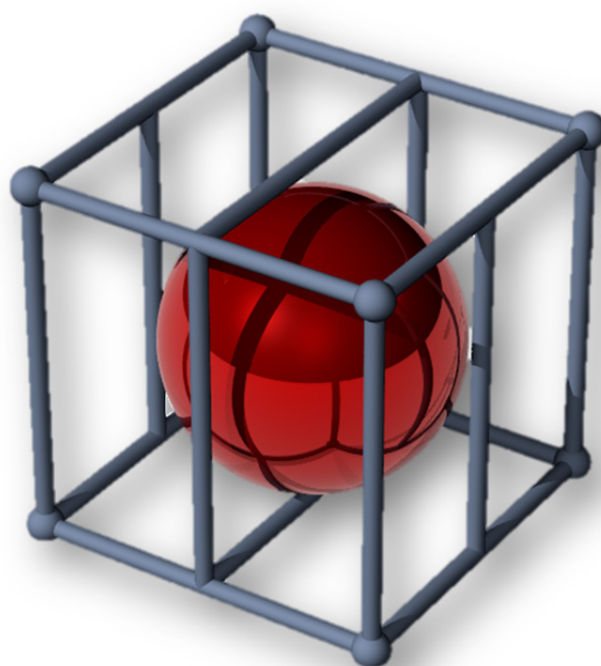


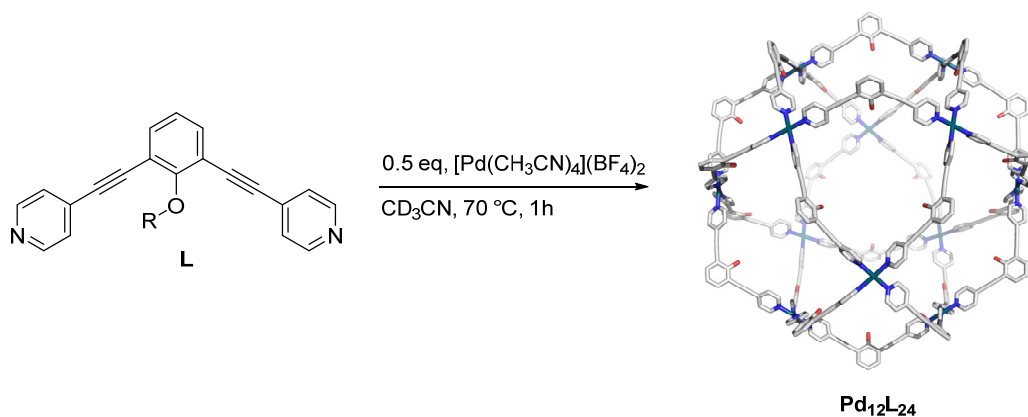
## Summary

### Transition Metal Catalysis in Confined Spaces



Chemical reactions are required for the conversion of feedstocks to valuable materials, such as different types of plastics, pharmaceutical ingredients and advanced materials. In order to facilitate the conversion of these feedstocks to a wide array of products, catalysis plays a prominent role. Catalysts, being able to facilitate shortcuts in the conversion of materials, make reactions more atom-economical and prevent the formation of waste. This makes catalysis an important field in chemistry and allows it to contribute to society by acquiring products in a sustainable way. However, the development of catalysts that display high reactivity and selectivity is not straightforward and new methodologies and catalysts are required to sustain and extend our high standard of living. In order to influence the selectivity in catalysis, the environment around the active site or active species can be changed. While traditional methods change the first coordination sphere around the catalyst by modification of the ligand, new methods in which a second coordination sphere is generated around the active site are arising. Such strategies result in metal complexes in well-defined spaces, which can force restrictions on the way a substrate can approach or bind to the active center. These second coordination spheres take example from nature's catalysts, enzymes, which are the most selective catalysts by far.

In **chapter 1** an overview is given of reported supramolecular structures that can form confined spaces. Different approaches to form the confined space are highlighted, like the host-guest approach and the ligand-template approach. In host-guest methods a host is first pre-assembled and afterwards a metal complex is embedded in its void. Investigations that use this approach are described in chapter 6. The ligand-template approach uses a ligand that has two functionalities; one to bind the metal complex used in catalysis and one to form an assembly around the metal. While our group has demonstrated that this is a very successful strategy for mononuclear systems, it would in principle also be suitable for the generation of multinuclear systems. By utilizing strategies that were designed by the group of prof. dr. Makoto Fujita, bent bispyridine ligands (abbreviated as L), can be bound to either palladium or platinum metal centers (M). This leads to large spherical assemblies, consisting of 12 metal centers and 24 ligands (so called  $M_{12}L_{24}$  spheres, depicted in Figure 1).

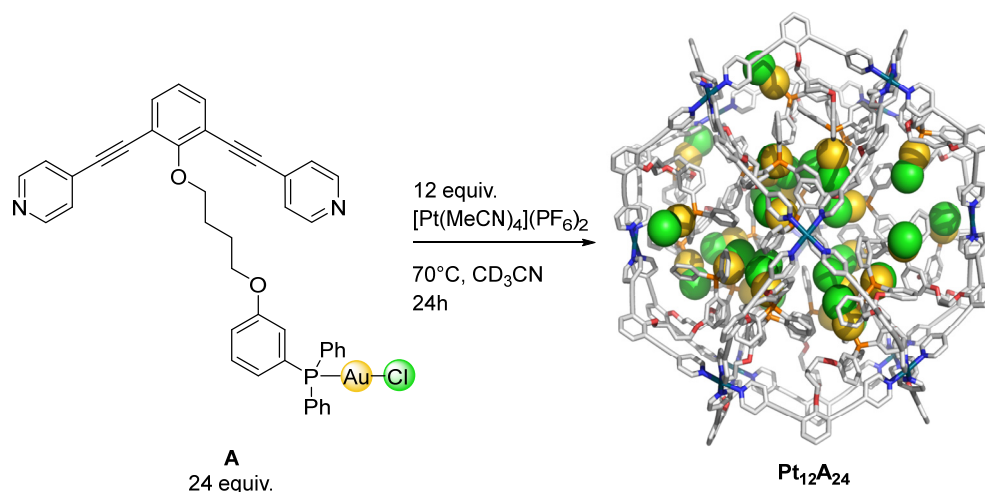


**Figure 1:** An amount of 24 bent bispyridine ligands can be assembled with 12 equivalents of palladium into large  $\text{M}_{12}\text{L}_{24}$  spheres.

The  $\text{M}_{12}\text{L}_{24}$  spheres have a cuboctahedron shape and are the thermodynamic final species that are formed under those conditions. Via synthetic methodologies the building block L can be modified and functional groups can be embedded at the inside of the spheres. This thesis demonstrates the use of this strategy for a ligand-template approach by functionalizing these building blocks with metal complexes. This results in a confinement of 24 metal complexes in a  $\text{M}_{12}\text{L}_{24}$  sphere.

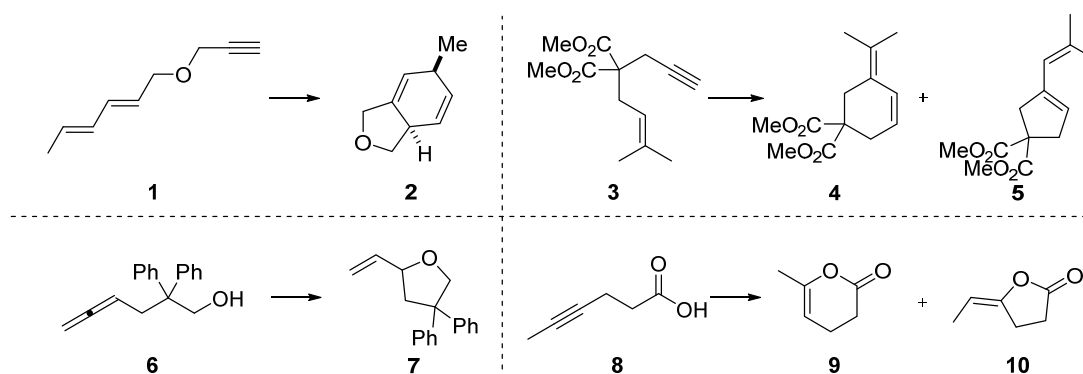
**Chapter 2** shortly introduces two important techniques used for the characterization of the assemblies in this thesis, diffusion ordered NMR spectroscopy (DOSY) and cold spray ionization mass spectrometry (CSI-MS). These techniques are applied to characterize different  $\text{M}_{12}\text{L}_{24}$  spheres. Based on different sizes, NMR spectra of spheres could be separated with DOSY when their peaks do not overlap in the  $^1\text{H}$  NMR spectrum. High resolution mass spectra for the spheres could be obtained with nanospray and cold spray ionization techniques, making it possible to determine elemental compositions and exact metal to ligand ratios of the spheres. Spheres consisting of different building blocks were mixed and heated, resulting in an exchange of building blocks and the formation of statistical mixtures of spheres. These mixtures could be characterized with CSI-MS and spheres with different ratios of building blocks were identified. The exact ratio of building blocks of all these spheres could be determined.

In **chapter 3** the inside of large  $\text{M}_{12}\text{L}_{24}$  spheres is functionalized with a phosphine moiety that binds a gold(I)chloride (complex **A** in Figure 2). Via the ligand-template approach, 24 gold complexes are confined in a small space. This results in a high local concentration of gold complexes inside the spheres.



**Figure 2:** Assembly of confined gold(I)chloride complexes in a self-assembled  $M_{12}L_{24}$  sphere.

It is noted that the palladium assemblies lack the stability needed for the catalytic transformation of strong coordinating substrates, like alkynes, as the sphere decomposes to the free building block. The more stable platinum analogues remain intact and can withstand harsher reaction conditions. Post-modification with a silver(I) salt leads to confined cationic gold(I) complexes which could catalyze the intramolecular [4+2] cycloaddition of **1** to **2** (see Figure 3). Dilution of the local concentration of gold complexes with a non-functionalized building blocks resulted in a slower conversion of **1**, showing the benefits of a high local concentration.

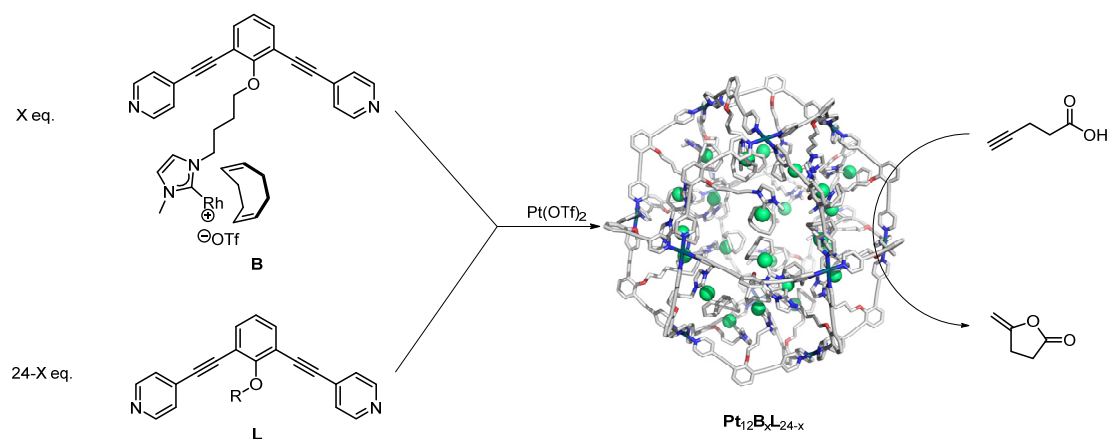


**Figure 3:** Various cyclization reactions, facilitated by the activated gold functionalized nanosphere ( $Pt_{12}A_{24}$ ).

In addition, the activated gold nanospheres were able to cyclize 1,6-enynes (like **3**) which resulted in a different product distribution compared to a mononuclear gold complex. Allene groups (like substrate **6**) and alkyne acids (**8**) were also converted. With the latter substrate, a different ratio of products was observed, compared to a mononuclear catalyst. Hence, the platinum assemblies, functionalized with a gold complex are a versatile new type of catalysts.

**Chapter 4** expands on the approach in which different ditopic pyridine building blocks are mixed to obtain statistical mixtures of spheres. A building block,

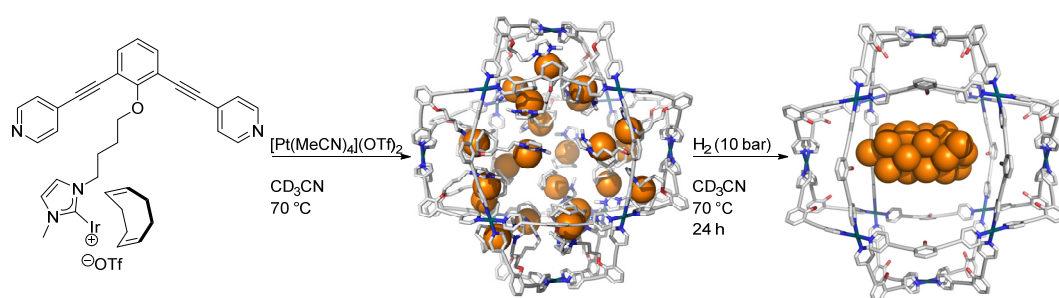
functionalized with an imidazolium moiety was proven to form different mixtures of palladium spheres with different type of building blocks containing either a methoxy or a guanidinium group. This concept was then applied to a N-heterocyclic rhodium carbene, that after the assembly is embedded at the inside of the sphere. This rhodium complex was active in the cyclization of 4-pentynoic acid (**11**) and could be diluted with different types of building blocks (depicted in Figure 4).



**Figure 4:** Dilution of rhodium carbene complexes (**B**) with different types of building blocks, resulting in a supramolecular approach to change the environment and concentration of a rhodium catalyst.

Based on the type of the building block that is used, the local environment around the rhodium complex is different. The type of environment influences the conversion rate of the substrate, demonstrating the power of this strategy.

A similar building block is used in **chapter 5** where iridium N-heterocyclic carbene complexes are pre-organized in the sphere (see Figure 5). These iridium complexes form small iridium nanoparticles after reduction with hydrogen gas.

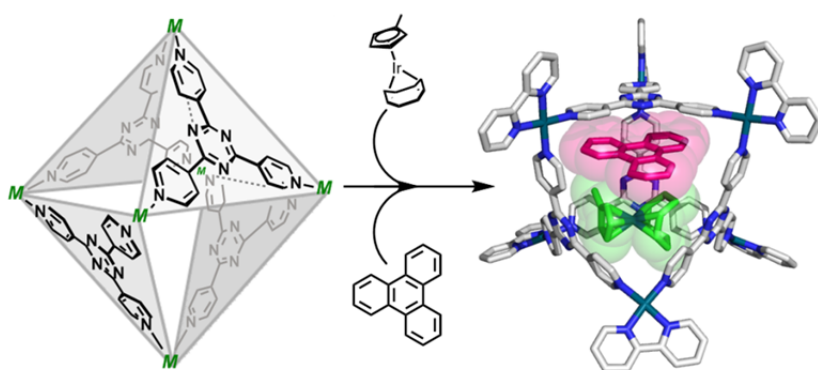


**Figure 5:** Formation of small iridium nanoparticles, confined in a platinum sphere.

The small nanoparticles are visualized with cryo-TEM measurements, indicating that they are approximately 1 nanometer in size. Dynamic light scattering experiments excluded the formation of large particles in solution. The nanoparticles are active in the hydrogenation of styrene and poisoning studies with mercury revealed that

colloidal nanoparticles are the active species. The high amount of poison that is needed in quantitative poisoning studies gives additional prove for the formation of small particles. This indicates that the sphere stabilizes the small nanoparticles and prevents the formation of large, thermodynamically more stable clusters. Interestingly, the small confined nanoparticles are more active in the hydrogenation of styrene, compared to a mononuclear complex. Further studies demonstrated that the nanoparticles can reduce different substituted double bonds and nitro groups. This example shows that the strategy allows to pre-organize and stabilize iridium complexes in a confined space, which gives new possibilities for the controlled formation of very small nanoparticles.

Having explored the ligand-template approach to confine metal complexes in a sphere, a host-guest approach to embed metal complexes in a cavity is discussed in **chapter 6**. For the host, the metallocage, previously reported by Fujita and co-workers is used. The metallocage with a octahedral shape is formed by 6 metal centers that are held together by 4 triazine panels (depicted in Figure 6). The system with nitrate anions at the cationic metal corners is water soluble and can host small molecules inside its cavity via hydrophobic interactions. In our work we demonstrate that a cyclopentadiene derived metal complex and a flat aromatic moiety are selectively co-encapsulated inside the metallocage. The formed ternary complex was confirmed with NMR spectroscopy and X-ray diffraction, showing the tight fit of the two guests inside the cage. Co-encapsulation of a metal complex and an organic substrate is a pre-requisite for a metal catalyzed reaction inside this cage.



**Figure 6:** Water soluble octahedral cage, able to co-encapsulate a metal complex with a flat aromatic molecule.

By changing the steric and electronic properties of the guests, different ternary complexes can be formed. Due to the co-encapsulation, a charge transfer band is observed in UV-Vis spectroscopy. The charge transfer band changes in these different ternary complexes and the energy of the charge transfer band correlates with the redox properties of the metal complexes. Being able to measure and fine-tune such

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subtle interactions, like charge transfer energies, could prove vital in designing future catalytic systems.

Having designed new supramolecular cages and spheres with metal complexes at the inside resulted in catalytic systems of which the properties are controlled by the second coordination sphere. The stability of the spheres, the ability to fine-tune the environment and post-modify the complexes in the spheres resulted in new types of catalysts that have different reactivity compared to mononuclear complexes. The effect of the confined space around the metal complexes can hence result in new ways to control selectivity in catalysis.