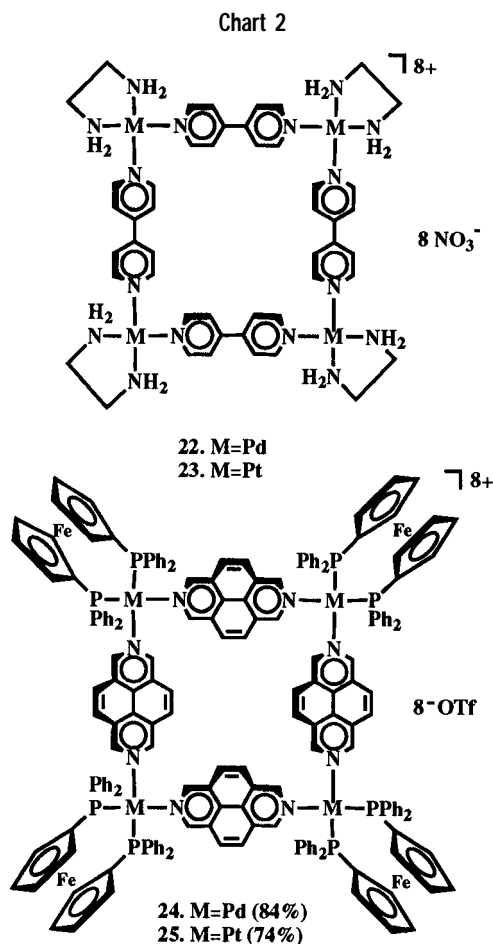
The shape of an individual two-dimensional polygon is determined by the value of the turning angle within its angular components. Thus, the combination of 60° turns with linear linking components will yield a molecular triangle, 90° turns a molecular square, 108° a pentagon, 120° a hexagon, etc. (Chart 1). For proper self-assembly to occur the building blocks must follow each other in correct order and remain bidentate in order to form these two-dimensional structures. Therefore, the design of a planar triangle requires three 60° bidentate angular com-

ponents (A^2_3) and three bidentate linear linking units (L^2_3); the combination of four bidentate angular components (A^2_4) with four bidentate linear linkers (L^2_4) will result in a square, and so on. The design of three-dimensional polyhedra is significantly more complex; it requires at least one type of linking component which has more than two coordination sites. For example, the combination of two tridentate angular (A^3_2) components with three bidentate linear linking units (L^2_3) will yield a species with the overall shape of a triangular prism and eight tridentate angular components (A^3_8) in combination with 12 linear bidentate units (L^2_{12}) will result in a cube. Likewise, using this simple notation an $A^3_8L^2_{12}$ system with planar tridentate linkers possesses the shape of a cuboctahedron, an Archimedean semiregular polyhedron (Chart 1).

Simple Molecular Squares

Molecular squares are one of the simplest but nonetheless interesting members of the family of polygons. They are macrocyclic species which contain 90° turns in the assembly that define their specific shape. The self-assembly of molecular squares based on simple modules may be achieved via the interaction of four bidentate angular units with four linear components and therefore having an $A^2_4L^2_4$ arrangement as shown in Chart 1B. The bisphosphane complexes **1** and **2** upon reaction with 1 equiv of 4,4'-bipyridine (**3**) in dichloromethane at room temperature give molecular squares **4** and **5** as identified by multinuclear NMR and single-crystal X-ray diffraction studies.⁸ Likewise the acyclic bisphosphane complexes **6** and **7** lead to the formation of the desired tetranuclear squares **8** and **9**, indicating that nonchelating phosphines may also be employed in this self-assembly process. Another variation of this approach includes utilization of the planar aromatic linkers 2,7-diazapyrene (**10**) and 2,9-diazadibenzo[*cd,lm*]perylene (**11**), resulting in molecular squares **12–15**, with deeper, larger cavities than assemblies **4–7**.

In the case of 1,4-dicyanobenzene (**16**) and 4,4'-dicyanobiphenyl (**17**) and the transition metal bisphosphanes, only the Pd(II)-containing analogue **1** yielded the expected products **18** and **19** (Scheme 1), whereas with the Pt(II) analogues, only oligomers were produced. This indicates that the self-assembly of these species is governed by at least two additional factors besides the valent angle: (a) dative bond strength and (b) the π -stacking interactions between each of the individual components. The delicate relationship between these factors can drastically influence the outcome and stability of the resulting products.⁸ As seen from the molecular model based on the X-ray structure of **5** (Figure 2a), there is a high degree of π -stacking between the phenyls of the chelated bisphosphane and one of the 4,4'-bipyridine rings that may ultimately be responsible for the stability of squares **4** and **5**. In contrast, when ligands **16** and **17** were used, the corresponding bimetallic species **20** and **21** were isolated (Scheme 1). In these cases the intermolecular π -stacking interaction of the phenyl groups on the metal units and the linker ligand is much weaker due to the unfavorable



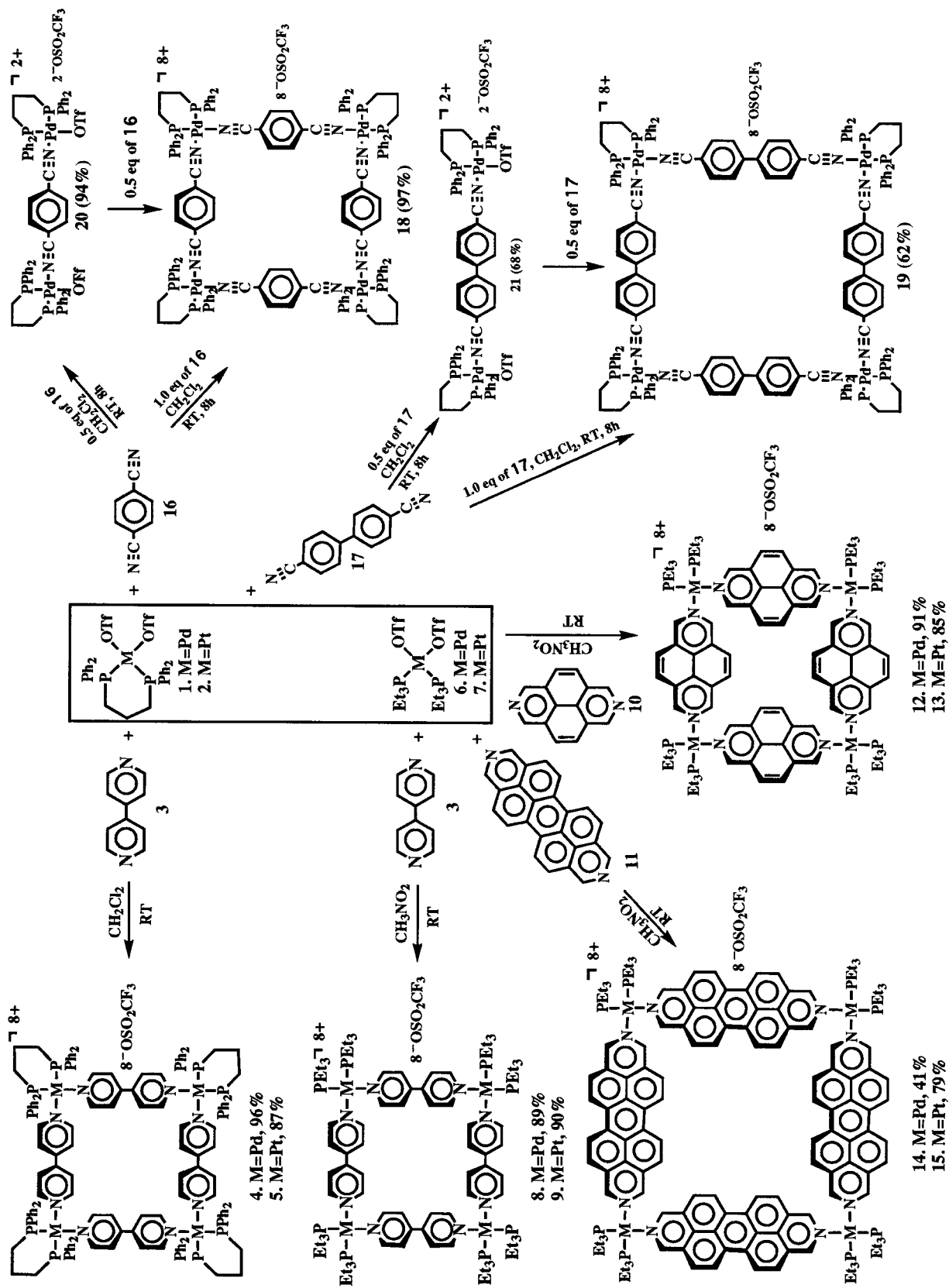
spatial disposition of the linker bound to the cyano groups. Hence, only the more labile Pd(II)-containing square is formed since it is capable of internal self-reorganization due to the weaker Pd–N≡C compared to the Pt–N≡C interaction⁸ which reduces the possibility of the thermodynamically unfavorable oligomerization.

The structure of molecular square **5** (Figure 1a) reveals a number of interesting geometric features. The entire molecule is slightly puckered. The deviation from planarity in the solid state is about 4 Å, but the shape of the molecule is that of a square. Particularly interesting is the stacking pattern of this assembly in the solid state (Figure 1a). The cationic parts of the square are stacked along the *b* axis about 14.5 Å apart, resulting in long, channel-like cavities. This interesting zeolite-like arrangement may find application in solid-state catalysis, especially in cases where the exact dimensions of the absorbing channel are of importance.

All molecular squares are isolated as robust, air-stable, microcrystalline solids. They are remarkably soluble in organic solvents, such as dichloromethane, acetone, nitromethane, and methanol, but completely insoluble in water. However in the solid state they occlude either solvent of crystallization or water which cannot be driven off even by prolonged heating in a vacuum. These features complement the analogous water-soluble squares **22** and **23** reported by Fujita and co-workers⁹ (Chart 2),

(8) Stang, P. J.; Cao, D. H.; Saito, S.; Arif, A. M. *J. Am. Chem. Soc.* **1995**, *117*, 6273. Stang, P. J.; Cao, D. H. *J. Am. Chem. Soc.* **1994**, *116*, 4981.

(9) Fujita, M.; Sasaki, O.; Mitsuhashi, T.; Fujita, T.; Yazaki, J.; Yamaguchi, K.; Ogura, K. *J. Chem. Soc., Chem. Commun.* **1996**, 1535. Fujita, M.; Yazaki, J.; Ogura, K. *J. Am. Chem. Soc.* **1990**, *112*, 5645.

Scheme 1. Self-Assembly of Polygons of A₂L₂L₄ Topology

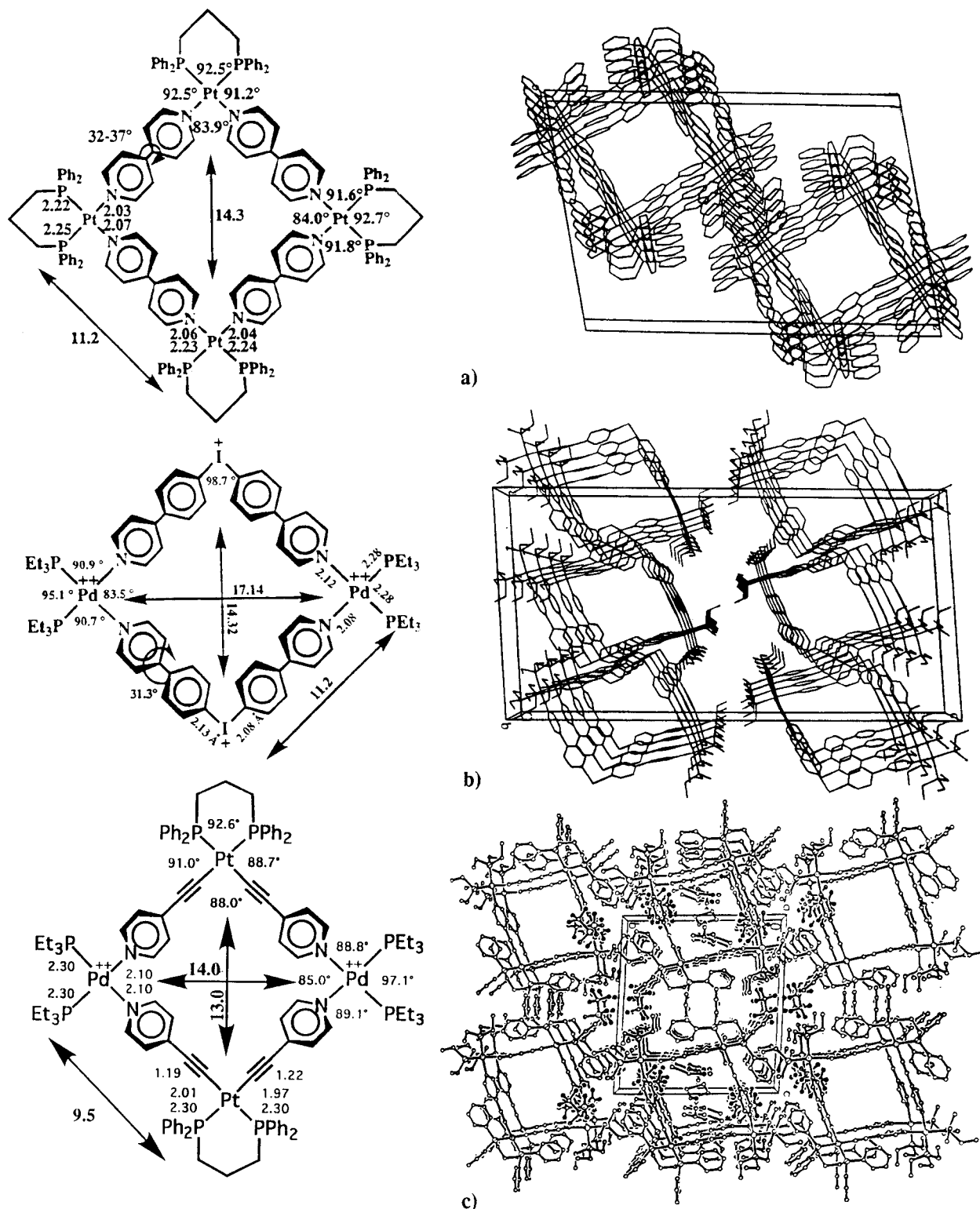


FIGURE 1. Crystallographic data (left) and solid-state packing diagrams (right) of molecular squares 5 (a), 29 (b), and 47 (c).

assembled from 4,4'-bipyridyl and the water-soluble enPd(II) dinitrate complex.

The versatility of this self-assembly strategy can be demonstrated by the preparation of an interesting class of heterobimetallic molecular squares incorporating mixed transition metals. When complexes of 1,1-bis(diphenylphosphino)ferrocene were treated with 2,7-diazapyrene they resulted in heterobimetallic assemblies **24** and **25** (Chart 2). Molecular squares **24** and **25** are interesting combinations of several redox-active ferrocenyl centers

with highly conjugated aromatic linkers.¹⁰ They are intensely colored both in solution and in the solid state and have interesting absorbance spectra, and their unique structure may suggest unusual electrochemical properties.

Hybrid and Mixed Metallic Molecular Squares

Such molecular squares can be prepared via the combination of two different pairs of bidentate angular units,

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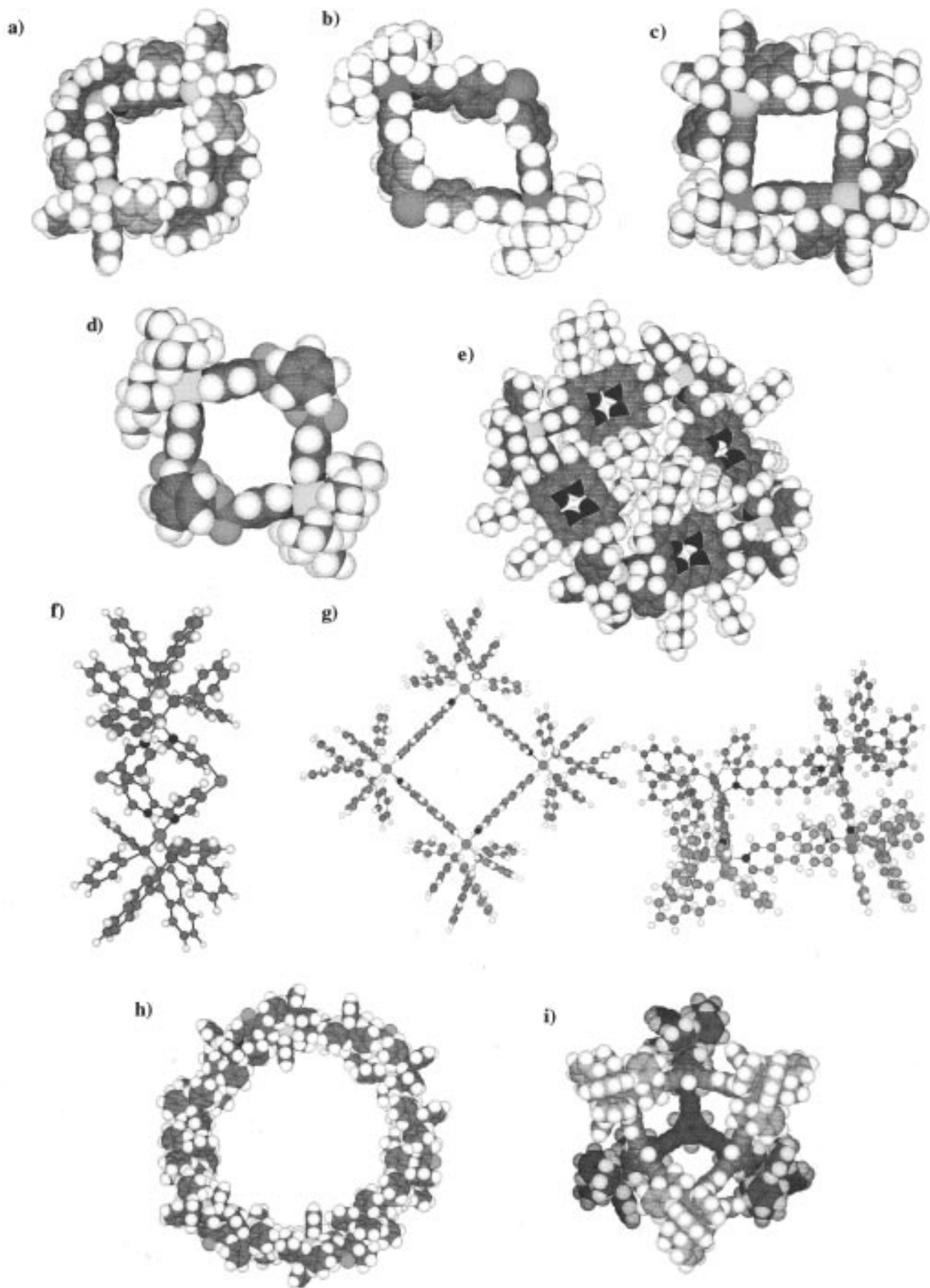


FIGURE 2. Molecular models of assemblies 5 (a), 29 (b), 47 (c), 56 (d), 67 (e), 76 (f), 80 (g), 90 (h), and 92 (i) illustrating the various shapes and cavities of metallamacrocyclic assemblies. Models a–c are based on X-ray structures; d, f, and g on MM2 forcefield simulations; and e, h, and i on ESFF forcefield simulations. Colors: gray, carbon; white, hydrogen; red, phosphorus; orange, oxygen; blue, nitrogen; violet, idoine; light blue, Pd; yellow, Pt.

which are self-complementary to each other. They are described in Chart 1D as $A^2_2A^2_2$ systems (the presence of a second **A** descriptor means a second different angular component). In practice this requires two 90° -bearing building blocks which are capable of reacting and forming the desired square by spontaneous self-assembly.

Among the variety of geometries that the main group elements can adapt, the T-shaped, pseudo-trigonal bipyramidal arrangement of the iodonium moiety with its near 90° angles is noteworthy.¹¹ The use of such iodonium-containing corner units in the self-assembly of molecular squares is summarized in Scheme 2. Since the hypervalent iodine serves the role of two of the 90° turns, only two transition metal centers are present in the resulting square with two alternate diagonal corners being occupied by the hypervalent iodine moiety. In the required bis-(heteroaryl)iodonium species **26** and **27** the lone pairs of the nitrogen atoms are located perpendicular to each other.¹² Interaction of equimolar amounts of these bis-(heteroaryl)iodonium triflates with the bistriflate complexes of Pd(II) or Pt(II) bisphosphanes **1** and **2** and **6** and **7** results in the ready formation of the hybrid molecular squares **28–35** (Scheme 2).^{13,14} The solid-state structure of square **29** was confirmed by single-crystal X-ray diffraction.¹⁴ A summary of the geometric data for this square as well as its space-filling model based on the X-ray data are presented in Figures 1b and 2b. Interestingly, the N–Pd(II)–N valent angle is only 84° ; however, the C–I–C bond angle is opened up to 98.7° , resulting in an overall rhomboid shape for the molecule. The solid-state stacking pattern of **29** is strikingly similar to that of square **5**: the cationic parts are located along the *b* axis, resulting in long channel-like cavities (Figure 1b) with 9.5 \AA between the stacked cationic near-planar rhomboids.

One of the major advantages of modular self-assembly is the ability to vary corner units and therefore charge density via different oxidation states or transition metals along with the cavity size which can be fine-tuned by use of connector ligands with differing sizes. When mixed neutral-charged or heterobimetallic molecular squares of the same topology $A^2_2A^2_2$ (Chart 1D) are desired, the simplest way to achieve this is to use the already available Pd(II) and Pt(II) bistriflate complexes **1** and **2** and **6** and **7** for the charged portions of the assemblies along with specially designed monomeric units which contain covalently bound neutral transition metal bisphosphane complexes (Scheme 2).¹⁵ Such neutral complexes can be prepared by the reaction of the chelated Pt(II) dichloride with aryllithium or (4-ethynylpyridyl)lithium at low temperatures, yielding the desired monometallic modules **38** and **39** (Scheme 2). Reaction of equimolar amounts of bistriflates **1** and **2** or **6** and **7** with either **38** or **39** afforded mixed heterobimetallic squares **40–47**.^{15,16} Fast atom bombardment mass spectrometry (FABMS) was especially useful in the characterization of these metallamacro-

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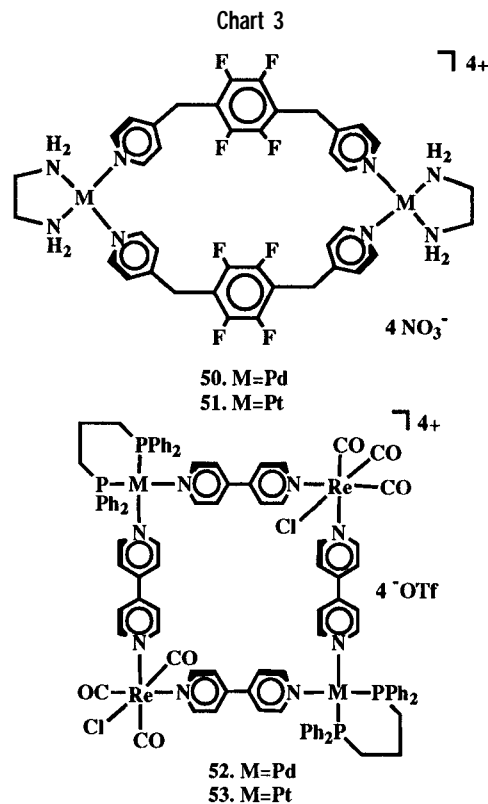
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cycles.¹⁷ Analysis of the data for squares **42**, **44**, and **47** provided a $M - 2OTf$ peak for **44** (1569.3 amu) with the $2+$ charge state and the $M - OTf$ peaks at 2933.0 amu for **42** and 2756.2 amu for **47** with experimental isotopic distribution patterns that matched the calculated ones, thereby establishing the stoichiometries and compositions of these assemblies. The structure of square **47** was also confirmed by X-ray, and the data are summarized in Figure 1c. A space-filling model based on these data is shown in Figure 2c. The geometry of this macrocycle is nearly planar with the 4-ethynylpyridine units slightly bent inward. The pyridyl ligands are nearly orthogonal to the transition metal coordination plane defined by the dppp ligand and do not display π -stacking interactions with the phenyl rings of the dppp. This is due to the presence of the alkyne spacer units in **47** which separates the phenyl groups of the dppp ligand and the pyridyl rings precluding any favorable interactions. The stacking diagram of square **47** in the solid state is shown in Figure 1c. Similar to the other molecular squares the cationic parts of the assembly are stacked over each other along the *a* axis, resulting in long channels formed by the cavities of the respective squares. On the basis of the binding properties of the π -bonds of acetylene to metals such as copper, silver, and gold, interaction of both squares **44** and **47** with 2 equiv of AgOTf in acetone afforded the complexes **48** and **49** via the so-called " π -tweezer effect" (Scheme 2).¹⁶

Further examples of modular self-assembly were reported by Fujita and co-workers, who prepared a series of water-soluble bimetallic Pd(II) and Pt(II) species **50** and **51** (Chart 3) derived from the transition metal dinitrates and organic angular linking units.¹⁸ A similar self-assembly strategy was employed by Hupp in the preparation

(17) Whiteford, J. A.; Rachlin, E. M.; Stang, P. J. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2524.

of luminescent heterobimetallic molecular squares **52** and **53** (Chart 3).¹⁹

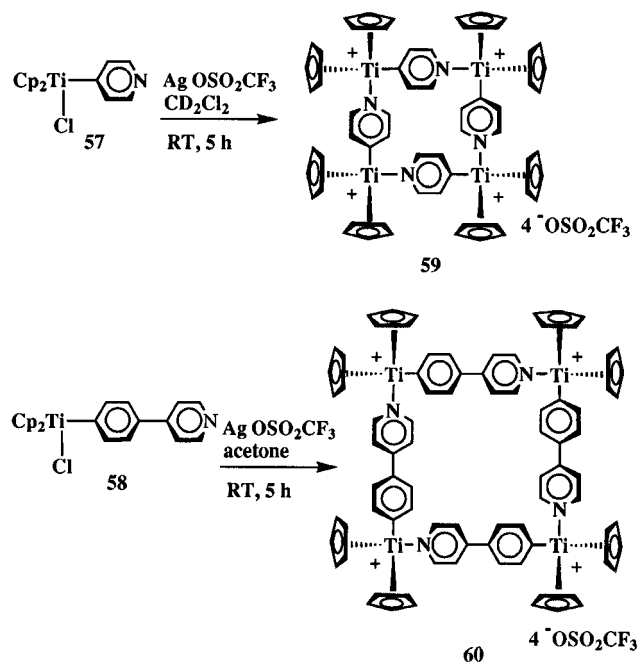
The list of available angular modules also includes ones that contain early transition metals. The metallocenes²⁰ with their distorted tetrahedral geometry and their rich and versatile chemistry are particularly attractive as potential building units. Titanocene complexes were chosen as examples of early transition metal modules due to their favorable valent angle between metal and attached ligands.²¹ Interaction of complex **54**²² with Pt(II) bisphosphane complexes **2** and **7** in nitromethane produced the macrocyclic assemblies **55** and **56** (Scheme 2). These assemblies also belong to the $A^2_2A^2_2$ type where the first angular component is the transition metal bistriflate **1** or **2** and the second the titanocene complex **54**. Both **55** and **56** were isolated as stable microcrystalline orange solids and characterized by various spectroscopic methods as well as by LSIMS.²³ Both **55** and **56** contain relatively flexible oxygen links and therefore are less conformationally rigid than all the previous molecular squares. An MM2-minimized model of square **55** is presented in Figure 2d, illustrating the unusual shape and cavity of this unique macrocycle.

Yet another interesting example of titanocene-based molecular squares was prepared from covalent building units **57** and **58** (Scheme 3). Reaction of these precursors with exactly 1 equiv of silver triflate in a solution of dichloromethane or acetone afforded the self-assembled products **59** and **60** as assessed by multinuclear NMR.²⁴ Although stable only in solution, these species represent an interesting example of an A^2_4 system containing four bidentate self-complementary angular building blocks.

Crown Ether-, Calixarene-, and Porphyrin-Based Assemblies

Crown ethers²⁵ and calixarenes²⁶ are among the classical covalent macrocycles that played an important role in the development of host–guest chemistry and the study of inclusion phenomena.²⁷ The analogous metallacrowns²⁸

Scheme 3. Early Transition Metal Molecular Squares of A^2_4 Type



and metallacalixarenes²⁹ are interesting transition metal analogues to crown ethers and calixarenes that preserve their guest-binding function. Since crown ethers are excellent hosts for hard metal cations and calixarenes have a high affinity for neutral guests, they are likely to extend the function of molecular squares when combined into a single self-assembled entity.

The known metallacrown Pt(II) dichloride³⁰ upon mixing with a slight excess of AgOTf in dichloromethane afforded the required precursor metallacrown bistriflate.³¹ Interaction of this bistriflate with either 4,4'-bipyridine (**3**) or 2,7-diazapyrene (**10**) resulted in macrocyclic squares **61** and **62** of topology $A^2_4L^2_4$ (Chart 4).³¹ Likewise, reaction of the known metallacalix[4]arene complex³⁰ with silver triflate afforded bistriflate complex **63**, which upon treatment with 4,4'-bipyridine (**3**) in dichloromethane at room temperature resulted in the formation of the unique multicalixarene assembly **64** (Scheme 4).³¹ Similarly, when **63** was reacted in a modular fashion with bis(heteroaryl)iodonium triflate **26** it afforded the hybrid, iodonium–transition metal bis-calixarene square **65** (Scheme 4). The tetrameric nature of **64** was confirmed by ESI-FTICR mass spectrometry.³² The isotopically resolved ESI-FTICR mass spectrum of this assembly is presented in Figure 3. The signals of **64** are centered around m/z of 2260 and 2266, which correspond to the triply charged cationic $[M - 3\text{-OTf}]^{3+}$ and $[M - 3\text{-OTf} +$

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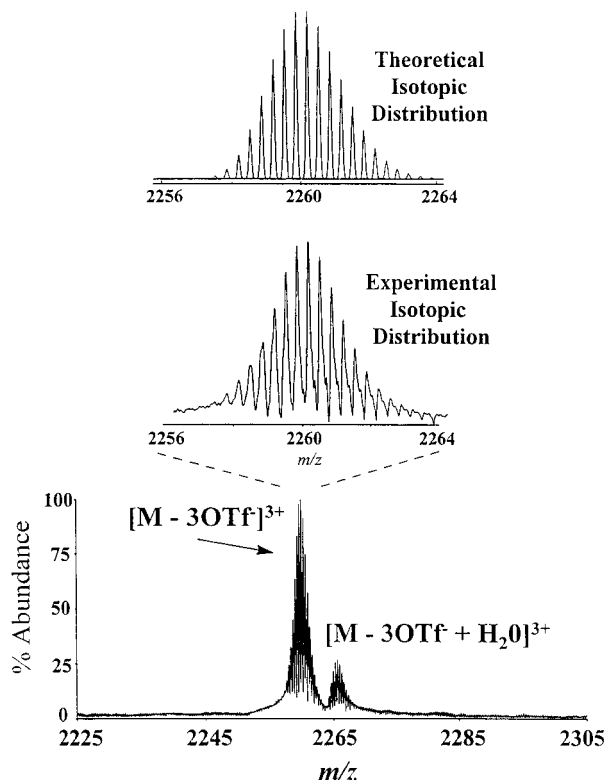
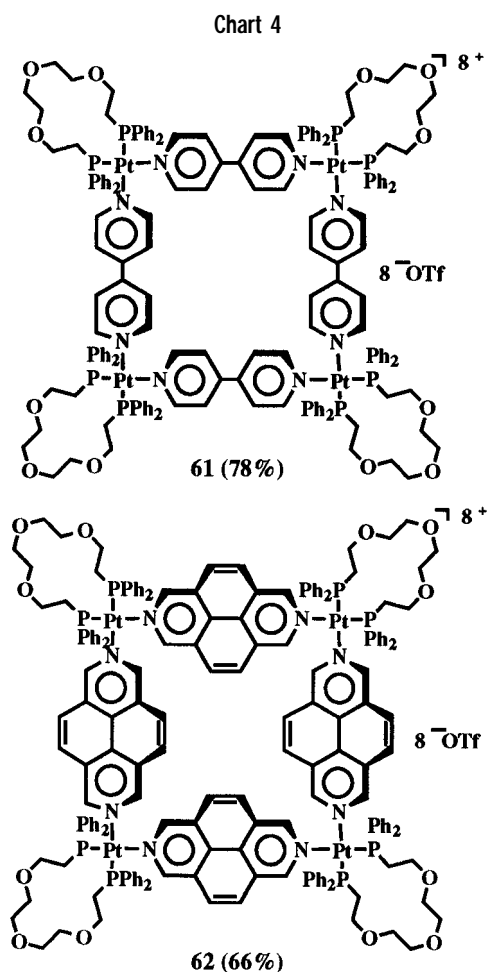
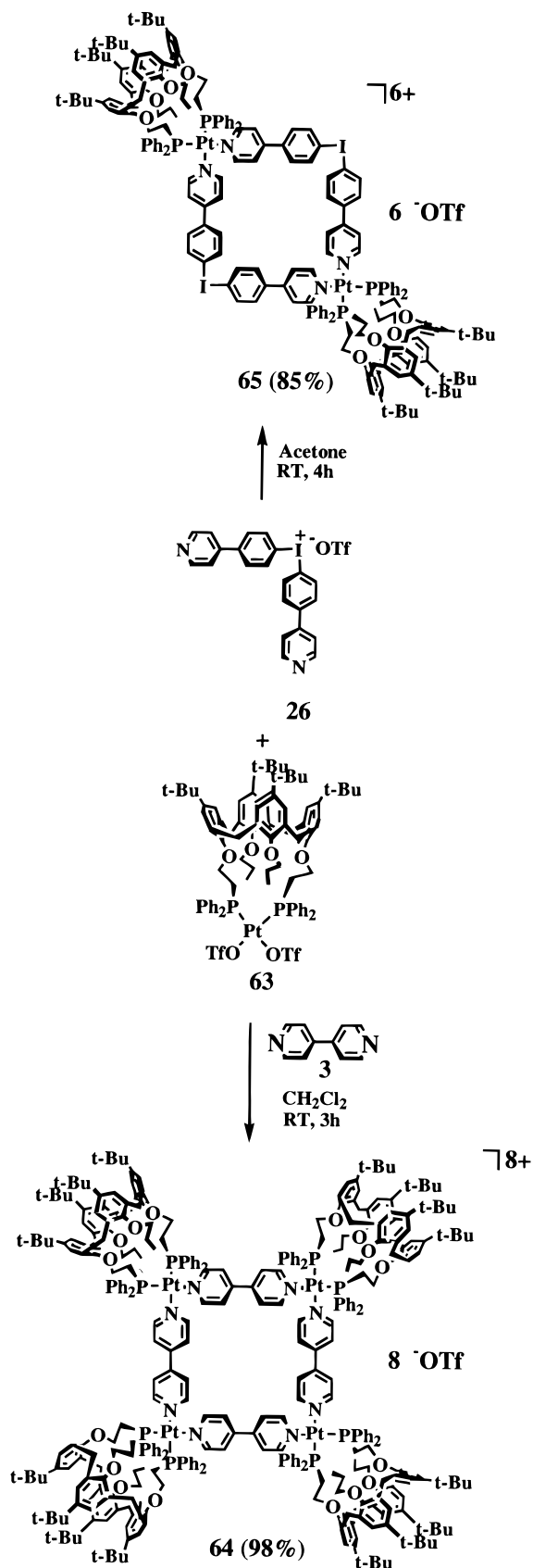


FIGURE 3. ESI-FTICR mass spectrum of molecular square 64.



$\text{H}_2\text{O}]^{3+}$ species. The expansion plot of the 3+ charged complex in Figure 3 shows the near-perfect match of the experimental and theoretical isotopic envelopes unambiguously

Scheme 4. Calixarene-Containing Molecular Squares



ously establishes the tetrameric nature of **64** and also proves the presence of at least one H_2O in this assembly. We hypothesize that the water is likely interacting with the cationic parts of the assembly via the oxygen lone pairs and is simultaneously hydrogen bonded to the crown

ether oxygen atoms.³³ These interesting features make assemblies **64** and **65** attractive targets in studies of molecular recognition, host–guest chemistry, etc. We have already started to examine their complexation properties and host–guest chemistry by observing the guest transportation³⁴ across a concentration gradient.

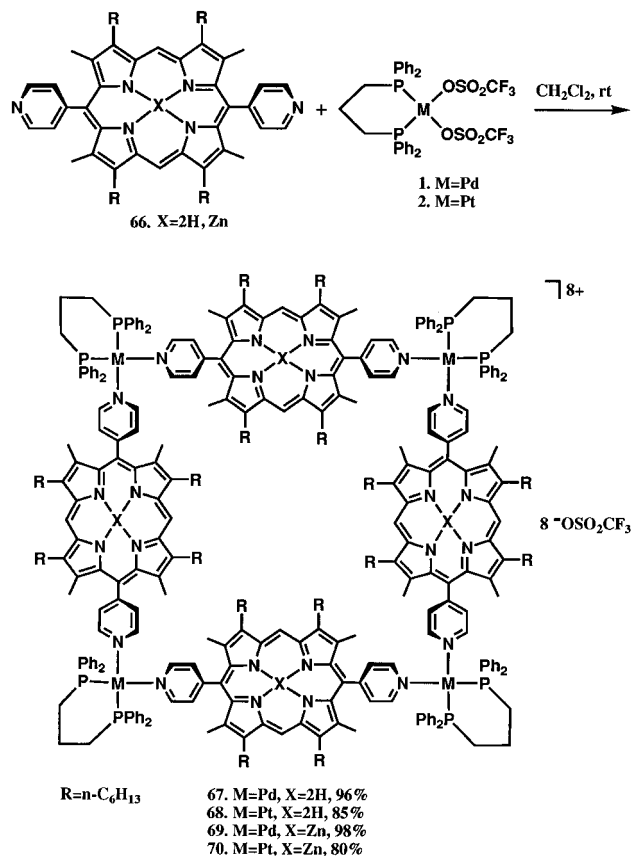
Among the goals of modern supramolecular chemistry is an understanding of complex processes in nature by studying artificial models that mimic the function of the desired natural phenomena. The photosynthetic reaction centers and the light-harvesting complexes of bacteria are examples of such natural aggregates.^{35,36} A step toward understanding their mode of action is to construct an artificial multichromophore aggregate suitable for the studies of directed energy- and electron-transfer processes.³⁷ Linked multiporphyrin arrays are good examples of such aggregates.³⁸ Since molecular squares are relatively conformationally rigid entities one may anticipate that porphyrin-based molecular squares should also possess this important photochemical attribute as the relative distance between the individual porphyrin chromophores, their orientation, and overlap have considerable influence on the photoactivity of the entire assembly.

Porphyrin-containing ligands that contain pyridine rings in a proper spatial orientation may serve as linear units of the square, whereas the transition metal bisphosphanes are angular building blocks for a $A^2_4L^2_4$ type system (Scheme 5). We prepared porphyrin **66** due to its solubility in common organic solvents. Upon mixing of **66** with Pd(II) or Pt(II) bistriflate complex **1** or **2**, the desired tetranuclear assemblies **67** and **68** were isolated as deep-purple solids.³⁹ When the Zn-containing porphyrin was used, the heterobimetallic assemblies **69** and **70** were isolated. Evidence of their conformational rigidity was obtained from a careful analysis of multinuclear NMR.³⁹ Since the porphyrin units are restricted in rotation around the metal–ligand axis they are located nearly parallel to the transition metal coordination planes as depicted in the space-filling model derived from ESFF forcefield simulations (Figure 2e).

Chiral Molecular Squares

Chirality is one of the unique features of objects in both the macroscopic and the microscopic worlds. Chiral molecules exist on this planet at least since the beginning of life, making life without chirality unimaginable and

Scheme 5. Porphyrin-Containing Assemblies of $A^2_4L^2_4$ Topology



unlikely. Thus, the understanding of the exact mechanisms of formation of complex asymmetric entities as well as the design of artificial chiral supramolecular species via self-assembly that may mimic biomolecules is an important new field of inquiry that presents a formidable challenge.

Using coordination as the motif and transition metals and organic ligands as building blocks, in principle, there are at least five ways of creating chiral supramolecular species via spontaneous self-assembly: (1) use of a chiral auxiliary coordinated to a metal, (2) use of an inherently chiral octahedral metal complex, (3) use of an optically active atropisomeric diaza-bisheterocycle (substituted 4,4'-bipyridines, bisquinolines, etc.) as linker ligands, (4) helicity or twist due to the use of diaza ligands which lack a rotation symmetry about their linkage axis, and (5) a combination of the above methods. As chiral auxiliaries are more readily available than either inherently chiral metal complexes or appropriate chiral bidentate ligands we chose to start with the first approach.

A family of optically active hybrid molecular squares (of $A^2_2A^2_2$ type) was prepared via the interaction of bis-(4-(4'-pyridyl)phenyl)iodonium triflate (**26**) and [Pd(R-(+)-binap)(H₂O)][OTf]₂ (**71**) or [Pt(R-(+)-binap)(H₂O)][OTf]₂ (**72**) (Scheme 6).⁴⁰ In this case the diaza ligands of the iodonium species possess rotation symmetries about their linkages; therefore, molecular squares **73** and **74** are optically active exclusively due to the chiral transition metal auxiliary (binap) in the assembly. Since both **73** and **74** possess D_2 symmetry, with one of the symmetry

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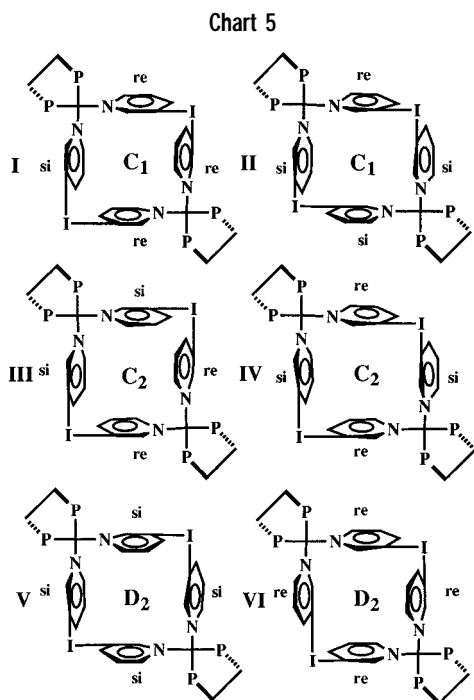
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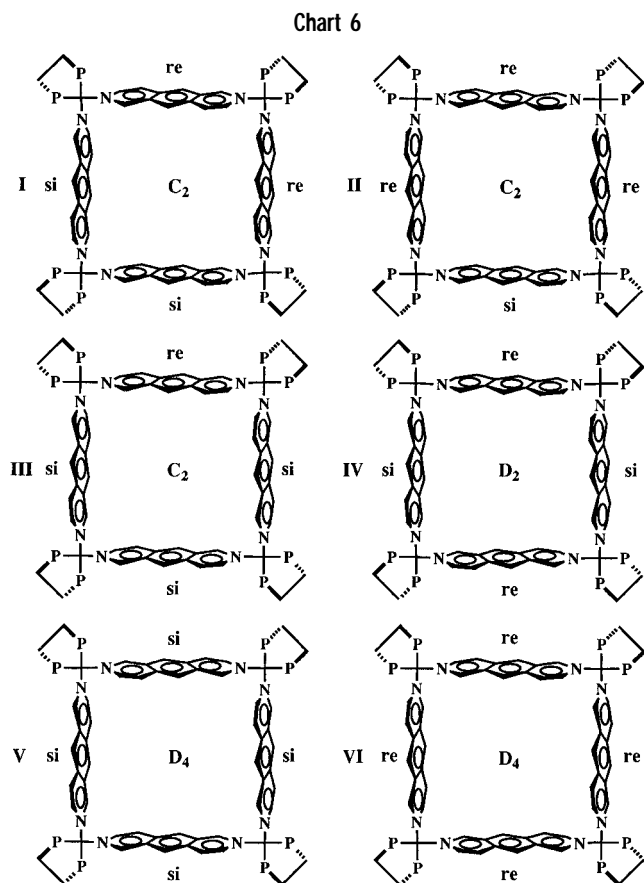
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axes across the plane of the transition metals and rotation of the pyridine ligands is restricted, the hydrogen atoms on the pyridine rings are diastereotopic as detected in the ^1H NMR.⁴⁰

Additional interesting examples of chiral hybrid molecular squares of the same basic type were prepared via reaction of bis(3-pyridyl)iodonium triflate (**75**) and chiral Pd(II) and Pt(II) complexes **76** and **77** (Scheme 6). Interaction of a chiral square planar Pd(II) or Pt(II) complex with an iodonium precursor where the heterocyclic ring lacks rotation symmetry about its linkage can result in the formation of six possible diastereomers as displayed in Chart 5. However, we anticipated that use of a chiral auxiliary, such as binap, would reduce the complexity of the stereochemical outcome via asymmetric induction upon the self-assembly process. Indeed, when chiral complexes **71** and **72** reacted with bis(3-pyridyl)iodonium triflate (**75**) in acetone, the result was the formation of an excess of one each of the preferred diastereomers of **76** and **77** as assessed by NMR (Scheme 6). Liquid secondary ion (LSI) mass spectra of **76** indicate the presence of the $[\text{M} - \text{OTf}]^+$ ion with an m/z ratio of 2770. For square **77** it was possible to detect only the doubly charged ion $[\text{M} - 2\text{OTf}]^{2+}$ with an m/z of 1398 and to unambiguously establish its charge state. These data as well as the close match of the calculated and measured isotopic patterns of these ions confirm the expected molecular weights for **76** and **77**, establishing that these products exist as A^2_2L^2_2 assemblies (Figure 2f).

The self-assembly of all-metal chiral molecular squares of the A^2_4L^2_4 variety was also carried out using the chiral Pd(II) and Pt(II) bistriflate complexes **71** and **72** and the C_{2h} -symmetrical diaza ligands 2,6-diazaanthracene (DAA, **78**) and 2,6-diazaanthracene-9,10-dione (DAAD, **79**).⁴¹ When either **71** or **72** is mixed with DAA in acetone at room temperature, the formation of a single diastereomer each of squares **80** and **81** is observed, as assessed by



NMR. The singlet in the ^{31}P NMR is indicative of the exclusive formation of only one highly symmetrical chiral product (Scheme 6). The absolute stereochemistry of **80** as shown was assumed upon the basis of the known X-ray structures of chiral binap transition metal diaryls⁴² in combination with MM2 forcefield calculations (Figure 2g).

In contrast, when DAAD (**79**) was employed as a connector ligand, the reaction mixture consists of a significant excess of one diastereomeric product, **82** or **83**, respectively, along with minor amounts of other diastereomers, as demonstrated by the ^{31}P NMR spectra. Integration of the ^{31}P spectra gave a diastereomeric excess of 81% for **82** and 72% for **83**. The macrocyclic nature of these species was established by multinuclear NMR and confirmed by mass-spectroscopic data for **83**. The fact that both of these types of assemblies are formed either as a single diastereomer or as a significantly enriched diastereomeric mixture is attributable to the high degree of asymmetric induction by the chiral bisphosphane complexes. In the absence of such induction, a mixture of six isomers may be formed, as indicated in Chart 6. We indeed observed such a mixture when the achiral transition metal bisphosphane complex **6** or **7** was used instead of binap.⁴⁰

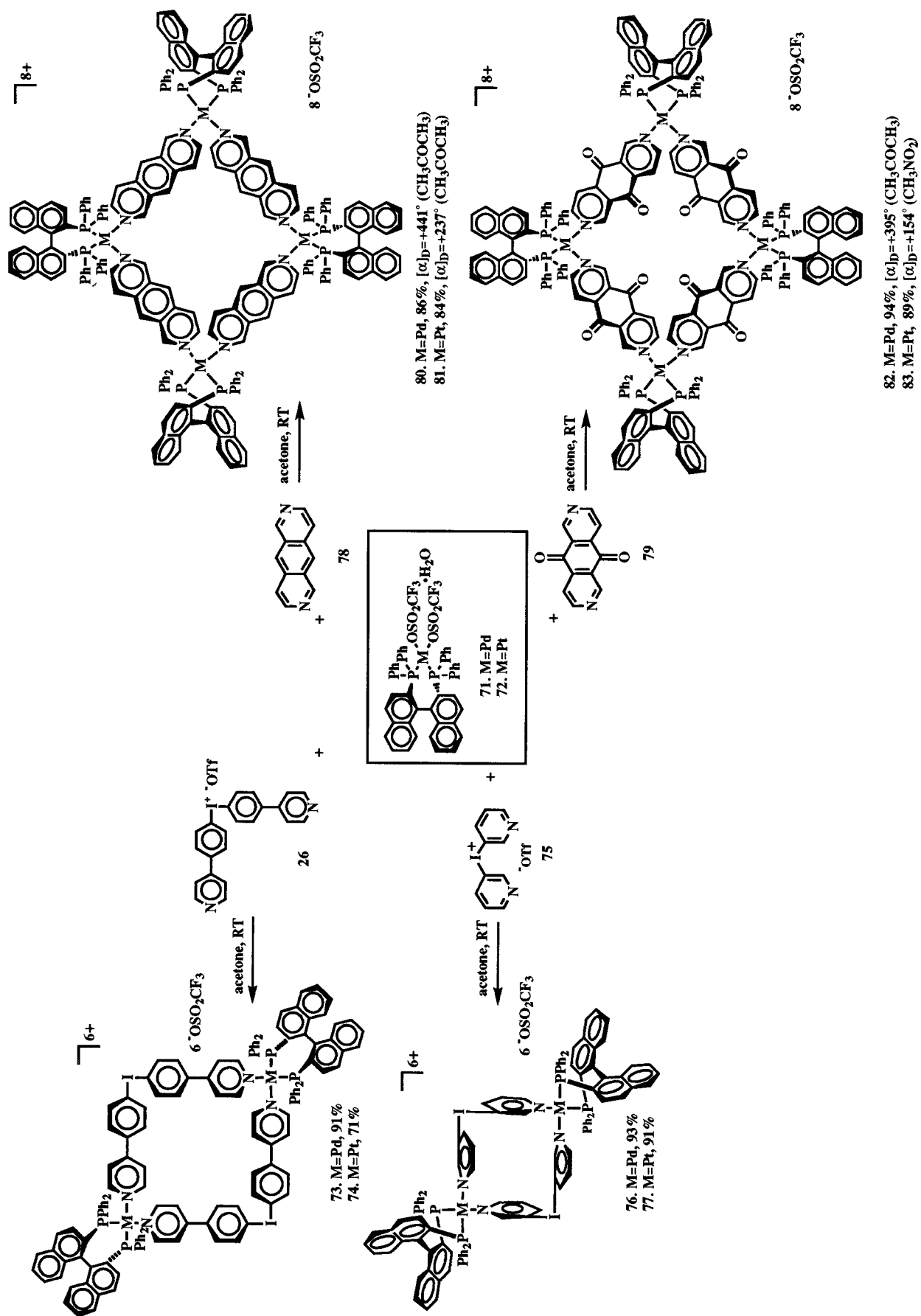
Nanoscale Molecular Squares and Hexagons

The formation of nanodimensional metallamacrocycles was achieved by applying a different self-assembly strategy: the linear organoplatinum linking unit **84** was interacted with modules **26** and **39** which possess roughly

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Scheme 6. Chiral Molecular Squares



90° geometries (Scheme 7).⁴³ Unit **84** was prepared from 4,4'-diiodobiphenyl and Pt(PPh₃)₄ via oxidative addition⁴⁴ followed by the treatment of the product with AgOTf. Self-assembly of **85** and **86** occurred by addition of either **26** in acetone or **39** in dichloromethane to **84**. The expected molecular weight of assembly **85** was confirmed by both MALDI and ESI-FTICR mass spectrometric techniques.⁴³ These two macrocyclic assemblies belong to the class of ultrafine particles, since their estimated dimensions are about 3.4 nm along the edge and 4.8 nm across the diagonal for assembly **85** and 3.0 and 4.3 nm for **86**.

The above description of diverse molecular squares amply illustrates the versatility and depths of this approach. As stated earlier, this methodology is broadly applicable to the formation of essentially all polygons and polyhedra. Since the covalent angle of an sp²-hybridized carbon is 120°, bis(4-pyridyl)ketone (**87**) was used as the corner unit, which upon interaction with spacer **84** in dichloromethane at room temperature afforded the desired hexamer **88** (Scheme 8),⁴⁵ a A₂²₆L₆²₆ supramolecular species. This is a truly remarkable process as 12 individual building blocks have to assemble in a proper cooperative manner to form the desired product. The bimetallic complex **89**, which is complementary to **84**, was also prepared via oxidative addition from 4,4'-diiodobenzophenone followed by treatment with AgOTf (Scheme 8). Upon simple mixing of **89** with 4,4'-dipyridyl (**3**) in dichloromethane, the desired hexagon **90** was formed.⁴⁵ These two aggregates are isostructural and have identical molecular weights of 12 433. This demonstrates the possibility of preparing nanoscopic isoelectronic isostructural species of identical shape and size by minor variation of the constituent components. An energy-minimized space-filling model of **90**, obtained via ESFF forcefield simulations is presented in Figure 2h. These assemblies are large macromolecules with an outside diameter of about 5 nm and an inside diameter of 3 nm with a cavity capable of encapsulating three buckyballs.

Three-Dimensional Nanoscopic Frameworks

Having established the efficacy of the coordination motif as a means to the spontaneous self-assembly of a wide range of polygons it was of interest to examine its application to three-dimensional systems and in particular the formation of polyhedra. With the experience gained in the self-assembly of molecular squares and hexagons and in particular chiral squares we set out to prepare an A₂²₆A₃³₄ type chiral polyhedron in the shape of an octahedron.

Specifically, we chose R-(+)-binap Pd(II) and Pt(II) bistriflate complexes **71** and **72** as shape-defining corner units due to the significant degree of conformational rigidity of binap, which is important, since the loss of conformational entropy is minimized upon binding of these rigid bistriflate complexes to the connector ligand. As a connector ligand, tris(1,3,5-(4'-pyridyl)ethynyl)ben-

zene (**91**) was prepared from 1,3,5-triethynylbenzene and 4-bromopyridine via cross-coupling. Addition of **91** to a dichloromethane solution of the transition metal bistriflates **71** and **72**, respectively, resulted in the formation of a single highly symmetrical entity with a stoichiometry of 6:4 (Scheme 9) as observed by NMR and confirmed by mass spectrometry.⁴⁶ The observed molecular weight of **92** and close match of the calculated and observed isotopic distribution patterns of the 4+ charge state (MW 7092.76) are in agreement with the theoretical weight of 7092.89 amu, corresponding to the cyclic assembly with loss of four triflate counterions. Analysis of the spectroscopic data as well as forcefield simulations have established the expected structure of the final products to be **92** and **93** as *T*-symmetrical, hollow macrocyclic polyhedra. A space-filling model of **92** derived from ESFF simulations is presented in Figure 2i. Similar achiral assemblies were reported by Fujita and co-workers,⁴⁷ who prepared water-soluble cages of the same topology from enPd(II) dinitrate and 2,4,6-tris(4'-pyridyl)-1,3,5-triazene. These cages encapsulated four molecules of adamantane derivatives, as established by X-ray data.⁴⁷ Another elegant example of three-dimensional polyhedra was recently reported by Raymond and co-workers,⁴⁸ who utilized the coordination chemistry of isophthalphenylhydroxamate complexes of octahedral metals such as Fe(III) and Ga(III) to form polynuclear clusters with the overall shape of a tetrahedron.

Application and Uses of Metallacyclic Polygons and Polyhedra

The long-term aims and goals of these investigations are the rational design of new materials with desirable properties and the manufacturing of nanoscale devices and molecular machinery. It is evident that self-assembly strategies offer advantages over classical, linear covalent synthesis in the formation of complex supramolecular entities and hence are likely to be the methodology of choice for nanotechnology. Present goals, in common with the aims of most of supramolecular chemistry, include uses in molecular recognition, host-guest chemistry, chiral recognition and catalysis, etc. To this end we have started to examine the complexation properties and host-guest chemistry of some of our metallacyclic polygons.

One way of assessing molecular recognition and complexation is to observe guest transportation across a concentration gradient.³⁴ Two anionic substrates were chosen as hosts: sodium tosylate and sodium 2-naphthalenesulfonate. The transport of these salts from one aqueous phase into another through the chloroform phase with and without assembly **64** was measured via periodic NMR sampling. Competition experiments revealed that sodium tosylate was carried across the chloroform phase preferentially over sodium 2-naphthalenesulfonate with a selectivity of 1.5–2.0.³¹ Although

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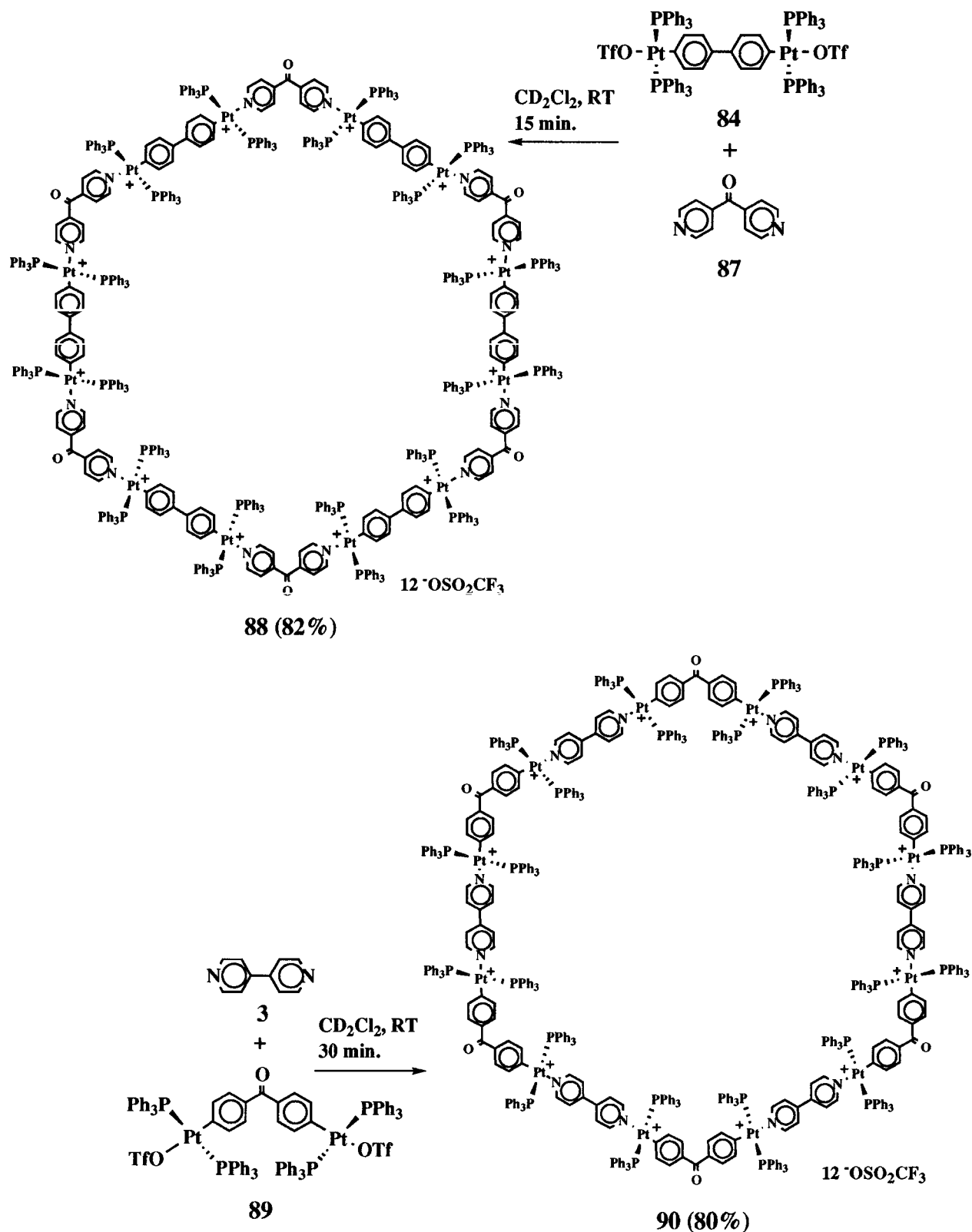
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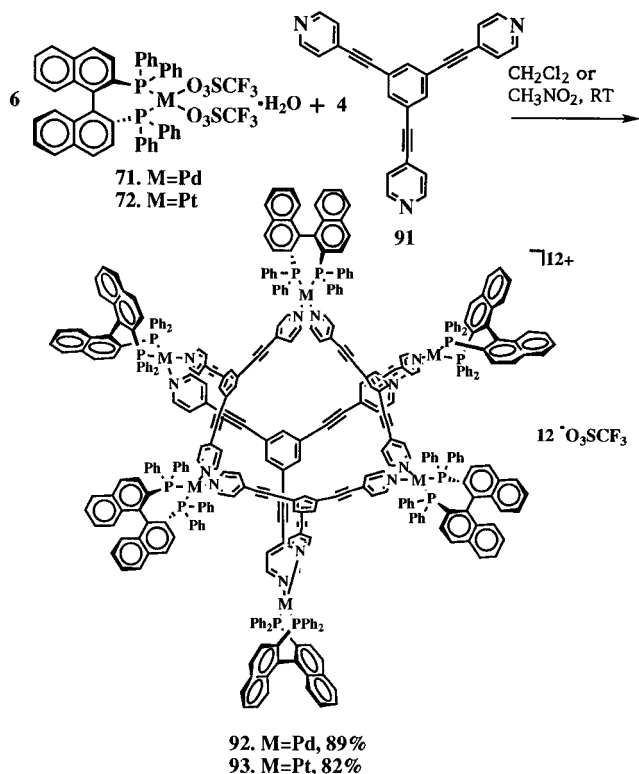
Scheme 8. Self-Assembly of Molecular Hexagons of $A_2L_2L_6$ Topology

preliminary, these data suggest that these macrocyclic assemblies have potential as host systems for the complexation of anionic guests, which unlike cationic and neutral substrate interactions are much less known to date.⁴⁹ Likewise, NMR investigations established that the molecular square 5 could serve as a host for 1,5-dihydroxynaphthalene, an electron-rich neutral guest.⁸

Conclusion and Outlook

We have developed and exploited the coordination motif as a useful strategy for the formation, via spontaneous self-

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Scheme 9. Chiral Polyhedra with T Symmetry

assembly, of unique metallamacrocyclic polygons and polyhedra, new members of the family of supramolecular species. It is evident that coordination offers advantages and unique design features in the assembly of discrete supramolecular species. These include (1) tremendous versatility due to the potentially large and diverse number of possible transition metal complexes and multidentate ligands available as building blocks, (2) bond energies of 15–30 kcal/mol per interaction that are between the ranges of the strong covalent bonding in classical macrocycles and the weak interactions of systems patterned after biological models, (3) excellent product yields inherent in the self-assembly process, (4) precise control, coupled with large variation, over the shape and size of the assemblies, (5) ready control of the polarity and charge state of the desired macrocycles due to the possibility of controlled formation of charged, neutral,⁵⁰ and mixed macrocycles, (6) relatively easy, simple access to chiral supramolecular entities with controlled stereochemistry,

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and (7) ability to create organic- or water-soluble systems, etc.

It is important to restate that our emphasis on molecular squares is but a start and illustrative example of the power, diversity, and broad applicability of the coordination motif in the self-assembly of a nearly infinite number and variety of metal-containing supramolecular species with well-defined shapes and sizes. Moreover it is evident that coordination can be combined with the classical covalent macrocycles as well as the hydrogen-bonding motif for the design of even more elaborate, complex, and sophisticated species.

Abiological supramolecular chemistry and spontaneous self-assembly are in their infancy. Nature has had billions of years to evolve optimal conditions and processes for the spontaneous self-assembly of supermolecules with specific biological functions, whereas chemists have only been involved in this exciting area for a couple of decades. The predictable design variations and architectural finesse afforded by coordination will further enrich chemist's ability in the rational predesigned formation of topologically even more complex artificial molecular systems. The number, type, sophistication, and beauty of synthetic supramolecular entities are limited only by the boundless imagination of chemists and the practical considerations of the currently available techniques for the separation, analysis, and proper characterization of the resulting product. Moreover, just as in nature, function and use will follow and derive from form and greatly enhance and enrich such rapidly growing interdisciplinary fields as material science, bioengineering, and others. We anticipate that the next century will see yet unimagined nanoscale devices and machinery as well as new materials with unique, unfamiliar properties which may ultimately be derived from many evolving ideas, including some of the presently still primitive concepts and principles discussed and illustrated herein.

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