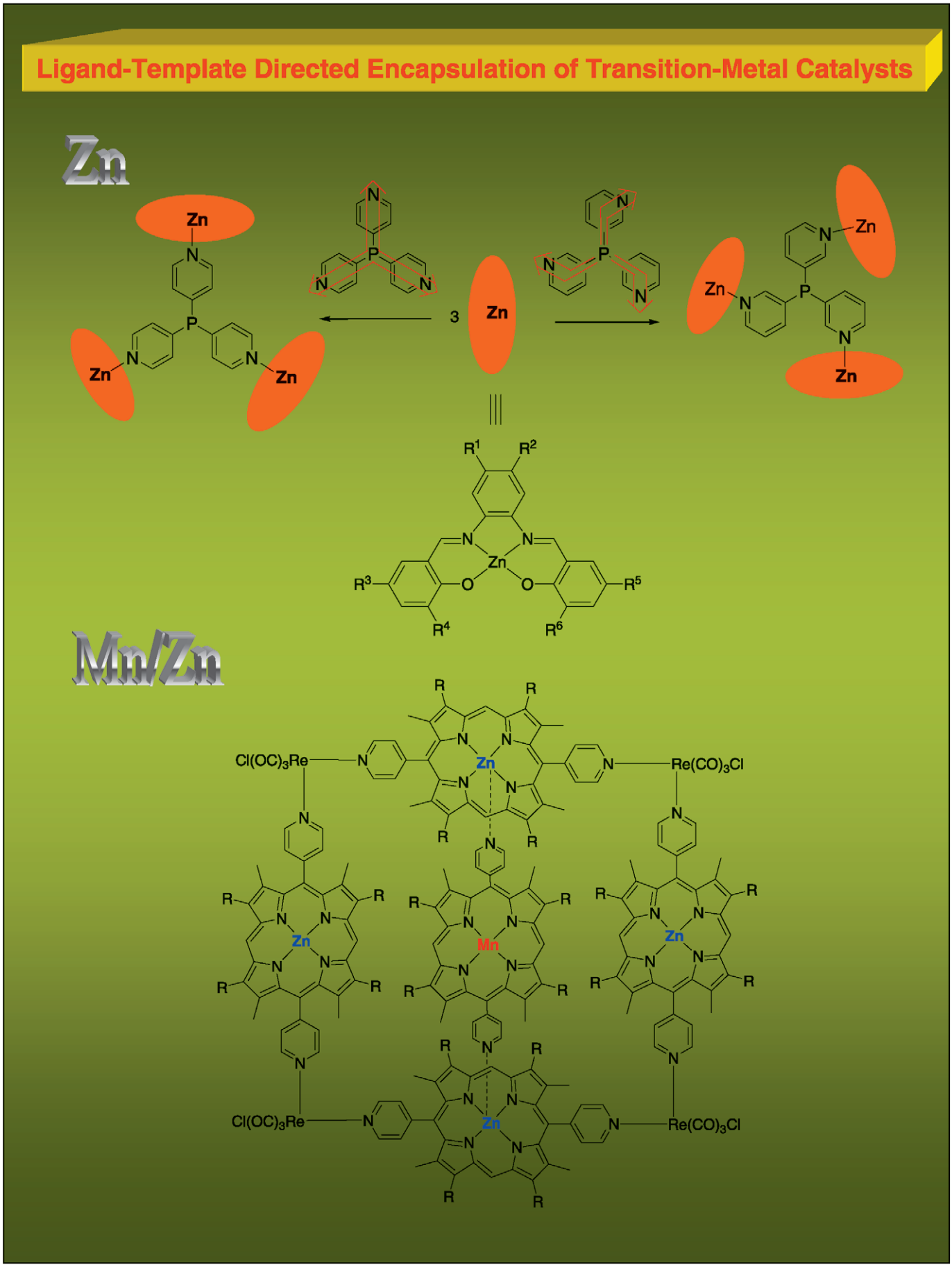

DOI: 10.1002/chem.200500875

Ligand-Template Directed Assembly: An Efficient Approach for the Supramolecular Encapsulation of Transition-Metal Catalysts

Arjan W. Kleij and Joost N. H. Reek*[a]

Abstract: Supramolecular encapsulation of small guest molecules inside well-defined cavities of molecular capsules has witnessed broad attention because of the unusual behaviour of these systems. The molecular capsules generally consist of rigid complementary building blocks that are held together by multiple, complementary non-covalent interactions. Interestingly, it has been shown that chemical transformations can take place inside these capsules and in some examples the reaction is accelerated, while in other cases otherwise instable intermediates could be isolated in the capsulated form. Many reactions of interest require a transition-metal (TM) catalyst, and the creation of new capsules in which such catalysts are implemented within the structure is thus required for the development of resourceful type of catalyst systems for these processes. In this concept article we will discuss new strategies to arrive at such systems, with a focus on a ligand-templated approach. In this approach, multifunctional ligands are used as templates for the encapsulation process by supramolecular building blocks and concomitantly for the formation of TM complexes that are active in catalytic processes. The obtained encapsulated transition-metal catalysts show unusual reactivity and selectivity behaviour that will be discussed in detail.

Keywords: C–C activation · homogeneous catalysis · molecular encapsulation · supramolecular chemistry · transition-metal catalysis

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Introduction

Supramolecular chemistry[1] has provided ways to design and construct molecular receptors that are held together via a set of non-covalent, complementary interactions. In particular, molecular capsules[2,3] have recently received a lot of attention, since this class of spherical compounds held together by non-covalent bonds enables the reversible encapsulation of a variety of organic molecules. It is for this reason that these types of assemblies hold great promise for a range of applications where control at the molecular level is of great importance. A fundamentally interesting prospective is the manipulation of single molecules,[4] that is, organic guests, within a predefined area of space that is controlled by the self-assembly of the individual components. Indeed, the focus of this research field has recently shifted towards applications, and chemical conversions have been carried out in capsular assemblies. Several interesting transformations have been studied such as Diels–Alder reactions, aza-Cope rearrangements, condensations and photochemically induced reactions. These reactions have in common that they proceed in the absence of additional catalysts. To extend this interesting field of supramolecular chemistry, general tools need to be developed that enable a variety of catalytic conversions to occur within these nano-environments. So far, only very few examples have been reported on sophisticated organic transformations (such as transition metal catalyzed C–C- and C–Y-bond formation, Y = heteroatom) that will lead to a broader applicability and thus a wider interest from the scientific community. After a brief summary of the systems developed by others, we will discuss the ligand-template directed assembly of capsules, a new strategy for the construction of capsules that have a catalytically active metal fragment encapsulated within the host system. The local micro-environment and pre-organization properties of the metallo-assembly together with their methodologies for their construction and catalytic properties are discussed.

Transformations within Hydrogen-Bonded Molecular Capsules

The first molecular capsules that were reported are formed by the assembly of self-complementary concave building blocks, based on glycoluril, calixarene and resorcinarenes, and held together by hydrogen bonds.[2] One of the properties provoked by the molecular encapsulation is the increase in the local concentration of the substrates. In the event that at least two molecules are enclosed, this high concentration can give rise to a more rapid reaction between the molecules and as such the encapsulation has a catalytic effect on the reaction. In addition, encapsulation can give rise to stabilization of reactive intermediates, a new way to control reactions by slow release of reactive components and the manipulation of the geometrical properties and reactivity of enclosed guests. An early example was provided by Rebek et al.[5] who used a hydrogen-bonded, self-assembled "softball" to accommodate benzoquinone and cyclohexadiene that reacted within the cavity to provide the Diels–Alder product (Figure 1). More recently, Rebek and co-workers have been using self-assembled homo-dimers based on functionalized resorcinarenes and calixarenes as capsular systems that are able to control the features of small, encapsulated organic molecules.[6]

In a somewhat different approach,[7] an introverted acid cavitand was used as a bowl-shaped host. The pendant carboxylic ester group of this cavitand is directed into a cavity that accommodates small amines. The pre-organization of these amines by the cavitand species was successfully applied in the methylation of the amine substrates. The methylester-functionalized host system was treated with a range of tertiary amines to afford the quaternized amine products. Rate accelerations of up to 2×10^4 were observed in the presence of the supramolecular host. The rate acceleration was explained in terms of the increase in the local substrate concentration as well as the solvating ability of the cavitand's aromatic surfaces and polar rims of the host system.

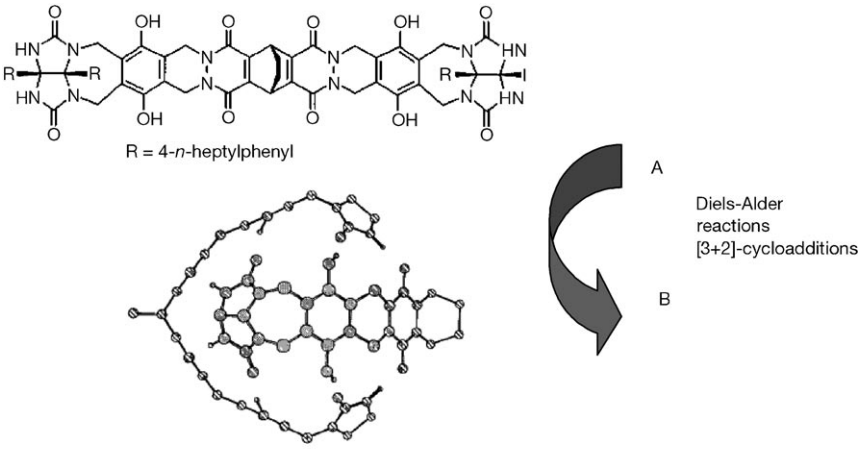


Figure 1. Typical example of a capsule formed by hydrogen bonding frequently used by the group of Rebek. Reprinted in part with permission from reference [5c].

Transformations within Supramolecular Metallocapsules

Fujita is one of the pioneers of the metallo-based supramolecular assemblies and has introduced molecular panelling[3a] as a strategy to obtain a variety of metallocapsules. Frequently used capsules, that can be easily prepared and obtained in large quantities, are the M_6L_4 metallocapsules (M = Pd(ethylene diamine), *N*,*N*,*N*′,*N*′-tetramethylethylene diamine, L = 2,4,6-tris(4-pyridyl)-1,3,5-triazine or comparable tris(pyridine) ligands).[8] These molecular containers are water-soluble and accommodate a variety of neutral hydrophobic organic substrates (Figure 2). As a first example, the Wacker oxidation of styrene was studied and shown to be accelerated significantly by the supramolecular assembly as compared to the parent palladium catalysts in the absence of the M_6L_4 metallocapsule, with the yield of the acetophenone product increasing from 4 to 82%.[9] Alkane oxidation via photochemical excitation mediated by a similar metallocage system was reported for adamantane.[10] The oxidation products of this reaction were produced in high yields assuming oxidation of one guest per host molecule. The host–guest complexation is vital for the reaction, since the adamantane remained unaffected in the absence of the host. Furthermore, a size-selectivity was observed and larger cyclic alkanes such as decalin and linear analogues that are not accommodated by the cage compound, are not oxidized in the presence of the metallocapsule. Close host–guest contacts were suggested to be essential to convert the substrate.

Raymond et al. reported the formation of tetrahedral host–guest assemblies of the type $[M_4L_6]^{12-}$, where L is a bridging naphthalene-based bis(bidentate) catecholamide ligand and M = Ga^{3+}, In^{3+}, Al^{3+} or Fe^{3+} ion (Figure 3).[11] These supramolecular structures were formed by self-assembly through coordinative metal–oxygen patterns and give rise to the exclusive formation of tetrahedral assemblies with a metal cation at each corner. The negatively charged assemblies are very soluble in polar solvents and even in water. The presence of aromatic units bridging the two catechol units of the building blocks results in the formation of metallocapsules with a hydrophobic cavity with nanosize dimensions (0.35–0.5 nm^3). This cavity can be exploited for the encapsulation of cationic species such as $[NR_4]^+$ (R = Me, Et), ferrocenium, cobaltocenium and related functional metallocenes.[12]

The same authors communicated the entrapment of the half-sandwich complex [Cp*-(PMe$_3$)Ir(Me)OTf] (Cp* = η^5-C_5Me_5), which is known for its ability to thermally activate

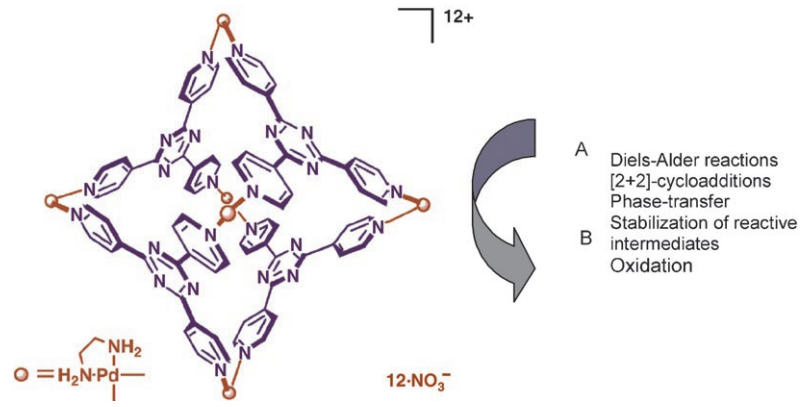


Figure 2. Typical example of a M_6L_4 metallocapsule frequently used by the group of Fujita. Reproduced in part by permission of The Royal Society of Chemistry from reference [3a].

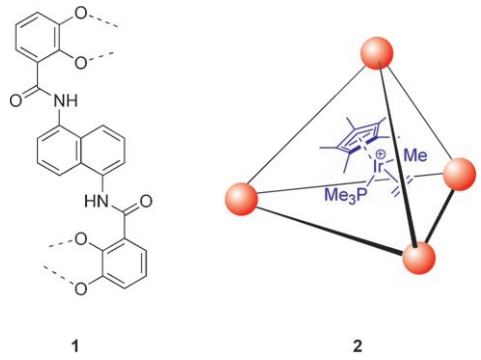


Figure 3. Tetrahedral assemblies of type $[M_4L_6]^{12-}$ capable of encapsulating half-sandwich, cationic Ir complexes.

the C–H bond of various organic substrates at relatively low temperatures.[13] An important step in the catalytic process is believed to be the dissociation of the triflate anion, thereby concomitantly forming a highly reactive mono-cationic Ir-intermediate. The iridium methyl ethene complex [Cp*-(PMe_3)Ir(Me)(C_2H_4)][OTf] was selected and this could be readily introduced within the supramolecular cavity $[Ga_4L_6]^{12-}$ (see Figure 3).

The encapsulated complex **2** was then subjected to C–H bond activation with aldehydes as substrates. Several aldehydes were activated to produce a series of product assemblies [Cp*(PMe_3)Ir(R)(CO)] where R is the alkyl fragment that was originally present in the aldehyde precursor.

Since the activation of an aldehyde results in the formation of an asymmetric Ir complex, the product assemblies are diastereomeric. The diastereomer ratio (*dr*) was monitored by NMR spectroscopy and proved to be size- and shape-dependent. The *dr* of the encapsulated C–H activated product increased with increasing size of the straight-chain alkyl aldehyde. Aldehydes larger than butyraldehyde (valeraldehyde, benzaldehyde) could not be activated and no product formation was observed. The shape selectivity was investigated with constitutional isomers of butyraldehyde (e.g. isobutyraldehyde), considered as a size-extreme for this supramolecular catalytic process. The more voluminous character of the isobutyraldehyde was hypothesized to be responsible for lower diastereoselective recognition. Additionally, of four five-carbon-skeletal structural isomeric aldehydes, only isovaleraldehyde could be converted into a product assembly and this result nicely demonstrates the delicate influence of the shape of the substrate.

More recently, the Raymond group communicated a similar approach towards supramolecular catalysis with the aim of activation of a unimolecular transformation, namely an aza-Cope rearrangement.[14] The rate constants for free and encapsulated rearrangements for various substrates were compared and significant rate accelerations of up to 854-fold were achieved.[15]

Supramolecular assemblies that are held together through coordination chemistry are receiving increasing attention. For instance, synthetic calix[4]arene homocapsules were constructed by Dalcanale et al.[16] by combining two ligand-derived calix[4]arene semi-spheres with a suitable ionic metal salt precursor (M = Pd, Pt). In these molecular capsules, the metal centers reside at the periphery of the structure, with their anionic counterparts occupying both the inner- and outer-sphere regions of the supramolecular system, and consequently these metal centers are not well-suited for catalytic conversions. The reaction could indeed take place outside the cavity and the capsule might disintegrate if the bridging metal centers are involved in the catalytic process.

Ligand-Template Directed Assembly as New Approach for the Formation of Encapsulated Catalysts

Porphyrins are currently used as multipurpose components in many different types of supramolecular assemblies,[17] and their photochemical and catalytic properties generally plays a crucial role.[18] In particular, the pyridine–M^{II}–porphyrin (M = Zn, Ru, Co) motif has been extensively exploited giving rise to aesthetically attractive superstructures.[19] The association of nitrogen ligands with porphyrins has been studied in great detail and currently pyridines and cyclic amines such as 1,4-diazabicyclo[2.2.2]octane (DABCO) are most widely used as components of functional supramolecular assemblies.

An interesting approach to arrive at molecular capsules using this type of pyridine–M^{II}–porphyrin interactions is referred to as templated encapsulation. In such an approach the guest molecule is equipped with a sufficient number of donor ligands for coordination to, for example, porphyrin

building blocks. Upon assembly formation the templates guest molecule is enclosed within a capsule defined by the porphyrin building blocks. The first example reported that used this approach involved the first-generation diaminobutane tetra(propylene imine) (DAB) dendrimer, which contains four amine groups, as a template–guest molecule. Upon addition of two equivalents of shape-complementary bis(zinc)–porphyrin a closed molecular capsule was formed, and held together by the template that was enclosed inside (Figure 4).[20] Interestingly, the guest molecule is enclosed in the capsule formed by the two building blocks, but the assembly process is fast enabling rapid exchange processes to occur, which is interesting if such supramolecular structures are applied in catalysis.

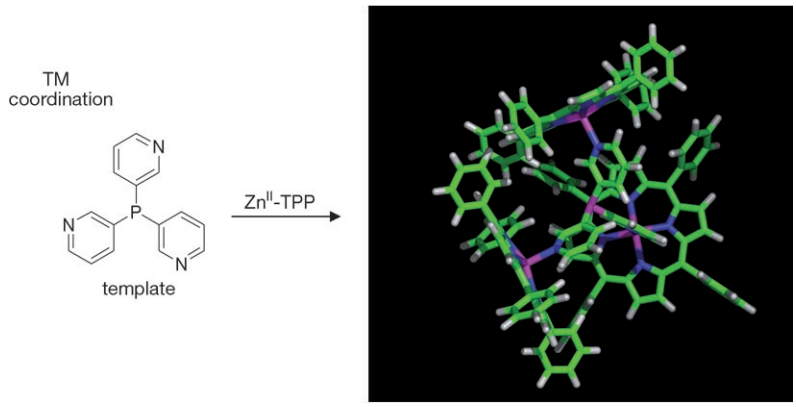


Figure 5. Templated approach to ligand encapsulation. The molecular modelling picture shows that the phosphine ligand is completely encapsulated.

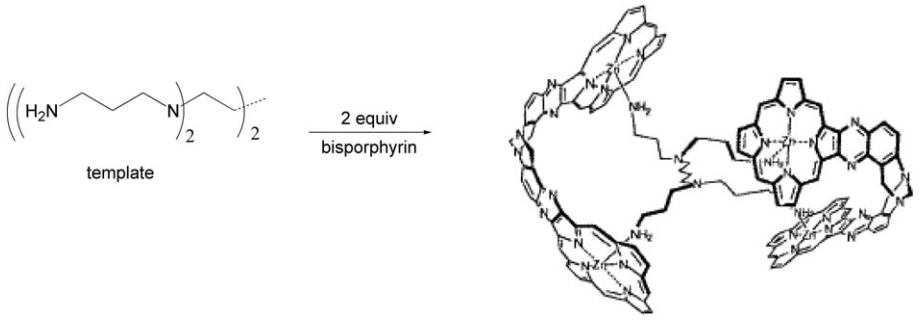


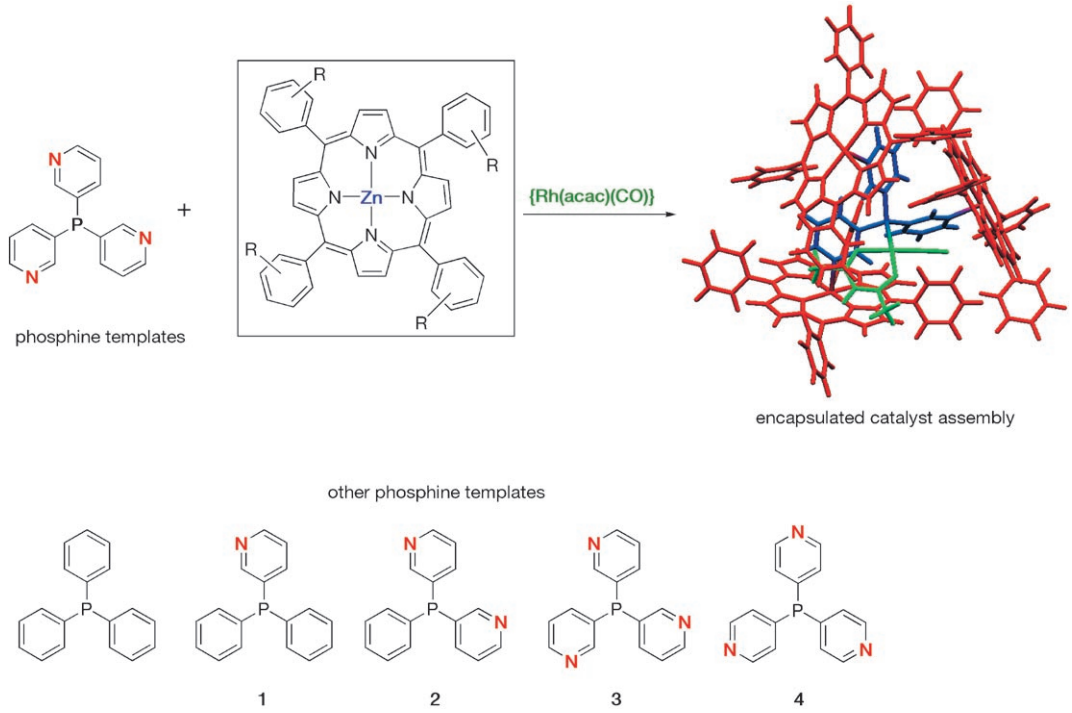
Figure 4. Templated approach to molecular encapsulation. Reprinted in part by permission of The Royal Society of Chemistry from reference [20].

We anticipated that the use of template ligands, molecules that have the ability to coordinate to zinc(II)–porphyrins via nitrogen donor atoms and have soft-donor atoms such as phosphines that can coordinate to catalytically active transition metal fragments, would lead to a new and general strategy to encapsulate transition-metal catalysts. Molecular modelling studies indeed show that the assembly of three porphyrin building blocks to tris(*meta*-pyridyl)phosphane results in complete encapsulation of the ligand (Figure 5). This strategy, which was recently introduced and studied in more detail in our group, will be highlighted in the following.

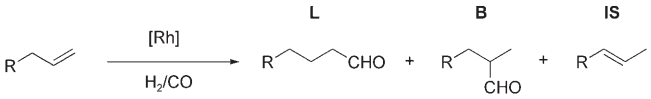
We started this templated approach to catalyst encapsulation using tris(*meta*-pyridyl)phosphane and zinc(II)–TPP (TPP = tetraphenylporphyrin).[21] From NMR and UV/Vis titration experiments we found a selective assembly process via coordination of the nitrogen to the zinc(II)–TPP, rendering the phosphine donor atom completely encapsulated by the three porphyrin components (Scheme 1). The phosphine center is still available for coordination to transition metals, providing readily access to hemispherically, encapsulated transition-metal complexes. Later we found that coordination of zinc(II)–TPP to tris(*meta*-pyridyl)phosphane is cooperative, that is, the last zinc(II)–TPP binds three times more strongly than the first one, probably because of π–π interactions between the *meso*-phenyl groups of two adjacent porphyrin units.[22] Importantly, in the presence of a [Rh(acac)(CO)$_2$] or PdCl$_2$ as metal precursors only monophosphine coordinated species were formed when the template-ligand was encapsulated by zinc(II)–TPP, indicating that the coordination of the nitrogen to the zinc(II)–TPP is sufficiently strong to enforce one of the phosphine ligands to dissociate (or prevent to coordinate) from (to) the metal complex. This shows that the strategy indeed leads to catalyst encapsulation and, in addition, into in a change in coordination sphere around the catalytically active transition-metal center.

Initial studies showed that the encapsulated palladium catalyst based on the assembly outperformed its non-encapsulated analogue by far in the Heck coupling of iodobenzene with styrene.[21] This was attributed to the fact that the active species consists of a monophosphine–palladium complex. A similar effect was observed in the rhodium-catalyzed hydroformylation of 1-octene (Scheme 2). At room temperature the activity of the catalyst was found to be ten times higher, and, interestingly, the encapsulated rhodium catalyst formed preferentially the branched aldehyde (**L**/**B** ratio 0.6), a selectivity that is very unusual. These effects were again partly attributed to the fact that only monophosphine coordinated rhodium complexes are formed, which was confirmed by high-pressure IR and NMR spectroscopic techniques.

The origin of the encapsulation effects on catalysis was studied in more detail at 25 °C. The supramolecular catalyst derived from monopyridylphosphane template **1** and



Scheme 1. Formation of catalyst assemblies by selective pyridine-Zn^{II} coordinative motifs using Zn^{II}–porphyrin complexes and different pyridylphosphane templates. Modelling picture on the right: porphyrin building block (red), templated ligand (blue), and encapsulated {Rh(acac)CO} species (green).

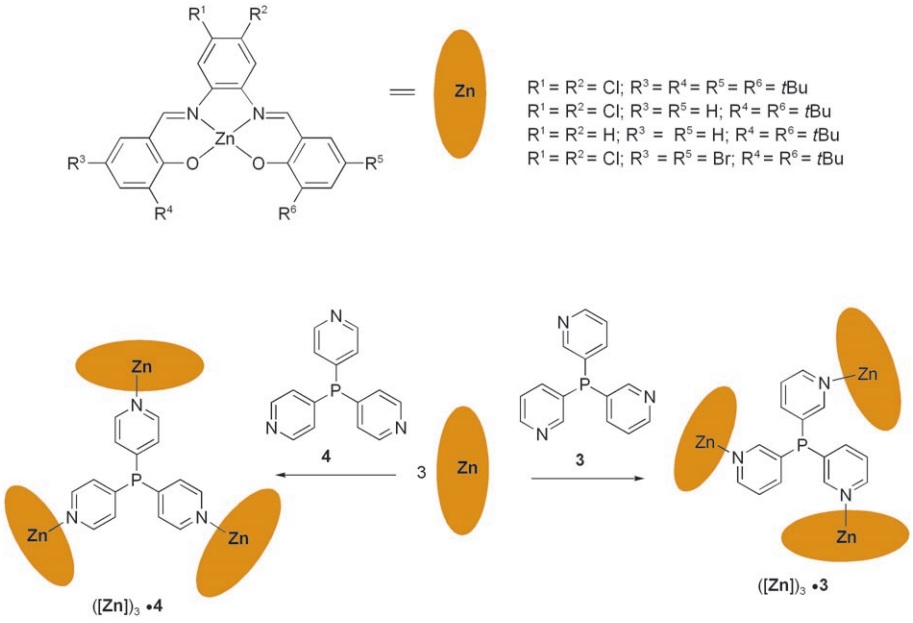


Scheme 2. Rh-catalyzed hydroformylation of alkenes leading to linear (L) and branched (B) aldehydes and isomerized (IS) olefins.

zinc(II)–TPP gives rather similar results as **1** in the absence of zinc(II)–TPP and the model PPh_3 catalyst. The regioselectivity (**L**/**B** = 2.8) obtained is comparable to what is usually encountered in this reaction, that is, the linear aldehyde is the predominant product. The use of bis(pyridyl)phosphane **2** as a template gives rise to a 2:1 assembly, which is approximately three times more active and leads to an increase in the selectivity for the branched product **B** (**L**/**B** = 1.1). According to high-pressure IR measurements this assembly also leads to the exclusive formation of monophosphine coordinated rhodium complexes. The effect of complete catalyst encapsulation becomes evident if this result is compared with that of catalyst assemblies obtained with the tris(pyridyl)phosphane template **3** and zinc(II)–TPP: a ten-fold increase in activity and a higher preference for the branched product was obtained (**L**/**B** = 0.6, 63% **B**). When **3** was combined with three equivalents of ruthenium(II)–TPP(CO), a similar increase in activity (eight-fold) and high selectivity for the branched product **B** was observed (**L**/**B** = 0.4, 67% **B**). The optimal ratio between the pyridylphosphane and metalloporphyrin was determined and for templates **2** and **3** the highest **B** selectivity were achieved at stoichiometric amounts (or excess) of porphyrin with respect to the number of pyridine donor atoms. At higher porphyrin concentrations, no increase in the selectivity for the branched product was observed, whereas lowering the porphyrin/phosphane ratio gave rise to increasing amounts of **L** product. In general similar catalytic effects were encountered at 80 °C, although the differences between the parent templates **1**–**3** and their encapsulated analogues were smaller. The approach was extended by using different substituted porphyrins and tris(pyridyl)phosphite building blocks, giving rise to a small library of encapsulated catalysts.

The geometry of the template-ligand is of crucial importance and small changes result in significantly different capsules and consequently in different catalytic behaviour. As outlined above, the use of tris(*meta*-pyridyl)phosphane (and also bis(*meta*-pyridyl)phosphane) in combination with zinc(II)–TPP leads to the formation of monophosphane-ligated metal complexes, in which the metal complex is effectively encapsulated. This is a result of the structure of the template with the nitrogen donor atoms pointing in almost the same direction as the lone pair of the phosphorus atom. In contrast, those of template **4** point away with an angle of approximately 109°. As a result, the structure of the tris-zinc(II)–TPP–**4** assembly has a much more open structure, as was evident from molecular modelling studies, which was later confirmed by an X-ray structure (Figure 6).[23] Interestingly, the structure formed in the solid state did not have the expected 1:3 ratio of building blocks as found in solution, but instead a 2:5 stochiometry was observed. One of

the zinc(II)–porphyrin units is part of two adjacent capsule assemblies as a result of a rather unusual hexacoordinated zinc metal, leading to assembly $[\mathbf{4}]_2$·[zinc(II)–TPP]$_5$. The presence of both hexa- and pentacoordinate zinc(II)–porphyrins within one supramolecular structure is very rare. Importantly, from the front view it is clear that the phosphine is far more accessible compared with that of assembly (zinc(II)–TPP)$_3$·**3** and as a consequence, the formation of bisphosphine ligated metal complexes is possible with these assemblies. This is clearly reflected in catalysis, since the assembly (zinc(II)–TPP)$_3$·**4** gave identical activity and selectivity in the hydroformylation of 1-octene as the rhodium catalyst based on **4** (in the absence of zinc(II)–TPP).[23]



Scheme 3. Formation of catalyst assemblies by selective pyridine–Zn^{II} coordinative motifs using Zn^{II}–salphen complexes and different pyridylphosphane templates.

More recently, this approach was further extended to the formation of catalyst assemblies comprising zinc(II)–salphen building blocks using the tris(pyridyl)phosphane templates **3** and **4** (Scheme 3).[24] We found a high binding constant for the pyridine association to zinc(II)–salphen in toluene (K_{ass} = 10^5–$10^6\,M^{-1}$), typically two orders of magnitude higher than the analogous binding of a pyridine to zinc(II)–TPP. The difference in coordination chemistry between template ligands **3** and **4** with zinc(II)–salphens was studied by IR and NMR spectroscopic studies and X-ray crystallographic analyses. Figure 7 presents the molecular structure of a 3:1 (zinc(II)–salphen)$_3$·**4** assembly together with a CPK representation of a computed structure of (zinc(II)–salphen)$_3$·**3**. Also in these salphen-based molecular capsules the phosphorus center is more enclosed in the assembly (zinc(II)–salphen)$_3$·**3**.

A monophosphane complex is predominantly formed when **3** is mixed with three equivalents of a zinc(II)–salphen complex and half an equivalent of [Rh(acac)(CO)$_2$] (acac = acetyl acetonate): beside the presence of the monophosphane–Rh^I complex, one equivalent of the free encapsulated phosphane can be detected by $^{31}P\{^1H\}$ NMR spectroscopy. In a similar experiment, the assembly based on template **4** and the zinc(II)–salphen complexes forms a bis(phosphine)–rhodium species. In the latter case, the bis(phosphine)–rhodium complex is completely encapsulated by six salphen building blocks. This difference in mono- versus diphosphine ligation to the Rh^I center and, to a lesser extend, the differ-

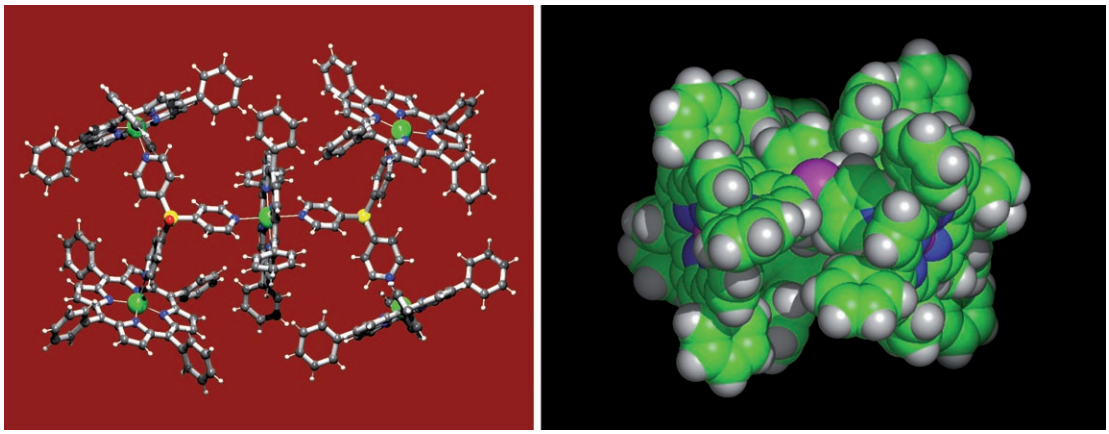


Figure 6. Plot of the molecular crystal structure of $[\mathbf{4}]_2$·[Zn^{II}TPP]$_5$ found in the solid state. A front view (right) showing that the phosphine of the template-ligand in this case is still rather accessible.

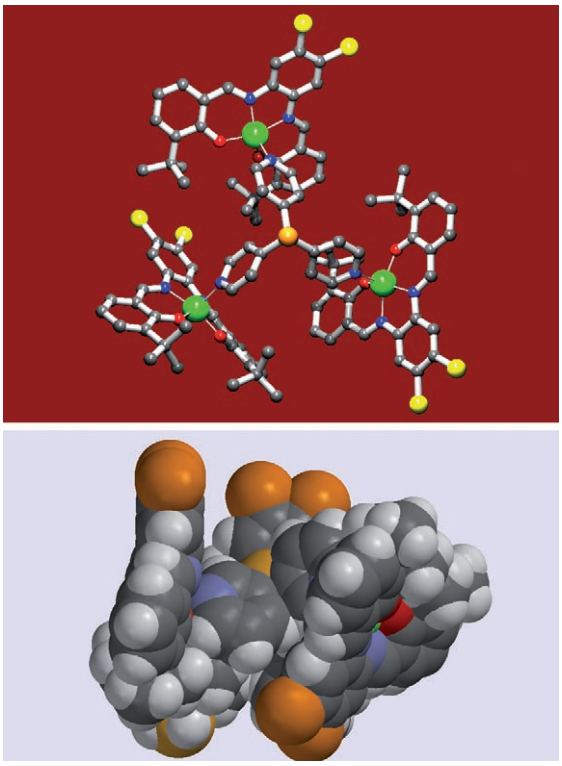


Figure 7. X-ray (solid state) structure of the assembly formed by tris(*para*-pyridyl)phosphane **4** and a Zn^{II}–salphen (top) and a CPK representation (bottom) of a calculated structure (PM3) of the assembly formed by tris(*meta*-pyridyl)phosphane **3** and a Zn^{II}–salphen.

ence in electronic features (and thus donating properties of the phosphine) between template ligands **3** and **4** can therefore be used to induce a different catalytic behavior. This template-effect in homogeneously catalyzed hydroformylation is explained below.

We have examined the effect of the pyridylphosphane template (tris-*para* **4** versus tris-*meta* **3**) using the zinc(II)–salphen mentioned above in the hydroformylation of 1-octene. As for the porphyrin assemblies, higher activity and selectivity towards the branched aldehyde was found (up to 57%) for the capsules based on template **3** and (several differently substituted) zinc(II)–salphen complexes, though in most cases the effects proved to be somewhat less pronounced. Interestingly, the assemblies based on **4** were *less* active than the non-encapsulated parent derivative **4** and PPh_3, with the typical l/b ratio found for bisphosphine ligated rhodium catalysts. The lower activity is explained by a complete encapsulation of the catalyst, reducing the accessibility of the active center for substrates, which might be useful for size-selective catalysis. The catalyst assemblies based on **3** showed significantly *higher* activity (at least five-fold) than parent **3**, which is in line with the results obtained for the porphyrin-based capsules.

A template directed assembly approach, although not mentioned as such in the original paper, used for a manganese–porphyrin catalyst was reported by Merlau et al.[25] They applied pyridyl appended Mn^{III}–porphyrin complexes, in which the pyridyl units form the template and the manganese center serves as the catalyst. A large pre-organized, Zn^{II}–porphyrin-derived cavity structure was used with zinc(II) centers as Lewis acidic receptor sites. Upon mixing these components an assembly is formed in which the Mn^{III}–porphyrin is encapsulated in the open box structure formed

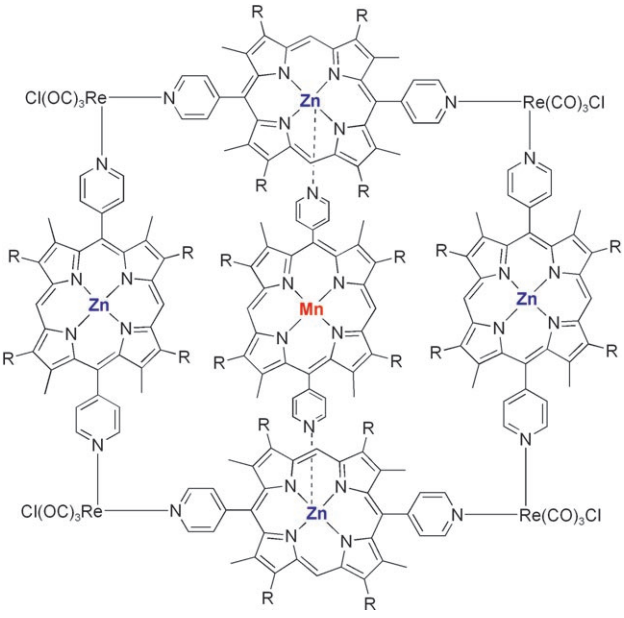
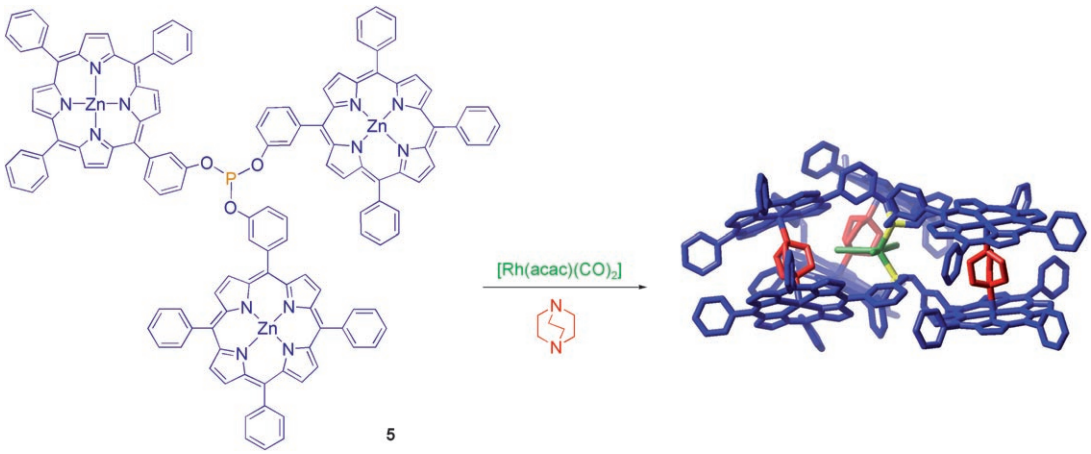


Figure 8. An encapsulated Mn^{III}–porphyrin by a directed assembly process using coordination chemistry.

by the Zn^{II}–porphyrins (Figure 8). The non-encapsulated manganese porphyrin degrades rapidly under aerobic conditions and consequently an oxo-bridged, catalytically inactive dimer is formed. Such a decrease in activity was precluded by this supramolecular encapsulation affording a ten-fold increase in turnover number and a substantial increase in lifetime of the Mn catalyst was observed. An even higher association with the cavity complex was noted for *meso*-tetra(4-pyridyl)porphinatomanganese(III) and as a result a further increase in catalytic stability and performance.

In the examples mentioned above the template-ligand was based on pyridyl groups that coordinate to porphyrin or salphen building blocks to form the capsules. The functional groups can also be switched; thus combining a porphyrin functionalized phosphorus ligand with nitrogen containing templates. Along these line, large sandwich-type assemblies have been constructed by using the tris(porphyrin)phosphite **5** and the ditopic ligand DABCO.[26] The combined UV/Vis titration and (high pressure) NMR spectroscopic data pointed to the selective formation of the assembled metallocage structure (Scheme 4) at a ration of dabco/**5** 1.5, with the catalytically active center at the inside of the structure. At this ratio a much lower catalyst activity (ca. four-fold decrease) is observed as compared to the system in the absence of DABCO. This is explained by the fact that the catalyst is now based on a supramolecular bidentate ligand, which typi-



Scheme 4. Formation of a bidentate-ligated sandwich structure between **5** and DABCO.

cally gives lower activity in the hydroformylation reaction than monophosphites. This supports the presence of a well-defined catalyst species, as depicted in Scheme 4, that is responsible for the catalytic activity. More importantly, a remarkable high selectivity for the linear aldehyde was observed (94% **L**), which also points at the formation of a relatively rigid bidentate ligand.

In summary, the design and construction of new, functional metallocapsules has become an exciting research area, entering the field of supramolecular catalysis. The most recent advances described in this concept paper clearly demonstrate that catalytic transformations within supramolecular hosts are no longer limited to simple organic transformations but can also be extended to more relevant and complicated bond breaking and making processes (i.e., C–C and C–Y bond formation). Whereas conventional chemistry relies on the use of covalent synthesis to prepare TM (pre)-catalysts, supramolecular assembly formation opens up ways to address the performance of a range of catalyst species simply by changing the molecular building blocks. Obviously, such an approach can create large libraries of catalytic species and variations in molecular dimensions, and electronic and steric effects of the building blocks will be less restricted to synthetic barriers. We therefore believe that the template-ligand approach to arrive at encapsulated catalysts is a step forward to practical applications and that it will be part of the catalyst toolbox of the future. Although the development of these novel supramolecular catalysts is still at an early stage, the present systems already show interestingly high activity and selectivity and catalyst performance beyond the scope of conventional homogeneous catalysis is foreseen. The next logic step in this field is the extension of these capsules to chiral analogues for unprecedented enantioselective conversions.

Acknowledgements

We thank the Netherlands Organization of Scientific Research (NWO, VICI grant) and the University of Amsterdam for financial support, and all co-workers, whose names appear in the references, for their contributions.

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Published online: February 22, 2006

