Dendritic Polyglycerol as Versatile Support for the Recycling of Transition Metal Catalysts

DISSERTATION

zur Erlangung des akademischen Grades des

Doktors der Naturwissenschaften (Dr. rer. nat.)

eingereicht im Fachbereich Biologie, Chemie, Pharmazie

der Freien Universität Berlin

vorgelegt von

Juliane Keilitz

aus Berlin

April 2010

Diese Arbeit wurde unter der Anleitung von Prof. Dr. Rainer Haag im Zeitraum von August 2006 bis April 2010 am Institut für Chemie und Biochemie der Freien Universität Berlin angefertigt.

1. Gutachter: Prof. Dr. Rainer Haag

2. Gutachter: Prof. Dr. Reinhard Schomäcker

Disputation am 3. Juni 2010

Acknowledgements

First of all I would like to thank Prof. Dr. Rainer Haag for the offering me this interesting research project and the opportunity to work in his group.

I thank Prof. Dr. Reinhard Schomäcker for taking over the second expertise and the fruitful collaboration with his group.

I am grateful to my collaborators Clara Valverde-Serrano, Dr. Jean-Daniel Marty and Dr. Christophe Mingotaud from the Université Paul Sabatier (Toulouse, France), Dr. Michael Schwarze and Dipl.-Ing. Jonas Dimroth (Technical University Berlin), and the CERC3 team from the groups of Prof. Dr. Andreas Liese (Technical University Hamburg-Harburg, Germany) and Prof. Dr Herfried Griengl (Graz University of Technology, Austria).

I would like to acknowledge the research students Tim Paul Gebauer, Stephen Schrettl, Sabrina Nowag, Ralf Albrecht, Ebru Koca, and several students from the P3 lab course for their help in the projects presented here.

Cathleen Schlesener, Winfried Münch, Andrea Schulz, Dipl.-Chem. Wiebke Fischer, Marleen Selent, and Gabriela Hertel are thanked for their help in the lab, with HPLC and SEC separation, TEM measurements and the supply with equipment.

Special thanks go to Jutta Hass for taking care of all the paperwork that keeps the group running.

I am grateful to Emanuel Fleige and Dr. Pamela Winchester for proof-reading.

My former and present colleagues from the lab and office, Dr. Chakib Hajji, Dr. Michal Radowski, Dr. Venkatakrishnan Thengarai, Florian Mummy, Emanuel Fleige, Cathleen Schlesener, Sabrina Nowag, Ying Luo, Maike Lukowiak, and Dr. Marcello Calderòn are thanked for the nice working atmosphere and their patience particularly with regard to music and stress.

For fruitful discussions and micellaneous help I thank Dr. Paul Servin, Junior-Prof. Dr. Christoph Tzschucke, and Dr. Constantin Czekelius.

I acknowledge the analytical department of the Institute of Chemistry and Biochemistry for numerous NMR and MS measurements as well as elemental analyses. I gratefully acknowledge Dipl.-Ing. Thomas Wons and Gerd Buchlow for ICP-MS measurement and I am especially grateful to the people from the material store for all last minute orderings.

I am grateful to the group of Prof. Dr. Christian Stark for “abandoning” their gas chromatograph and the group of Prof. Dr. Hans-Ulrich Reißig for the possibility to use it.

Last but not least I thank all former and present group members of the group of Prof. Dr. Rainer Haag for the great working atmosphere and special thanks go to the hard core of the “coffee group” Aileen Justies, Marie Weinhart, Emanuel Fleige, Timm Heek, Florian Mummy, and Christian Kördel.

Finally I would like to thank my best friends Nadine Szabó and Kay-Oliver Thiel, my family, and especially my husband Daniel Leiser for their support

Contents

1 Introduction

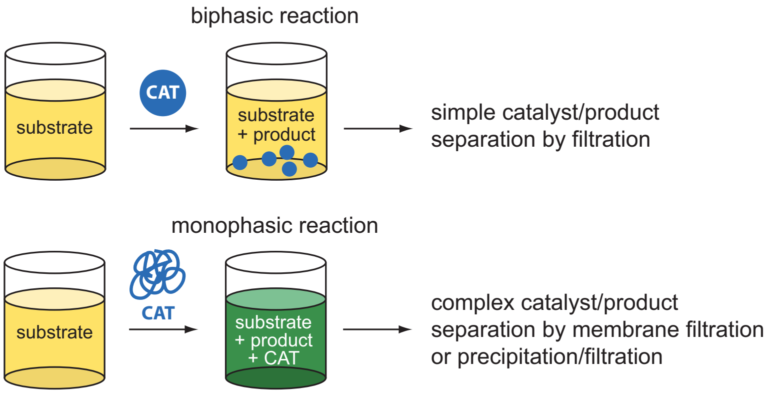
1.1 General Aspects

There is a strong demand for the development of sustainable methodologies in organic synthesis. Catalysis is a powerful means towards this goal, because it allows for more efficient reactions, the application of reduced (catalytic) amounts of potentially hazardous and expensive (metal) catalysts and diminished waste production. Particularly asymmetric catalysis[1-3] is of growing importance for the industrial production of fine chemicals,[4] since of most natural products, drugs, plant-protecting agents, or fragrances, only one enantiomeric form is biologically active.[5,6] For example, the market share of enantiomerically pure drugs increased from 27 % in 1996 to 39 % in 2002[7] and due to economic and environmental reasons this fraction will increase even more in the future. Further driving forces to use the enantiomerically pure form of a racemic active compound in pharmaceutical industry are the application of lower dosages and the extension of patent terms. In the agrochemical industry, improved economics of the production process and the application of reduced quantities are attractive, causing less impact on the environment.[8]

The field of catalysis is mainly dominated by metal catalysis with a new but less prominent area of organocatalysis.[9] One can distinguish between homogeneous and heterogeneous metal catalysis. Heterogeneous metal catalysis includes bulk metal catalysts as well as supported metal particles which can be as small as a few nanometers. To achieve asymmetric induction, modification of metal surfaces with chiral compounds is a successful approach.[10,11]

To date the overall production of achiral chemicals is still mainly achieved with heterogeneous catalysts, but for chiral compounds an increasing portion of homogeneous catalysis is employed.[4] A vast number of chiral ligands and their transition metal complexes have been reported, and many are known to be highly effective in terms of efficiency and selectivity.[1-3] Due to their well-defined catalytic sites, homogeneous catalysts are often superior to heterogeneous ones, but there are certain drawbacks, e.g., the high costs of ligands and noble metals, tedious separation of catalyst from products, recycling problems, as well as high levels of metal contamination in the products.[4,8,12,13] A possible solution of these problems is catalyst immobilization which allows for simplified separation, recovery and recycling of ligands and catalysts, as well as reduced contamination of products.[14-20] Apart from the easy separation, immobilization of chiral catalysts can also enhance the catalytic performance[21,22] by site isolation[23,24] or site cooperative effects.[25-27]

Homogeneous metal catalysts have been immobilized on a large variety of supports,[14-16,20,28-32] and the majority on heterogeneous ones. Besides the advantages of heterogeneous immobilization like simplified recovery and reuse of the often expensive or toxic catalysts and potential application to continuous flow type processes, several disadvantages,[17] such as lower activities and enantioselectivities, are present. These drawbacks derive from the heterogeneous (biphasic) reaction conditions which lead to mass transfer limitations, unfavorable reaction kinetics, and ill-defined catalytic sites.[20] Additionally, low loading capacities, problematic mechanical stability, and difficult analysis of the catalytically active species on the support can be disadvantages of heterogeneous immobilization.[17]



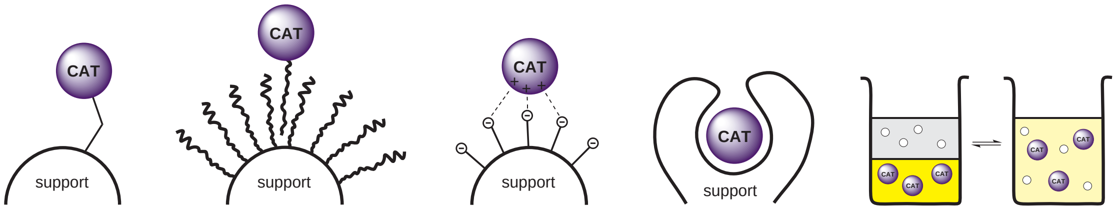
Scheme 1. Strategic differences between the use of a solid supported catalyst and a soluble polymer supported catalyst.[33]

A promising alternative is the utilization of soluble supports which has the potential to combine the advantages of homogeneous catalysis and heterogeneous immobilization (Scheme 1). With soluble supported catalysts organic reactions can be run under homogeneous conditions and thus often achieve a similar performance compared to their non-supported counterpart.[15] Of particular interest is the potential application of homogeneously supported catalysts in continuous membrane filtration processes.[34,35]

1.2 Homogeneous Immobilization of Metal Complexes for Catalysis

1.2.1 Immobilization Approaches

Immobilization of homogeneous catalysts can be achieved by various methods, including covalent attachment, adsorption or ion-pair formation, encapsulation or entrapment, or immobilization in liquid systems.[14] A schematic representation is shown in Figure 1. All of these approaches are suitable for the immobilization of metal complexes onto soluble supports.



Covalent attachment

Adsorption

Ion pair formation

Entrapment/ encapsulation

Liquid (biphasic) systems

Figure 1. Schematic representation of immobilization approaches for catalysts onto soluble or solid supports.[14]

Covalent attachment is by far the most popular and versatile approach for the immobilization of homogeneous metal catalysts and can be achieved by either copolymerization of functionalized ligands with a suitable monomer or by grafting functionalized ligands or metal complexes onto a preformed support. The major drawback of this method is the need for modification of the chiral ligand in order to construct an attachable unit. This leads to higher preparation costs and might have negative consequences in regard to the conformational preferences of the supported complex which lead to unpredictable and possibly negative effects on the catalytic performance.[28,31] Therefore, the point of attachment should be as far away as possible from the catalytically active center in order to disturb the chiral induction as little as possible. Additionally, many other parameters, e.g., type of support, solvent, spacer length and flexibility, and degree of surface coverage, have to be chosen carefully to achieve catalytic performances equal to the non-supported catalyst.[18,36] However, due to the stable covalent bonds leaching from the support is generally low.

Adsorption by van-der-Waals or hydrogen bonding as well as ion-pair formation between a support and the metal catalyst is another effective means for immobilization because it avoids chemical modification of the ligand.[31] However, the stability of the adsorptive or ionic bond strongly depends on the reaction conditions, e.g., solvent and ionic strength of the surrounding medium.

Encapsulation and entrapment of catalysts inside a support requires a porous scaffold with pore sizes that are small enough to sterically prevent leaching during reaction. It can be achieved by two different methods: (1) build-up of the catalyst inside the support ("ship-in-a-bottle"),[37] or (2) synthesis of the support in presence of the catalyst.[38,39] This method avoids elaborate catalyst modification, but the resulting catalysts often suffer from diffusion limitations, especially when larger substrates are used.

Catalysts supported by liquid systems include liquid biphasic systems, supercritical solvents like *sc*CO_2, or the supported liquid phase (SLP) approach. In liquid biphasic systems two immiscible solvents are utilized, of which one is solubilizing the catalyst and the other one the substrates, products, and reaction partners. Common solvents for the catalyst are ionic liquids (ILs)[40-44] and perfluorinated solvents.[45-47] Supercritical (*sc*)CO_2 is a special solvent because it has a very low viscosity, liquid-like solubilizing power, and is readily tunable by changing the operating temperature and pressure. Its environmentally benign nature, easy availability, being non-flammable, and low toxicity make it an attractive alternative for organic solvents.[48] In the supported liquid phase (SLP) approach, a solution of the homogeneous catalyst is attached to the surface of a porous support which is in contact with another solvent phase containing substrates, products, and other reaction partners. This method does not require modification of the catalyst, but suffers from restricted solvent choice and mass transfer limitations.[49,50]

1.2.2 Separation of High Molecular Weight Catalysts from Reaction Mixtures

The separation of precious ligands or metal complexes from reaction mixtures is one of the major benefits of supported catalysts. While heterogenized catalysts are easily separated by filtration, there is no generally applicable method for the separation of soluble supports from small molecular weight compounds in solution. To date a number of reviews dealing with separation techniques have been published.[33,46,51-56] In principle, soluble polymers can be separated from low-molecular weight compounds by either making use of their physicochemical properties or by size.

1.2.2.1 Separation by Physicochemical Properties

Precipitation and filtration is the most frequently used method to separate soluble supported catalysts from reaction mixtures. Thereby, precipitation of the polymer can be induced by either adding a non-solvent, or changing the solution behavior with temperature or a small amount of additive (e.g. pH change).[56]

Solvent precipitation is mainly applied to induce polymer insolubility. It makes use of the insolubility of a specific polymer in a solvent in which the products and reactants are readily soluble. The reaction mixture is poured into an excess of this second solvent and after quantitative precipitation, polymer and products can be separated by filtration. This strategy has been widely applied for poly(ethylene glycol) (PEG) (soluble in most organic solvents and water; insoluble in hexane, diethyl ether, cold ethanol, *tert*-butyl methyl ether and isopropanol) and non-crosslinked polystyrene (NCPS) (soluble in non-polar solvent; insoluble in methanol).[33]

Thermal precipitation is less common because it requires that the polymer has a lower critical solution temperature (LCST) behavior in an accessible temperature range. It has been reported for catalysts supported on poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide) block copolymers and poly(*N*-alkylacrylamides).[57-59]

Precipitation by a pH change can be used with polymers that contain basic or acidic groups.[60] Addition of a small amount of acid or base changes the solubilization behavior completely and induces precipitation. Changing the ionic strength can also be a means to induce insolubility of polymers as described by Bergbreiter and coworkers.[57]

In all cases, trapping of products and reactants in the precipitating polymer can occur. Therefore, repeated precipitation/filtration is usually recommended.

Another common approach for the separation of soluble polymer-bound catalysts is liquid-liquid extraction which requires that the solubility behavior of the polymer differs strongly from that of the product and reactants. This requirement is met by water-soluble polymers as well as by fluorous solvents, which are immiscible with conventional organic solvents and can solubilize perfluoro-tagged polymers.[46]

1.2.2.2 Separation by Hydrodynamic Volume (Size)

For a separation by size the homogeneous polymer support should have medium molecular weights of 5,000 to 10,000 g mol^{-1} and narrow molecular weight distributions (PD < 2).

Membrane filtration techniques are the most common methods to separate soluble high molecular weight compounds from low molecular weight compounds in solution.[53,61] Membrane filtration processes can be classified into micro-, ultra-, nanofiltration, and reversed osmosis, depending on the size of the particles that are retained by the membrane (Figure 2).[62] For catalyst separation usually ultra- or nanofiltration is used.

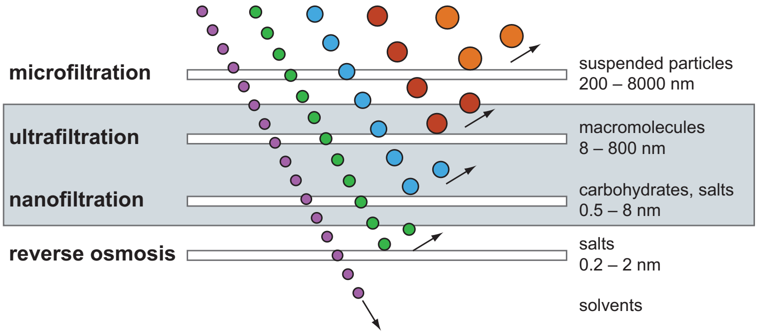


Figure 2. Classification of membrane filtration types by size.[62]

Filtration membranes are characterized by their molecular weight cut-off (MWCO) which is defined as the molecular weight at which 90 % of the solutes are retained by the membrane. As membrane materials two types are used: organic (polymer) membranes[63-65] and inorganic (ceramic) membranes.[66,67] Thereby, it should be taken into account that the actual pore size of polymeric membranes is greatly influenced by the temperature and solvent.[68]

In dialysis the reaction mixture is filled into a dialysis tube consisting of the membrane. This tube is surrounded by solvent and small molecules can diffuse out while big molecules (> MWCO) are retained. The driving force for separation is the difference in concentration between the two solutions separated by the membrane. Since permeation only takes place until equilibrium has been achieved (similar to a "tea-bag"),[69,70] the solvent has to be changed several times to achieve reasonable purity.[46,61]

Ultra- or nanofiltration achieve higher purity and have potential for continuous application.[16,53] Solvent-resistant stirred cells are commercially available,[71] and are equipped with a polymeric membrane in the bottom part of the setup (Figure 3). A constant pressure of nitrogen or argon gas is applied from the top and under continuous stirring the sample is pushed through the membrane. The polymeric catalyst remains in the cell while the small molecular weight fraction is collected beyond the membrane.

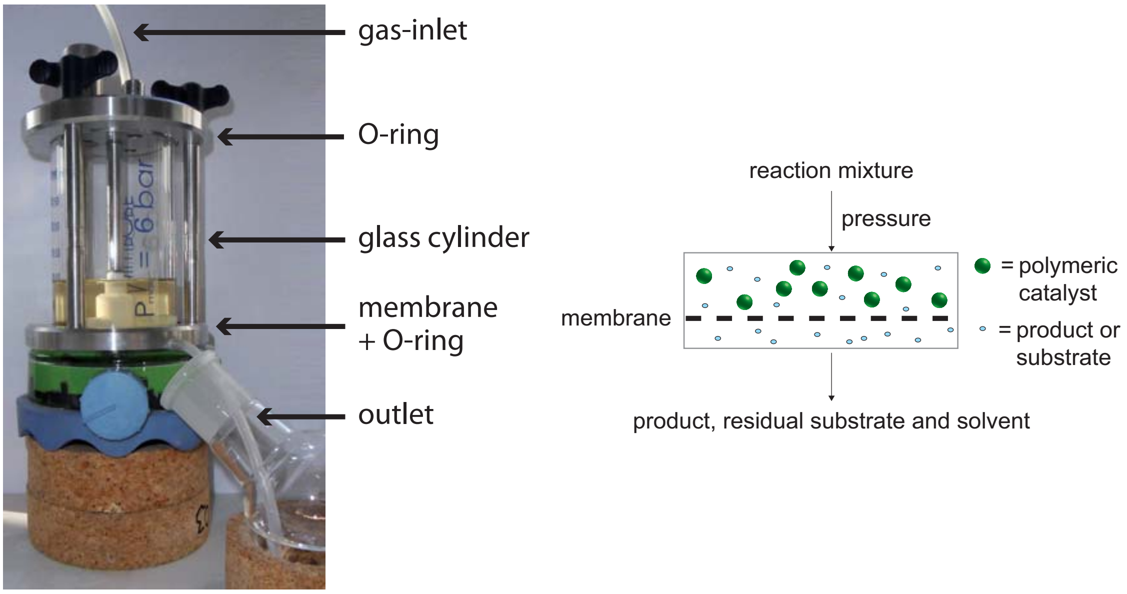


Figure 3. Ultrafiltration setup.

Continuous flow membrane reactors (CFMR) use the basic principle of ultrafiltration.[34,35,62,72] The membrane retains a soluble polymer-bound catalyst and low molecular weight substrates are continuously transformed while they pass the reactor. In CFMRs, concentrations and residence times can be regulated which prevents long exposure of substrates and products to the catalytically active center, thereby avoiding or reducing side reactions. Ideally, pure compounds can be collected beyond the membrane and the total turnover number of a catalyst can be increased manifold.[53,73]

Another means to separate molecules by their hydrodynamic volume is size exclusion chromatography (SEC) or gel permeation chromatography (GPC)[46] which utilizes a stationary phase with a defined pore sizes. Molecules with a large hydrodynamic volume cannot diffuse in the pores of the stationary phase and therefore have lower retention times than small molecules which diffuse in and out. This technique can be applied on analytical or preparative scale (up to 100 mg) but is rather costly.

1.2.2.3 Catalyst Leaching

Leaching of catalytically active species is one of the major problems in supported catalysis.[12] Two forms of leaching are known: leaching of the supported catalyst through the filtration membrane and metal leaching from the support into the solution and further through the membrane.[62] The latter is usually caused by decomposition of the catalytic unit or the connection to the support.

Two problems are connected to metal leaching: loss of the expensive catalyst and contamination of the product with lost metal. For industrial application, e.g., in a CFMR, retentions of at least 99.99 % per reactor volume are required to obtain profitable catalyst systems. Unfortunately, this high retention is usually not achieved and in literature maximum retention values of 99.8 % are reported.[74,75] However, contamination of the product should be limited to an acceptable amount, especially when the product is an active pharmaceutical compound.

1.2.3 Soluble Supports for the Anchoring of Metal Complexes

The first application of a soluble support was introduced in 1971 by Bayer and co-workers, who used soluble poly(ethylene glycol) (PEG) as support in peptide synthesis and afforded separation by ultrafiltration.[76,77] A few years later, a rhodium-complex anchored to polystyrene was applied to homogeneous hydrogenation and hydroformylation reactions.[78] However, this report did not attract much interest and it took another 20 years, until in 1996 Janda and co-workers[79] reported an efficient polymer-supported chiral catalyst for asymmetric synthesis. Since then, a wide variety of polymers has been applied as soluble polymeric supports for chiral ligands and metal catalysts, e.g., functionalized soluble polystyrenes,[80,81] poly(ethylene glycol)s,[33,82] poly(methyl methacrylate)s,[83] poly(vinylpyrrolidines)s,[83] polyelectrolytes,[84] dendrimers,[19] or hyperbranched polymers.[30,85]

In principle, soluble supports can be classified into two main groups: linear and branched polymeric supports. Thereby, linear polymeric supports can be decorated with only one or two functional end groups or functional groups along the whole polymer chain, whereas branched architectures are grouped into star shaped polymers, dendrimers and dendrons, and hyperbranched polymers (Figure 4).

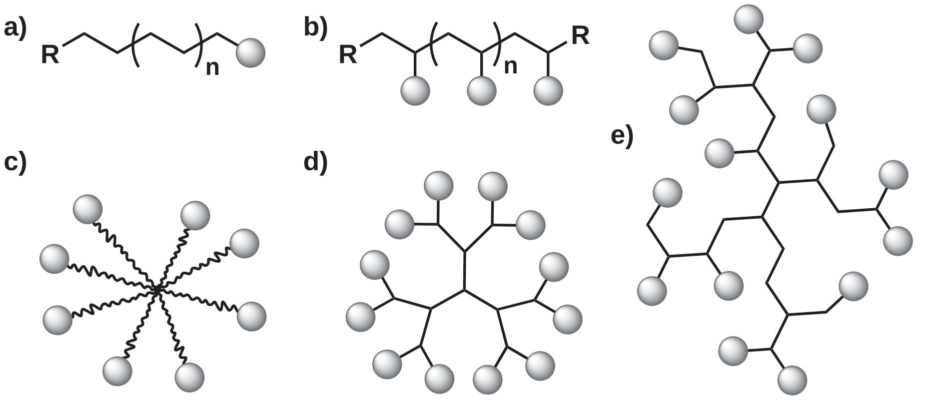


Figure 4. Classification of soluble polymer supports into linear polymers with (a) one functional end group or (b) functional groups throughout the polymer chain, and branched polymer architectures with (c) star shaped polymers, (d) dendrimers, and (e) hyperbranched polymers.

Additionally, hybrid forms between those different types are known, e.g., linear polymers with dendronized side groups[86,87] and linear or starlike polymers with dendritic end groups,[88,89] but have not been used as catalyst supports.

1.2.3.1 Linear Polymers as Catalyst Supports

The most common linear supports with only one or two functional end groups are non-crosslinked polystyrene (NCPS) and poly(ethylene glycol) (PEG, typically PEG_{5000}) (Figure 5). Their major drawback is the low loading capacity which derives from the linear structure (e.g. 0.2 mmol g^{-1} for $mPEG_{5000}$; 0.4 mmol g^{-1} for PEG_{5000}). Linear polymers found broad applications as catalyst supports and are usually recovery by solvent precipitation/filtration methods.[33]

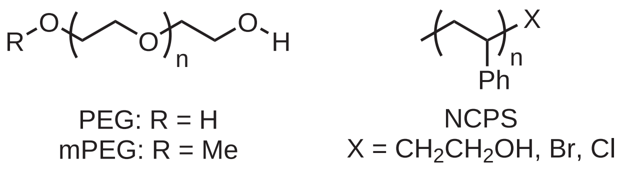


Figure 5. Chemical structures of poly(ethylene glycol) (PEG/mPEG) and non-crosslinked polystyrene (NCPS).

Linear polymers with functional groups on each monomer unit (Figure 6), have a significantly higher loading capacity than mono- or di-functionalized linear supports, but their properties, like solubility and chemical stability, as well as their materials properties can be problematic for a broad application in organic synthesis and catalysis.[51] Nevertheless, many have been used for the immobilization of catalysts, like NCPS with side functional groups,[90,91] poly(acrylic acid),[92,93] or poly(*N*-vinyl-2-pyrrolidone) (PVP).[94]

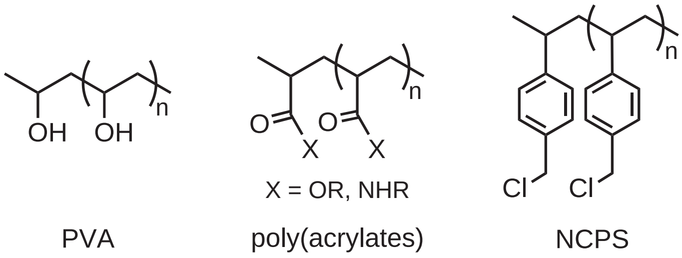


Figure 6. Structures of side functionalized linear polymers poly(vinyl alcohol) (PVA), poly(acrylates), and chloromethylated polystyrene.

1.2.3.2 Branched Polymer Architectures as Catalyst Supports

To overcome the problems connected to linear polymers, the use of branched polymer architectures is a promising alternative.[51,95]

Star polymers consist of several linear polymer chains (arms) attached to a central core. They are an easily accessible branched structure which can be build up in a single reaction step.[96,97] Catalytic units can be attached either in the core,[98,99] at the end groups of the arms,[100] or distributed throughout the arms.[101,102] Positioning of the catalytic moiety in the core favors site isolation and shielding against the environment, but results in relatively low loading capacities.

A special class of branched polymer architectures are the perfectly branched dendrimers.[103] “Cascade molecules” were first introduced in the late 1970s by Vögtle and co-workers[104] and since then have been investigated intensively,[103,105,106] particularly in regard to their application as soluble supports in catalysis.[16,19,95,107-109]

Dendrimers are characterized by their well-defined highly branched structure, high loading with functional groups, low viscosity, and high solubility in a wide range of organic solvents, which can be controlled by the end group functionality. Dendrimer-immobilized catalysts can show the kinetic behavior and therefore activity and selectivity of conventional homogeneous catalysts. Due to the high local concentration of functional groups in dendrimers, the attachment of catalytic moieties can lead to improved or diminished activity and selectivity, so-called “dendritic effects”.[21] Those include enhanced stability through steric isolation or cooperativity through close proximity of reactive groups. Thereby, the dendrimer structure can be used to control the interaction between catalytic units or with the environment. Catalytic units can be introduced throughout the dendrimer structure at the core, branching units, or periphery (Figure 7).

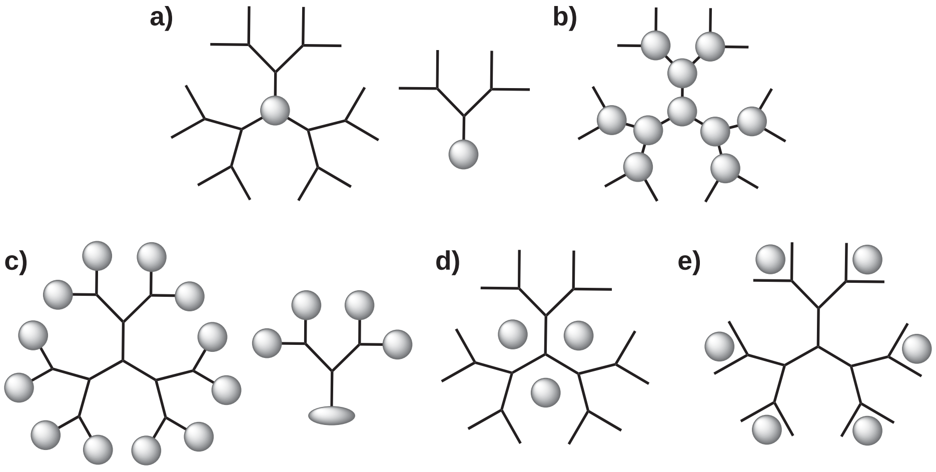


Figure 7. Possible locations of catalytically active units (●) in dendritic structures: covalently linked (a) in the core, (b) at each branching unit, or (c) at the periphery, or non-covalently (d) entrapped in the dendrimer cavities, or (e) bound to the periphery.[110]

Introduction of the catalyst at the core[111-113] results in a very poor loading capacity and usually slower reaction rates. However, site isolation is favored and by changing the dendrimer structure the solubility properties of the catalyst as well as its selectivity can be adjusted.[114,115]

A close proximity of catalytic sites is achieved via the attachment of catalytic moieties onto the dendrimer periphery[110] or by introducing catalysts at each branching point. The latter approach is less common and rarely described in literature.[116,117]

The peripheral functionalization (see Figure 7c) is the most frequently used approach in dendrimer immobilized catalysis and numerous reviews have been published.[16,95,107,118,119] The catalyst units are densely packed at the dendrimer surface, are highly accessible for substrates and reactants, and can easily interfere with each other, either increasing (positive dendritic effect) or decreasing (negative dendritic effect) the catalytic performance.[21] A wide variety of reactions with dendritic catalysts has been described, including asymmetric hydrogenation, hydroformylation, Heck reaction, oxidations, Stille couplings, Knoevenagel condensations, asymmetric transfer hydrogenation, metathesis, epoxidation, hydrolytic kinetic resolution, and hetero-Diels–Alder reactions.[16]

Other immobilization approaches are the non-covalent entrapment of catalysts in the internal cavities or attachment via van-der-Waals, ionic or hydrogen bonding between dendrimer and catalyst (Figure 7d and e).[120]

In addition to the facile attachment of catalytic units, dendrimer supports are particularly suited for separation by membrane filtration.[30,62,95] Unfortunately, they have a serious disadvantage which is the tedious and expensive multistep synthesis of higher generation dendrimers with molecular weights suitable for membrane separation techniques ($\geq$ 1500 g mol^{-1}). Due to the high costs for the synthesis of dendrimers, their commercial applications are rare.

Randomly branched polymeric structures are a powerful alternative to expensive dendrimers[18,30,85,121] because they can usually be prepared in one step which allows the production of large quantities.[85,122] Hyperbranched polymers are polydisperse and the reactive groups are distributed throughout the structure, but in principle, their properties are very similar to those of analogous dendrimers.[51] In catalysis they often achieve similar results, showing that structural perfection is not always required.[85,108] A wide range of hyperbranched polymers is known[123] and a selection is presented in Figure 8. To date some are even commercially available, e.g., poly(ethylene imine), Boltorn polyesters, polyglycerol, or Hybrane polyesteramides.[51]

Among those, hyperbranched polyglycerol **1** (hPG) is especially interesting because of its high chemical stability in comparison to polyesters or polyamines. This dendritic structure can be obtained with different molecular weights in a one-step polymerization reaction[127,129] and recently even very high molecular weight hPG **1** became available.[130-132] hPG **1** can be easily functionalized and its versatile properties, e.g., high loading capacity (13.5 mmol g^{-1}), good solubility, and noncoordinating properties, make it an appropriate support for metal catalysts.[30,54,133-137] Due to the versatility and high biocompatibility,[138] it has also found widespread application for biomedical purposes which have been recently reviewed.[139-141]

In the following chapter, selected examples of homogeneously supported metal complexes will be presented. The major focus will be on reported dendritic effects as well as the recycling of supported catalysts.

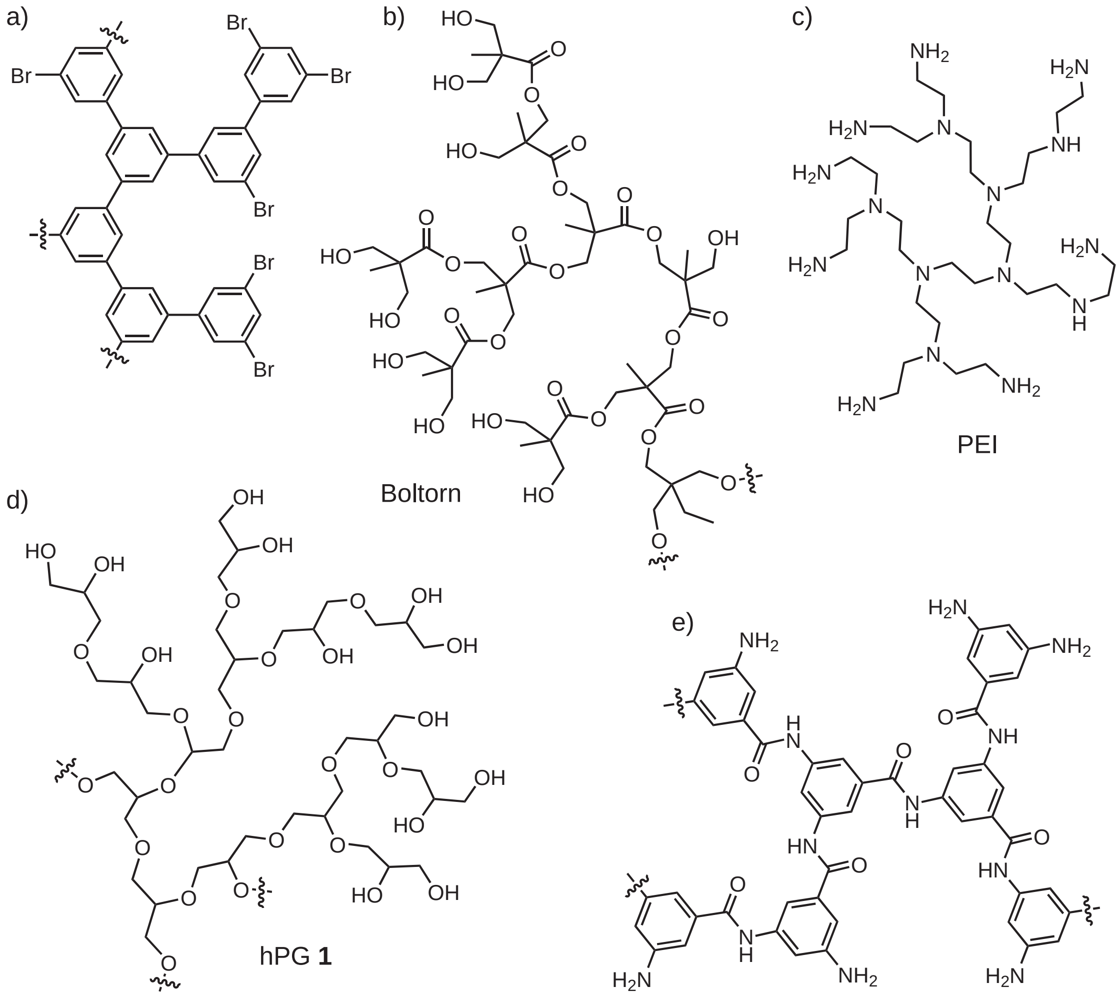
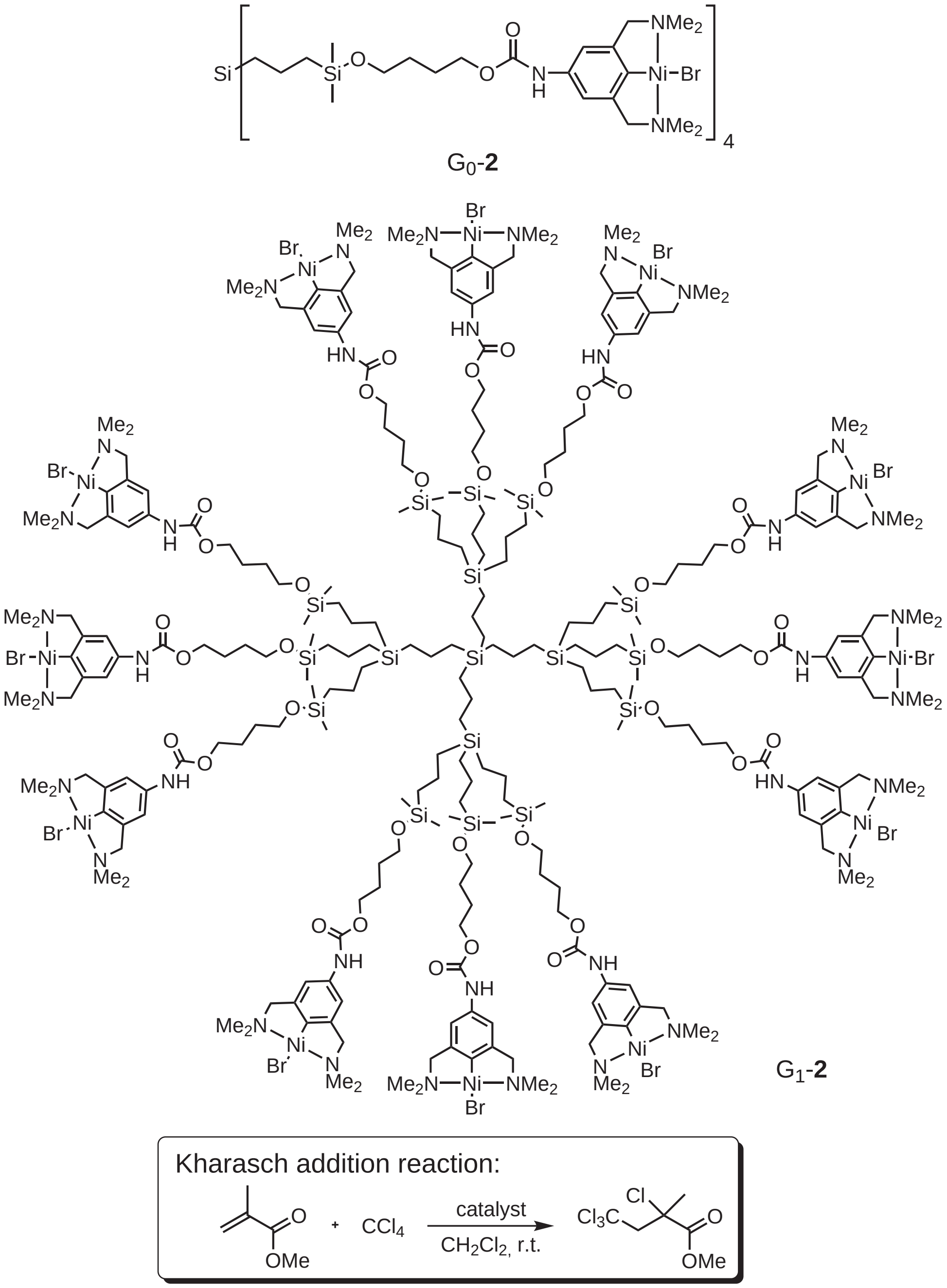


Figure 8. Representative fragments of the structures of some hyperbranched polymers reported in literature: (a) hyperbranched polyphenylenes,[124] (b) hyperbranched polyesters,[125] (c) hyperbranched polyamines,[126] (d) polyethers,[127] and (e) polyamides.[128]

1.2.4 Homogeneously Supported Metal Complexes for Catalysis

In case of core-functionalized dendrimer catalysts dendritic effects can result from site and transition state isolation,[142] while in peripheral functionalized dendrimers the high local concentration of catalytic units or cooperativity can be advantageous or disadvantageous.[26,74]

In 1994, the group of Van Koten was the first to describe a dendritic effect upon immobilization of a NCN-pincer nickel complex in the periphery of carbosilane based dendrimers of different generation (Scheme 2).[74,143,144]



Scheme 2. Kharasch reaction and the corresponding carbosilane-based dendrimer catalysts G$_0$-**2** and G$_1$-**2** by Van Koten.[143]

The G$_0$-**2** and G$_1$-**2** catalysts were employed in the Kharasch addition reaction of polyhalogenoalkanes to an olefinic C=C double bond and similar reaction rates compared to the parent catalyst were obtained.[143] This led to the suggestion that each catalytic entity acted independently. To investigate the factors that might influence the catalyst performance, a small library of NCN-pincer nickel-containing dendrimers was synthesized with varying density of catalytic units at the periphery of the dendrimer.[74,144] This was achieved with different spacers in the dendritic framework and different substitution patterns at the branching points (Figure 9).

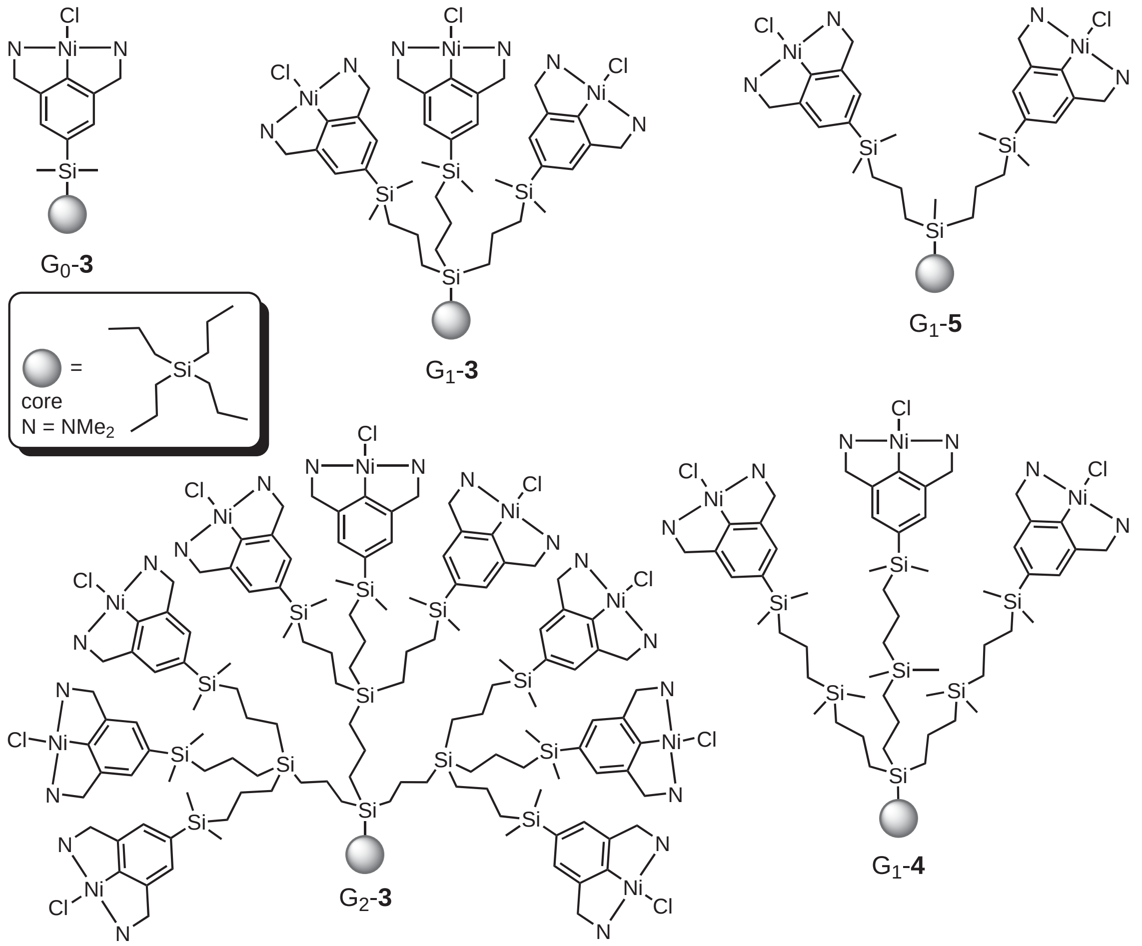


Figure 9. Structures of Van Kotens carbosilane-based catalysts (for clarity reasons only one fourth of the complete structure is shown).[74,144]

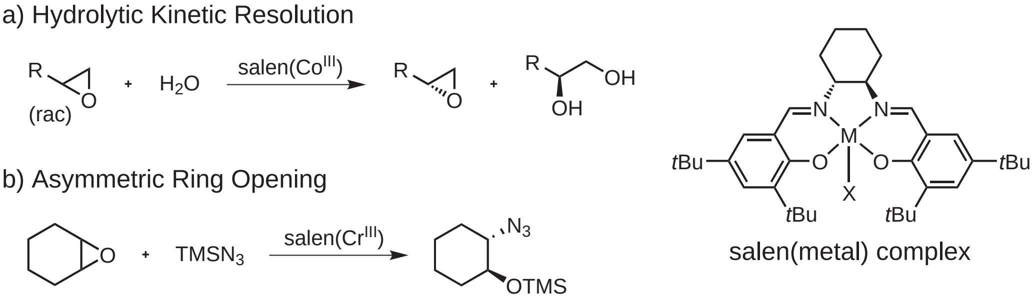
When these catalysts were applied to the Kharasch addition, a significant difference in activity was observed. G$_0$-**3** exhibited a similar activity in comparison to the monomeric analogue whereas already G$_1$-**3** (with three metallated pincers per silicon branch) experienced a fast deactivation due to catalyst degradation. The second-generation catalyst G$_2$-**3** showed almost no activity. At the same time, G$_1$-**4** and G$_1$-**5**, with longer spacers or less pincer complexes per silicon branch, respectively, did not show any deactivation. Taking the radical mechanism of the Kharasch addition into account, the deactivation was ascribed to homocoupling between intermediate $^{\bullet}CCl_3$ radicals when a high local concentration of radicals was generated, i.e. at a close proximity of nickel complexes on the surface. The irreversible coupling of two $^{\bullet}CCl_3$ radicals to Cl_3C-CCl_3 leads to the formation of inactive Ni^{III} species and therefore deactivation of the catalyst.

This negative dendritic effect can be avoided via reduction of the local radical concentration by dilution of nickel complexes on the surface as achieved for G_1-**4** and G_1-**5**.

Of particular importance was the fact that no metal leaching from the catalyst was observed, demonstrating the general stability of NCN-pincer type organometallic complexes. For application of G_1-**3** in a continuously operating membrane reactor retention of 99.75 % was demonstrated. However, a fast deactivation of the catalyst was observed with almost no more conversion after 33 hours (64 reactor volumes) that could not be explained with catalyst loss, but deactivation.[74]

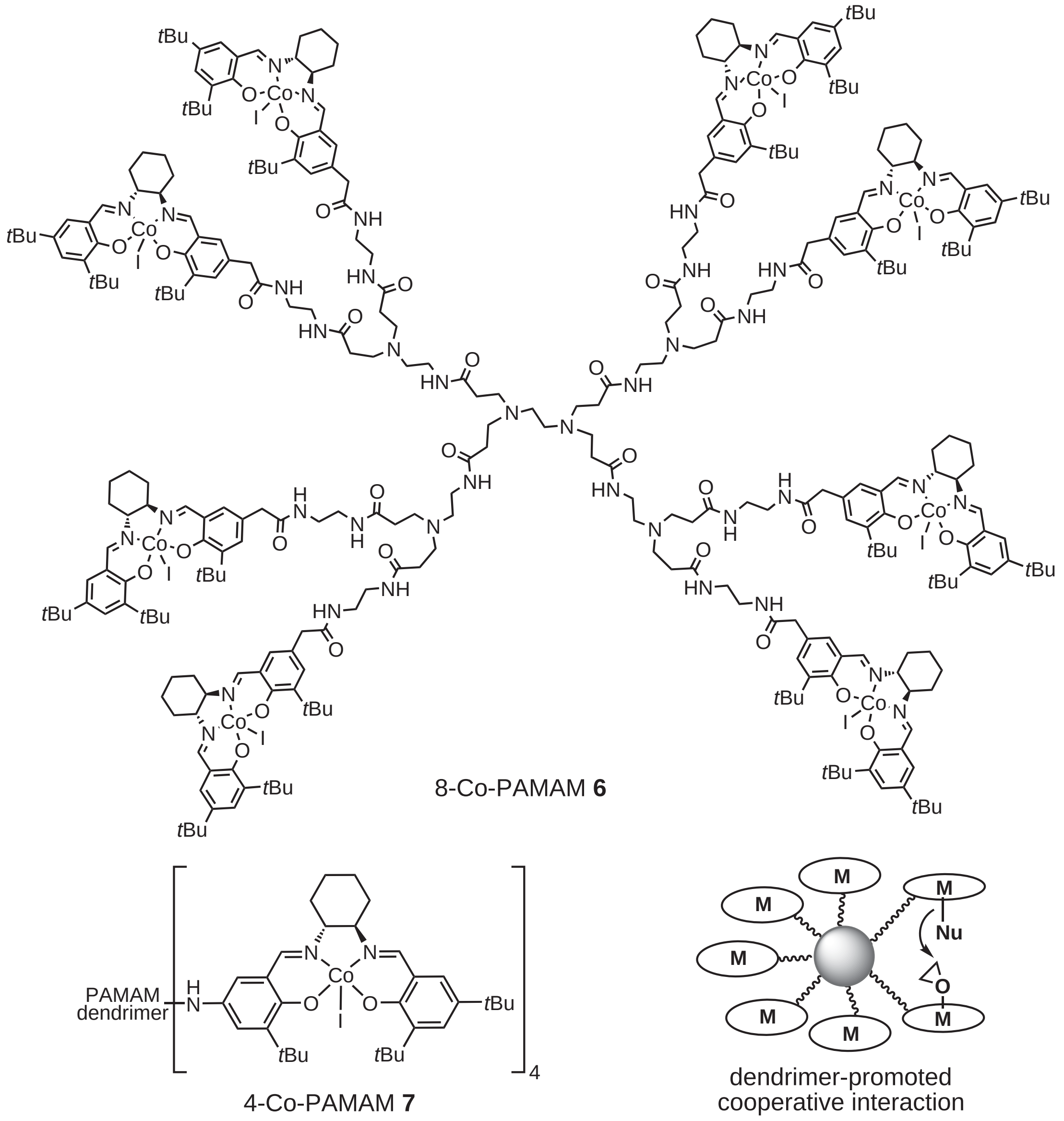
Further negative dendritic effects have been described in the literature, e.g., for Heck reactions,[145] or Sonogashira coupling.[146]

Particularly prominent examples for the observation of positive dendritic effects are salen(metal) complex catalyzed epoxide ring opening reactions (Scheme 3).[26]



Scheme 3. Epoxide opening reactions catalyzed by salen(metal) complexes: (a) hydrolytic kinetic resolution of epoxides with water and (b) asymmetric ring opening of *meso* epoxides with $TMSN_3$.

After the discovery that the salen(Cr^{III}) catalyzed asymmetric ring opening (ARO) of epoxides with $TMSN_3$ proceeds via a cooperative bimetallic mechanism (see Figure 10),[147,148] Jacobsen and coworkers designed PAMAM supported salen(Co^{III}) catalysts 4-Co-PAMAM **6**, 8-Co-PAMAM **7** and 16-Co-PAMAM **8** for the hydrolytic kinetic resolution of terminal epoxides (Figure 10).[26] At very low catalyst loadings of 0.027 mol% an analogous monomeric catalyst showed no significant conversion, while 8-Co-PAMAM **7** achieved complete kinetic resolution and high enantioselectivity of the remaining epoxide (> 98 %). Comparison of the dendritic catalysts **6**, **7** and **8** with a dimeric model compound, revealed that the dendritic catalysts were significantly more reactive, although the maximum reactivity per cobalt-unit was achieved with 4-Co-PAMAM **6**.



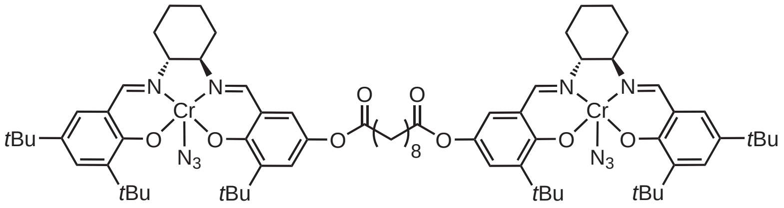
8-Co-PAMAM **6**

4-Co-PAMAM **7**

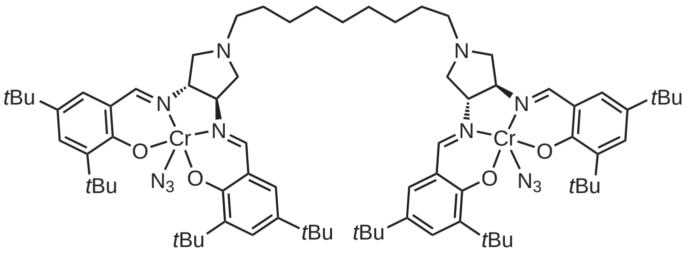
Figure 10. Dendrimer supported salen(Co^{III}) complexes **6** and **7** for enhanced bimetallic cooperative interaction between catalytic sites.[26]

This example was a clear prove for the close proximity and high local concentration of catalytic units in the periphery of a dendrimer and several similar examples have been described in the literature.[21,135,149-152]

An aggravating factor in salen(metal) catalyzed epoxide opening reactions is the dependency of the achieved enantiomeric excess on the orientation of the catalytic units to one another. Jacobsen and coworkers synthesized dimeric salen(Cr^{III}) complexes **9** and **10** to enforce cooperative bimetallic interaction in the so-called head-to-head (**9**) or head-to-tail (**10**) geometry (Figure 11).[148]



10 (head-to-tail dimer)



9 (head-to-head dimer)

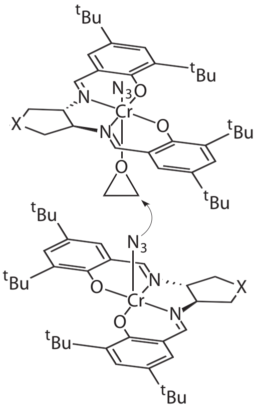


Figure 11. Dimeric salen(Cr^{III}) complexes for asymmetric ring opening reactions and schematic representation of the desired head-to-tail orientation.[148]

It was observed that the head-to-tail arrangement is beneficial for the achievement of high enantioselectivities. With the head-to-head dimer **9**, a very low enantiomeric excess (*ee*) of only 8 % was observed in the ARO of cyclopentene oxide with $TMSN_3$, while the head-to-tail dimer **10** achieved an *ee* of 94 % which is similar to the values obtained with the monomeric analog.

Liese, Haag, and coworkers demonstrated that such a positive dendritic effect can also be obtained when hyperbranched polymers are used as catalyst support.[135] hPG-supported salen(Co^{III}) **11** (Figure 12) was applied in the hydrolytic kinetic resolution of 1,2-epoxyhexane and showed an enhanced activity compared to the monomeric analogue. This was a prove that the hyperbranched backbone promotes cooperative interaction between catalyst units which was before only described for dendrimers. Thus, structural perfection is indeed not necessary and the hyperbranched structure takes a shape similar as compared to a dendrimer.

A problematic aspect of the described approach is the required synthesis of unsymmetrical salen analogues.[133] Due to the labile nature of the imine bond,[153] mixtures of symmetrical and unsymmetrical salen derivatives are obtained which dramatically decreases the yield of the desired derivative. Additionally, the applied build-up of the ligand on the polymeric support can lead to ill-defined species because full conversion of all polymeric functional groups can usually not be guaranteed.

Therefore, the direct coupling of a symmetrical ligand or catalyst to the polymeric support in a final step is highly desirable.

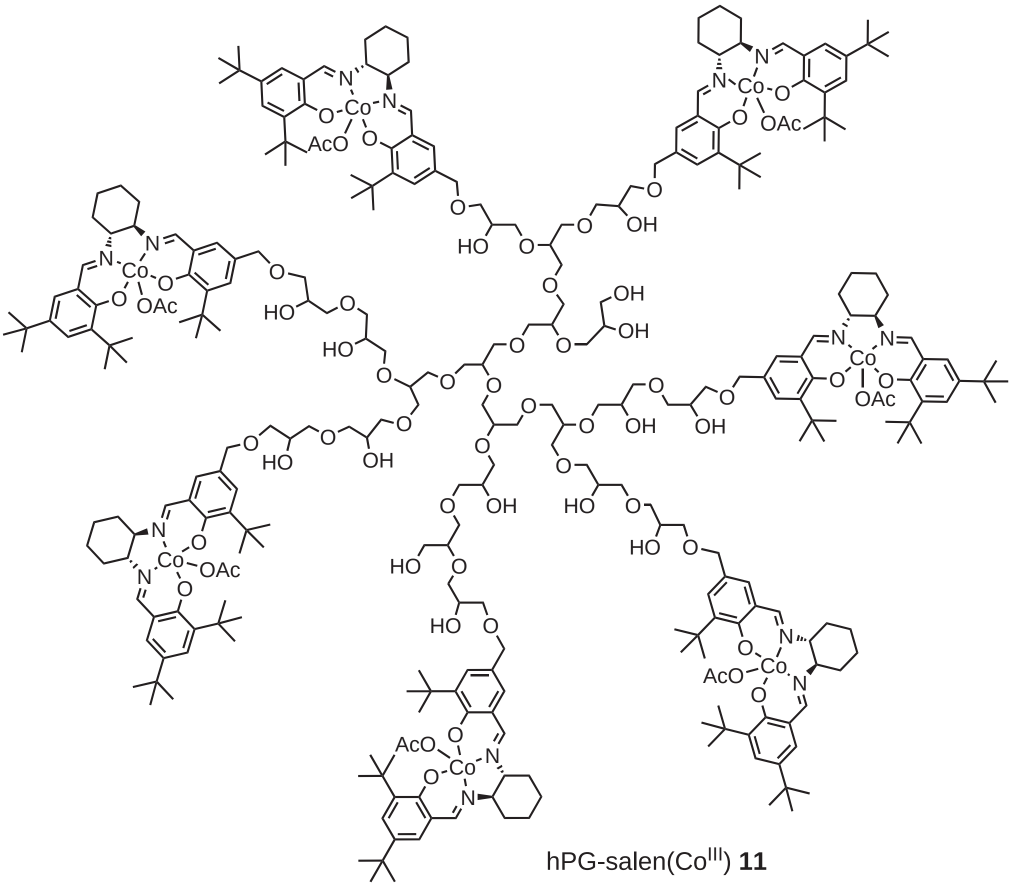
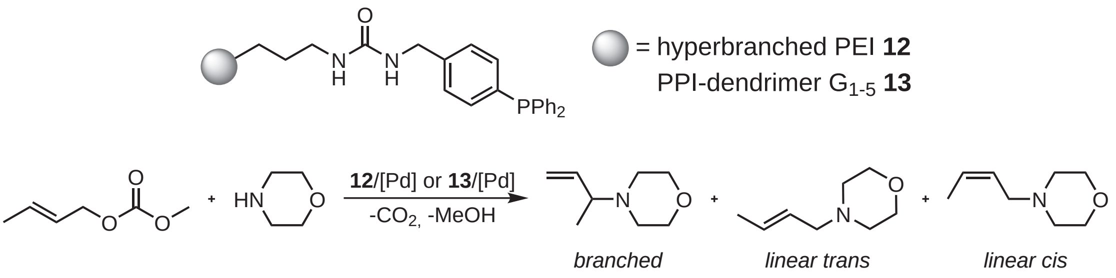


Figure 12. hPG-supported salen(Co^{III}) catalyst for the hydrolytic kinetic resolution of epoxides.[135]

A comparison between inexpensive hyperbranched polymers and perfect dendrimers was reported by Reek, van Leeuwen and coworkers.[121] They compared the performance of Pd-catalysts immobilized on perfectly dendritic poly(propylene imine) (PPI) and hyperbranched poly(ethylene imine) (PEI) (Scheme 4).



Scheme 4. Comparison of catalysts supported on hyperbranched poly(ethylene imine) and PPI-dendrimer in allylic amination with morpholine.[121]

Both catalyst systems catalyzed the allylic amination reaction with morpholine (Scheme 4) and although the PEI supported catalyst **12** was more sensitive to small changes of the ligand/Pd ratio, it showed a higher activity than the perfect PPI catalyst **13**. The selectivity of both catalysts between branched, linear *trans* and linear *cis* products is comparable to that achieved with PPh_3 as Pd ligand. Application in continuous flow processes showed full retention of the macromolecular catalysts by a nanofiltration membrane, but the activity decreased due to loss of palladium.

Chen and coworkers attached TsDPEN derivatives to dendritic structures to use them in Ru^{II} catalyzed asymmetric transfer hydrogenation (ATH) reactions. (Figure 13).[154-156] Asymmetric transfer hydrogenation uses hydrogen sources other than hazardous hydrogen gas and has therefore emerged as a highly attractive method. A number of reviews have been published summarizing the developments in this area.[157-163]

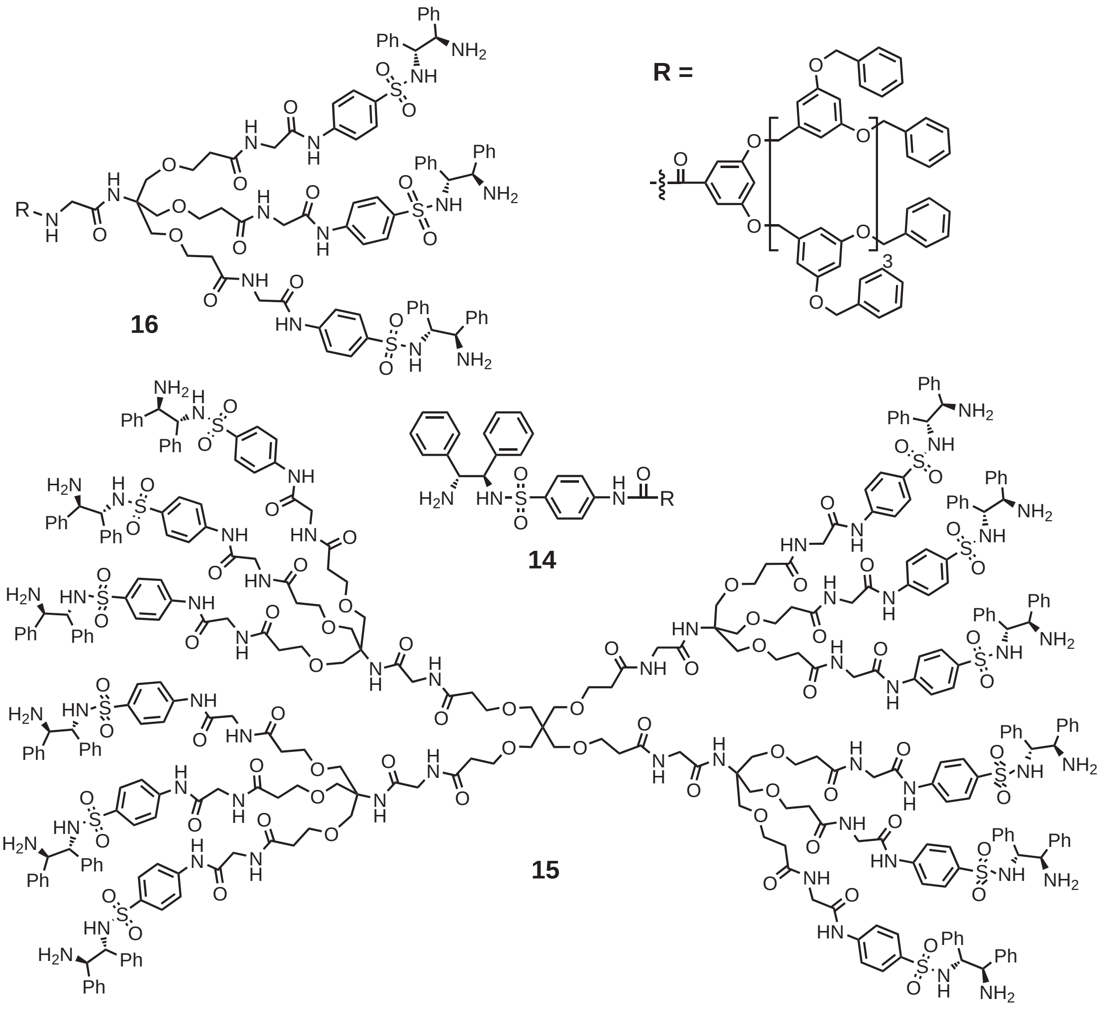
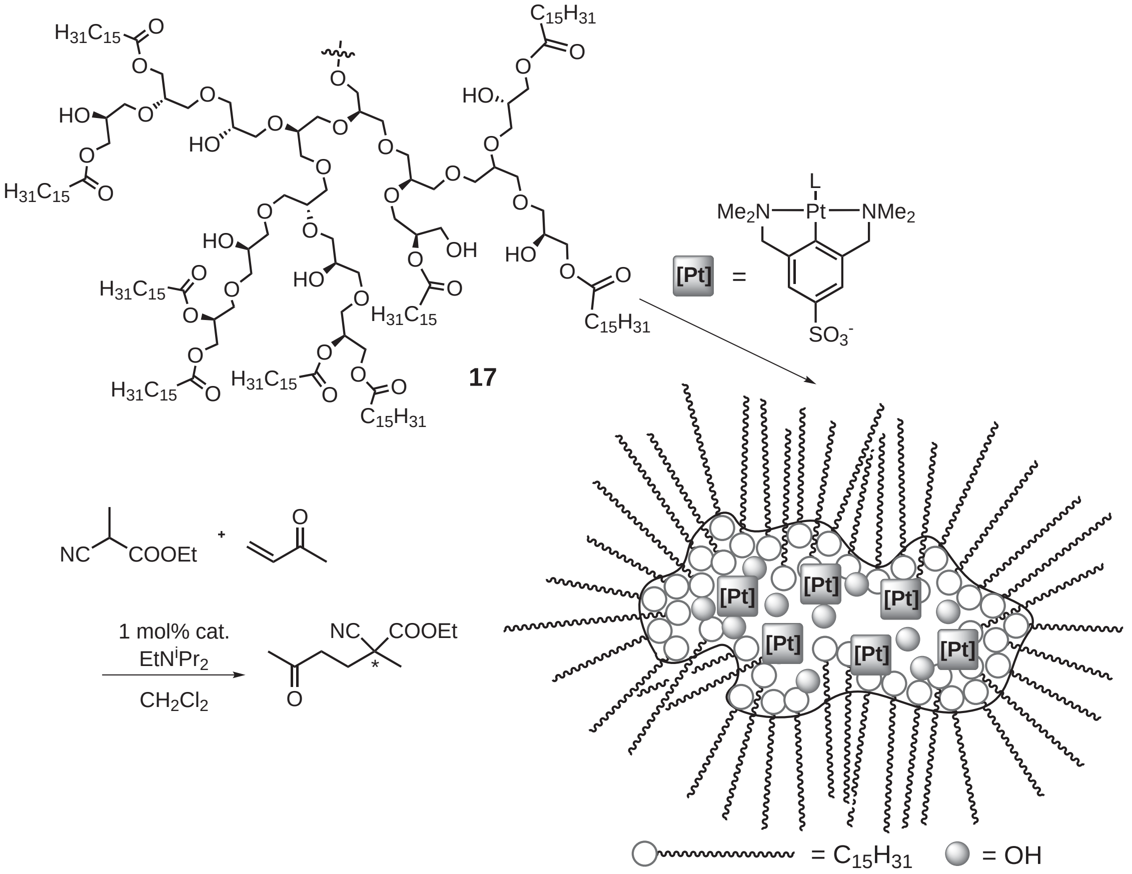


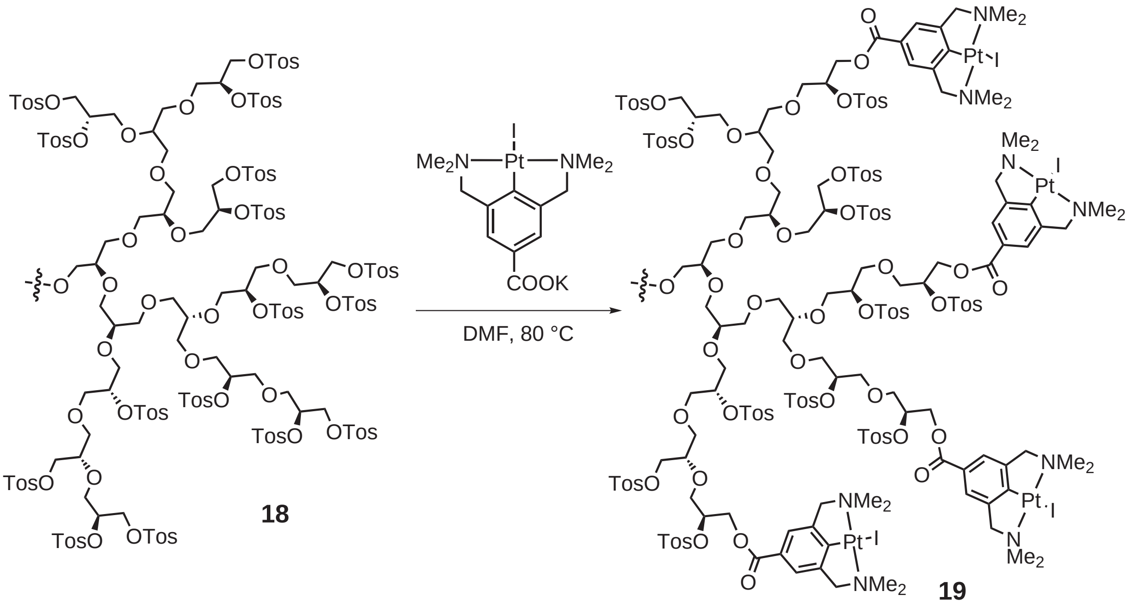
Figure 13. Homogeneously supported TsDPEN derivatives by Chen and coworkers for the Ru^{II} catalyzed asymmetric transfer hydrogenation of prochiral ketones.[154-156]

Dendronized catalyst **14**/Ru^{II} achieved excellent enantioselectivities with acetophenone in the presence of HCOOH/Et_3N as hydrogen donor and was recycled up to six times, with only slightly reduced conversion and *ee* in the sixth run.[154] To increase the catalyst loading the dendritic system **15** with 12 TsDPEN units in the periphery was developed and **15**/Ru^{II} was as selective as the unsupported catalyst (97.7 % *ee* for acetophenone) but it was difficult to achieve an effective recycling.[155] Therefore, a hybrid dendrimer **16** was prepared which achieved similar enantioselectivities in Ru^{II}-catalyzed transfer hydrogenation of acetophenone. [156] Recycling was possible with **16**/Ru^{II}, but did not exceed the performance of **14**/Ru^{II}.

Optically active hPG **1** based polymers **17** and **18** have been developed by Van Koten, Stiriba, Frey and coworkers for the non-covalent encapsulation and covalent attachment of NCN-pincer complexes (Scheme 5a and b).[164-166] Application in an asymmetric Michael-addition reaction revealed that the chiral polymer backbone does not induce chirality in the product. However, the encapsulated as well as the covalently linked platinum complexes were successfully recovered by dialysis and reused.



Scheme 5a. Chiral hPG derivatives for the non-covalent immobilization of NCN-pincer Pt complexes (L = H_2O, OH^-).[164-166]



Scheme 5b. Chiral hPG derivatives for the covalent immobilization of NCN-pincer Pt complexes.[164-166]

Altogether, the application of dendritic and hyperbranched polymers as soluble supports for metal catalysts is a broad field which is still under investigation and offers room for significant improvement. Various key criteria have become apparent that should be fulfilled in order to render the immobilization of a catalyst useful: (1) easy preparation, (2) catalytic performance should be better or at least comparable to the small molecular weight analogue, (3) facile separation with high recovery, (4) easy recycling without loss of activity or selectivity, (5) high stability under the reaction conditions, and (6) low leaching of the active species.[167]

1.3 Homogeneously Stabilized Metal Nanoparticles for Catalysis

Supported noble metals, e.g., Pd, Pt, Rh, Ru, Ni, and Cu, are typical catalysts for preparative hydrogenation reactions.[168] Since only the surface atoms are active, very small particles of the metal have to be highly dispersed in order to give a high specific surface area.[169]

Metal nanoparticles are characterized by their small size and during the last decades they have attracted increasing attention owing to their unique properties in comparison to the bulk metal or single metal ions.[170] The large surface-to-volume ratio renders them incredibly attractive for catalytic applications,[171-174] but they have also been investigated in fields like microelectronics,[175] chemical sensing, [176] data storage,[177] or biomedical applications.[178]

Due to their small size, they are very prone to agglomeration which in most cases leads to loss of the desired properties, e.g., activity or selectivity in catalysis. Therefore, one of the major challenges is the efficient stabilization of metal nanoparticles without passivating their active surface atoms.[171] Additionally, control of the size, shape, composition, and solubility is highly desirable to be able to tune the activity and selectivity of nanoparticles for catalytic applications.[179]

The majority of metal nanoparticle stabilization is accomplished with heterogeneous materials, like metal oxides or carbon supports, and a number of recent reviews is available dealing with heterogeneously supported metal nanoparticles.[169,180-182] Heterogeneous immobilization can be accompanied by a partial passivation of the active sites by the support. Therefore, it is desirable to develop new supports for metal nanoparticles in solution which are able to maintain the advantages of heterogeneous supports, such as easy recovery and high stability, and overcome the mentioned problems of stabilization and surface accessibility.

Synthesis of metal nanoparticles can be achieved by two methods. Mechanical fragmentation of metallic aggregates (physical method) usually leads to rather large particles (> 10 nm) with very broad size distributions and is rarely reproducible.[171] Therefore, today the direct chemical reduction of a respective metal salt in solution in presence of a suitable stabilizer is the most frequently used approach. Other approaches include thermal, photochemical, or sonochemical decomposition of organometallic precursors, ligand displacement reactions from organometallic compounds, condensation of atomic metal vapor, or the reduction by electrochemical methods.[171]

1.3.1 Stabilization Approaches

The stabilization of metal nanoparticles in solution is either achieved by electrostatic or steric interactions (Figure 14) and one can further distinguish between (1) electrostatic stabilization by surface adsorbed anions, (2) steric stabilization by the presence of bulky groups, (3) the combination of these two approaches, resulting in electrosteric stabilization with surfactants, and (4) stabilization with a ligand.[171]

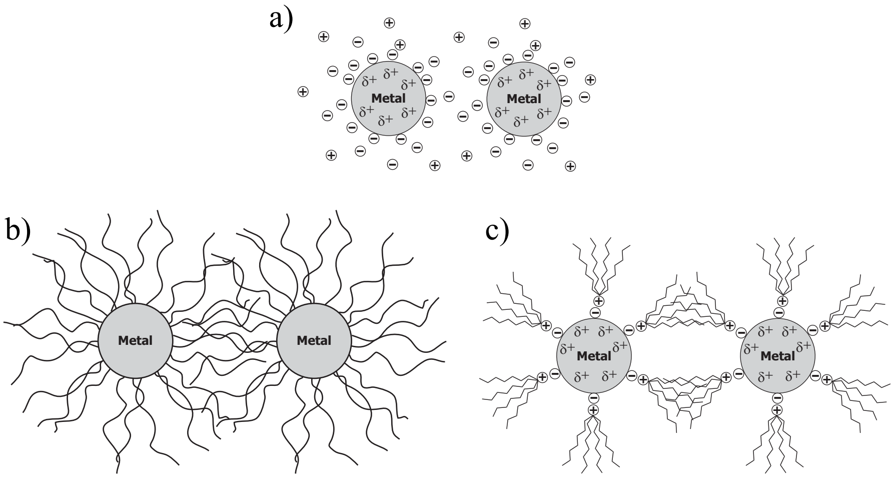


Figure 14. Schematic representation of (a) electrostatic, (b) steric, and (c) electrosteric stabilization of metal nanoparticles.[171,183]

Electrostatic stabilization is generated by ionic compounds such as halides, carboxylates, or polyoxoanions dissolved in solution. The adsorption of these compounds and their counterions on the metallic surface generates an electrical double-layer around the particles (Figure 14a), resulting in a Coulombic repulsion.[184] Unfortunately, these systems are very sensitive towards changes of ionic strength or temperature.[171]

Steric stabilization is achieved by macromolecules such as polymers or oligomers which adsorb at the particles surface and provide a protective layer (Figure 14b).[171] In contrast to electrostatic stabilization which is mainly used in aqueous medium, steric stabilization can be used in both, aqueous and organic, media. Fine-tuning of the stabilization can be achieved by changing the length and/or nature of the adsorbed macromolecules.

Electrosteric stabilization combines electrostatic and steric interactions (Figure 14c), and is generally provided by means of ionic surfactants.[185-187] These compounds consist of a polar headgroup which can generate an electric double layer and an oligomeric or polymeric side chain providing steric repulsion.

Stabilization by a ligand occurs by coordination of metallic nanoparticles with ligands such as phosphines,[188-191] thiols,[192-194] amines,[195] or carbon monooxide.[196] Stabilization by a solvent has also been reported, but is not very common.[197]

1.3.2 Separation of Metal Nanoparticles Stabilized in Solution

Only sterically or electrosterically stabilized metal nanoparticles can be efficiently recovered from reaction mixtures and eventually be reused. In principle, the methods described for the separation of homogeneously supported metal complexes from reaction mixtures are also applicable to polymer-stabilized metal nanoparticles, but examples in the literature are rare.

Precipitation of polymer stabilized metal nanoparticles is a straightforward approach that only requires the insolubility of the stabilizing polymer under certain conditions (solvent, temperature, pH). This approach has been applied by Marty, Mingotaud, and coworkers who were able to reversibly precipitate bolaamphiphile surfactant stabilized gold nanoparticles by changing the pH.[187] Astruc and coworkers precipitated palladium-dodecanethiolate nanoparticles after Suzuki-Miyaura reaction and were able to reuse the catalyst for six consecutive runs with only slightly decreased activity.[198]

Liquid-liquid extraction is the most common approach for the separation of metal nanoparticles stabilized by water-soluble compounds, in fluorous systems or ionic liquids. Roucoux and coworkers applied ammonium salt stabilized rhodium nanoparticles to the hydrogenation of arenes under biphasic conditions.[199] Recovery of the catalyst was achieved by phase separation and recycling was performed for five consecutive runs with stable activity.

Membrane filtration techniques are also easily adaptable and ultrafiltration has been reported for the separation of Pd nanoparticles after use in a hydrogenation reaction.[200] The application of palladium nanoparticles for cyclohexene hydrogenation in a continuously operated membrane reactor has been reported by Mecking, Vogt, and coworkers.[201] A hyperbranched core-shell polymer with a hydrophobic outer shell efficiently stabilized palladium nanoparticles and after 28 reactor volumes the activity was only decreased by 25 %.

Purification by centrifugation or size exclusion chromatography (SEC) was described by Feldheim, Franzen, and coworkers for molecularly bridged gold nanoparticle dimers, trimers, and tetramers.[202]

An interesting approach is the utilization of magnetite nanoparticles decorated with catalytically active metal nanoparticles (Figure 15).[203,204] After reaction, the catalyst can be easily recovered by application of an external magnetic field and decantation.

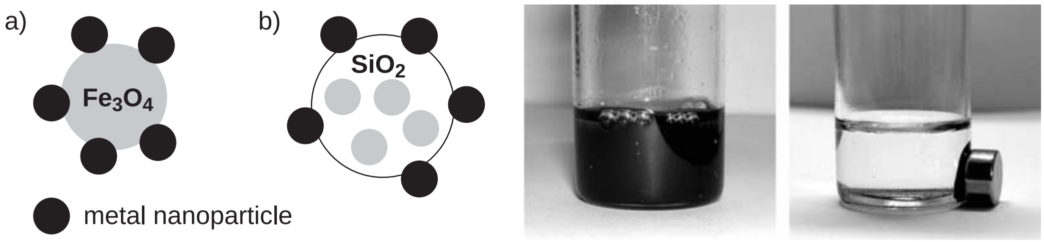


Figure 15. Catalytically active nanoparticles supported on (a) magnetic particles[203] and (b) silica coated Fe_3O_4.[204]

The leaching issue in homogenized metal nanoparticle catalysis is even more important[183] than for supported metal complexes. The presence of nanoparticles does not ensure that these are the true catalyst. For C-C coupling reactions for example, leaching of Pd atoms and/or ions is a key issue and has been discussed extensively. The question whether low coordination sites on the clusters[205,206] or Pd atoms or ions[207-209] catalyze the reaction is still not solved, but leaching of Pd atoms and ions from Pd nanoparticles in Heck and Suzuki reactions has been proven.[210,211]

1.3.3 Soluble Polymers as Stabilizer for Catalytically Active Metal Nanoparticles

In this chapter only neutral polymeric stabilizers will be discussed and the same classification as described for supports of metal complexes is used, i.e. linear and branched polymer architectures will be discussed separately.

1.3.3.1 Linear Polymers for the Stabilization of Metal Nanoparticles

The application of homopolymers for the stabilization of catalytically active metal nanoparticles is dominated by poly(*N*-vinyl-2-pyrrolidone) (PVP, Figure 16).[212-214]

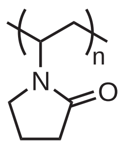


Figure 16. Chemical structure of poly(*N*-vinyl-2-pyrrolidone) (PVP).

In contrast, block copolymers have found widespread application for the stabilization of metal nanoparticle catalysts. They consist of two or more homopolymer subunits which are covalently linked and can have different properties. Depending on the amount of blocks, di- or triblock copolymers are obtained. If the units of a block copolymer have different solubility properties, they are amphiphilic and can self assemble to form micelles which can encapsulate metal nanoparticles.[200] A number of block copolymers like Pluronics,[215-218] poly(ethylene oxide)-*block*-polystyrene-*block*-poly(4-vinylpyridine),[219] poly(ethylene oxide)-*block*-poly-2-vinylpyridine,[200] poly(ethylene imine)-*block*-poly(ethylene oxide),[220] or polystyrene-*block*-poly-4-vinylpyridine[221] have been used to stabilize metal nanoparticles. However, application to catalysis is only rarely described.

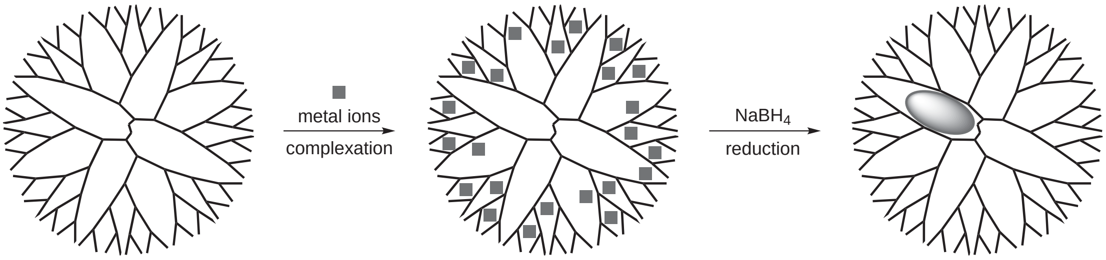
1.3.3.2 Branched Polymers for the Stabilization of Metal Nanoparticles

The classification of branched polymer architectures into star polymers, dendrimers, and hyperbranched polymers has already been described above. While star polymers are only rarely applied to stabilize metal nanoparticles,[222] the use of dendrimers is as well explored as their use for the immobilization of metal complexes.

Since the initial reports about dendrimer encapsulated metal nanoparticles in 1998 by the groups of Crooks,[223] Tomalia,[224] and Esumi[225] this research area expanded rapidly and to date a number of reviews about dendrimer-stabilized nanoparticles and their various applications are available.[172,179,226,227]

As outlined by Crooks[179] dendrimers are particularly suitable for the encapsulation of metal nanoparticles because due to their well-defined composition and structure, they afford well defined nanoparticles which are stabilized within the dendritic structure and therefore cannot agglomerate. The dendritic host only stabilizes by steric effects and does not passivate the surface of the nanoparticles which are able to participate in catalytic reactions. Tailoring of the dendrimer properties can be used to control the solubility of the nanocomposite or to control access of molecules to the encapsulated metal nanoparticle. Thereby the branches are employed as selectivity gates, allowing or refusing access of molecules.[223,228]

The synthesis of metal nanoparticles inside dendrimers can be achieved by two methods.[179] The direct reduction of dendrimer/metal ion composites or by intradendrimer metal-displacement reactions of Cu^0 nanoparticles with more noble metal ions.[229] In case of direct reduction, the metal ions first have to be encapsulated either in the core or at the periphery of the dendritic structure by coordination to heteroatoms of the dendrimer (Scheme 6). This is similar to the “ship in a bottle” approach described earlier for the encapsulation of metal complexes in porous materials. Subsequent reduction of the metal ions leads to dendrimer encapsulated zero-valent nanoparticles.[223] In this process, the size of the resulting nanoparticles can be controlled by the type and generation of the dendrimer, as well as the ratio of metal ions per dendrimer.[230]



Scheme 6. Nanoparticle synthesis as postulated by Crooks.[226]

Thereby the question arises whether the metal nanoparticles are really situated in the core or if rather dendrimers are adsorbed around a nanoparticle (Figure 17) or if the dendritic core is even encapsulated in the nanoparticle.[172] This has only been directly addressed in a few publications by Esumi and Crooks.[227,231,232] The general answer is that it depends on the size of dendrimer and nanoparticle, the surface and internal functional groups of the dendrimer, and the nature of the nanoparticle if an inter- or intradendrimer complex is formed, or a mixture of both is present.

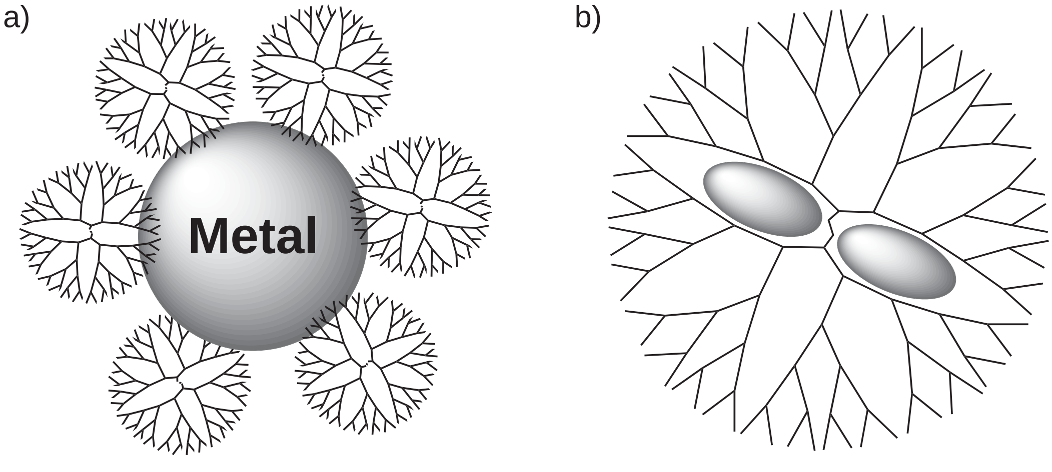
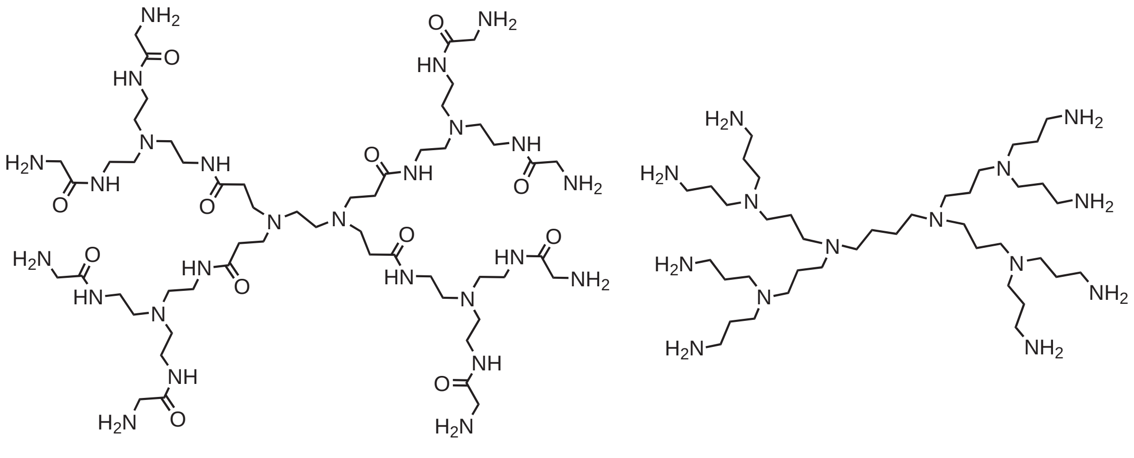


Figure 17. Possible stabilization mechanisms: (a) intermolecular and (b) intramolecular dendrimer-nanoparticle complexation.[231]

Encapsulation of 1-3 nm diameter nanoparticles within single dendrimers has been shown by TEM staining studies and small-angle X-ray scattering (SAXS) analysis.[233] Additionally, the generation dependent selectivity in catalytic reactions is a strong indication for the formation of intradendrimer encapsulated nanoparticles.[232] If the nanoparticles are significantly bigger than the cavities in the stabilizing dendrimer, interdendrimer complexes have to be formed but it is difficult to prove if the dendrimer is encapsulated in the nanoparticle during formation or if it only adsorbs on the surface.



G1 PAMAM Dendrimer

G1 PPI Dendrimer

Figure 18. Structures of the first generations of the two commercially available dendrimers poly(amido amine) (PAMAM) and poly(propylene imine) (PPI).

The two families of commercially available dendrimers most frequently used for the encapsulation of metal nanoparticles are shown in Figure 18. In general, PPI dendrimers are smaller than PAMAM (2.8 nm versus 4.5 nm for the fourth generation), but significantly more stable (470 °C versus 100 °C respectively).[179] Dendrimer encapsulated nanoparticles in catalysis have been mainly used for hydrogenation reactions, but also a range of C-C coupling reactions were reported.[172,179,226,227,234]

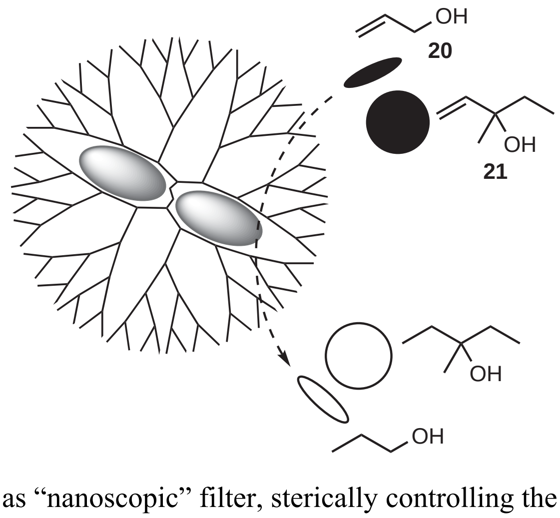
Due to the easier synthesis of hyperbranched polymers, they are attractive alternatives for dendrimers.[30] Although their structure is less defined, they exhibit similar properties as dendrimers and are similarly suited for the stabilization of metal nanoparticles. The question of the nanoparticle location arises here as well and is even more difficult to answer. No reports referring to this can be found in literature but it can be assumed that similar criteria are applicable as described for perfect dendrimers.

Catalytic applications of metal nanoparticles stabilized by hyperbranched polymers have been mainly reported for hydrogenation,[201,235-237] and the following chapter presents selected examples with special emphasis on recycling and selectivity issues.

1.3.4 Homogeneously Stabilized Metal Nanoparticles for Catalysis

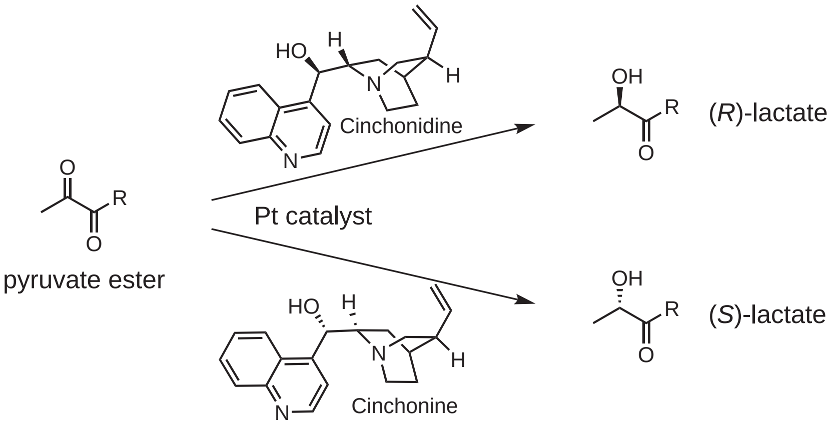
Stabilization of metal nanoparticles in dendritic polymer architectures offers the possibility to control the solubility properties of the resulting catalyst by fine-tuning the polymer structure. Additionally, by changing the dendrimer generation or the functional groups in the periphery the stabilizer can be used as "nanoscopic" filter, controlling the access of molecules to the catalytically active center.

This was demonstrated by Crooks and coworkers, who prepared PAMAM stabilized Pd and Pt nanoparticles for use in homogeneous hydrogenation reactions.[228] High catalytic activity was observed for the hydrogenation of *N*-isopropyl acrylamide and allyl alcohol in aqueous solution. It was shown that the hydrogenation rate can be controlled by using dendrimers of different generations. In a later study the selectivity of the dendrimer branches was demonstrated by hydrogenating a mixture of allyl alcohol **20** and the more bulky 3-methyl-1-penten-3-ol **21** with PAMAM-G4/Pd^0 as catalyst (Scheme 7).[232] After 2.5 hours 50 % of the allyl alcohol **20** was reduced while only 1.6 % of **21** was converted; after an additional 2.5 hours 100 % of **20** and only 11 % of **21** were hydrogenated. This experiment clearly demonstrated the ability of the dendrimer branches to act as a "nanoscopic" filter.



Scheme 7. Dendrimer as "nanoscopic" filter, sterically controlling the access of substrates to the catalytically active Pd nanoparticles.[232]

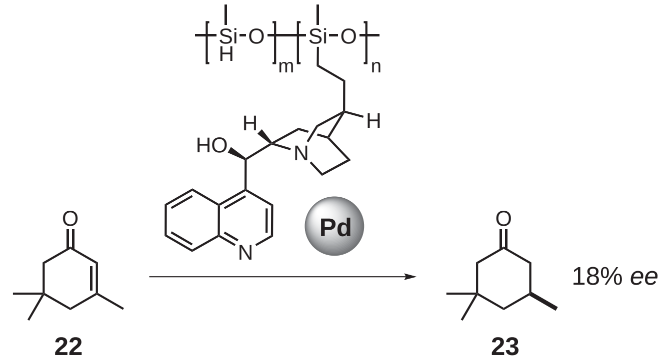
When soluble polymers are used as nanoparticle support, the question arises if and how much the adsorption of the polymer passivates or blocks the catalytically active surface. This is particularly interesting for asymmetric hydrogenation reactions, where the metal surface has to be modified by adsorption of a chiral reagent.[11] Pt catalysts, e.g., commercial 5 % Pt/Al_2O_3, modified with cinchona alkaloids are nowadays among the most selective catalysts for the hydrogenation of α-keto acid derivatives (Scheme 8) and other activated keto groups.[238,239]



Scheme 8. Enantioselective hydrogenation of pyruvate esters with cinchona alkaloid modified Pt catalysts.[238]

To investigate if polymer stabilized Pt nanoparticles can be successfully modified, Bradley and coworkers compared the catalytic performance of PVP-stabilized Pt nanoparticles with commercial 5 % Pt/Al_2O_3.[240-243] They were able to demonstrate that PVP does not hinder access of the modifier to the surface, but may by adsorption reduce the number of surface-modified sites available for the enantioselective hydrogenation.[241] However, enantioselectivities of up to 97.6 % *ee* for (*R*)-methyl lactate were reported for the asymmetric hydrogenation of methyl pyruvate with PVP-stabilized Pt nanoparticles which is similar to results obtained with commercially available Pt/Al_2O_3.[242] Other approaches utilized Pt nanoparticles stabilized by solvent,[197] surfactant,[244] or the chiral alkaloid itself.[245] Only in case of surfactant stabilized Pt nanoparticles, recycling for up to three consecutive runs with up to 55 % *ee* has been reported.[244]

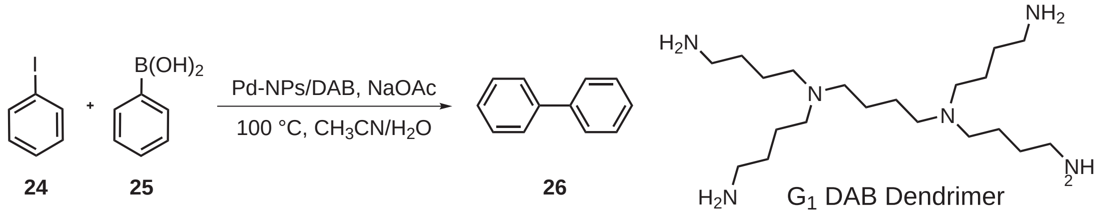
An interesting approach by Marty and coworkers described the synthesis of a polysiloxane polymer with covalently attached cinchonidine moieties (Scheme 9).[246] Therein stabilized Pd nanoparticles were investigated in the asymmetric hydrogenation of isophorone **22** under mild conditions (2 bar hydrogen pressure), achieving 18 % *ee* which is similar to other reports in literature.



Scheme 9. Pd nanoparticles stabilized in olysiloxane polymer with covalently attached cinchonidine moieties for the asymmetric hydrogenation of isophorone.[246]

The authors claim that this catalyst system is generally applicable to a range of catalytic reactions where cinchonidine is used to modify the surface of a metal nanoparticle. However, it has to be taken into account that at higher hydrogen pressures, cinchonidine is hydrogenated as well and thereby looses its catalytic properties.[247,248]

Astruc and coworkers prepared (diamino butane) (DAB) dendrimers of five generations to support Pd nanoparticles with sizes between 1.7-2.8 nm.[249] The catalytic performance in the Suzuki-Miyaura cross-coupling reaction between iodobenzene **24** and phenylboronic acid **25** (Scheme 10) was studied. For low generation dendrimers a higher activity was observed, but also the Pd nanoparticles had an increased tendency to aggregate and form Pd black. In this case, stability could only be achieved at the expense of catalytic activity or vice versa. Recovery was possible by phase separation of the water-soluble catalyst, but a second run revealed a significantly decreased activity.



Scheme 10. Suzuki-Miyaura cross-coupling reaction between iodobenzene **24** and phenylboronic acid **25**.[249]

A new hyperbranched PAMAM analogue (HYPAM, Figure 19) was introduced by Marty and coworkers for the stabilization of gold nanoparticles in water.[250,251] Similarly stabilized Pt nanoparticles were utilized for the selective hydrogenation of the C=C versus C=O double bond of isophorone **22** (Scheme 9).[237] Although the catalytic activity was relatively low, recycling for 10 runs was possible without decrease in activity or selectivity.

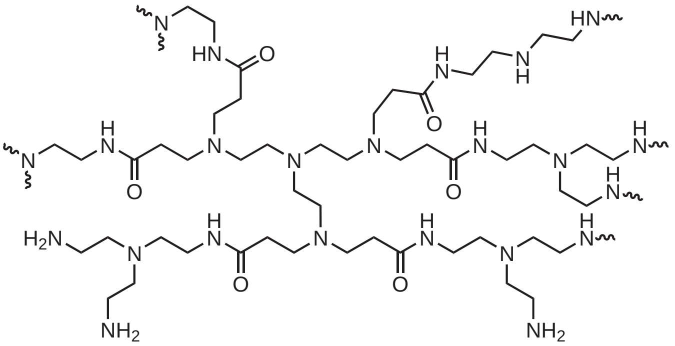


Figure 19. Structure of HYPAM, a hyperbranched PAMAM analogue.[250]

Mecking and coworkers introduced hyperbranched polyglycerol with a hydrophobic shell **17** (see Scheme 5) for the synthesis of Pd nanoparticles in organic solvents such as toluene or chloroform.[235] These carriers permitted high metal loadings (one Pd per 2 OH groups of the polymer) as well as repeated drying and redispersion of the stabilized nanoparticles. Hydrogenation of cyclohexene as model reaction showed a slightly higher activity for the developed catalyst than with Pd/C. The catalyst could be recovered by distillation, dialysis, or ultrafiltration, whereby no metal deposition on the membrane was observed. Additionally, the successful application in a continuously operated membrane reactor was demonstrated.[201] After 28 reactor volumes the total turnover number was increased to 29000, while the activity was only reduced by 25 % which was ascribed to deposition of Pd on the reactor membrane.

The area of homogeneously stabilized nanoparticles for application in catalysis still has high need for improvement. In the future, metal nanoparticle catalysts should fulfill certain criteria: (1) specific size (1–10 nm), (2) well-defined surface composition, (3) isolable and redissolvable (“bottleable”), (4) high catalytic activity in solution with reproducible performance, (5) long lifetime, and (6) high reusability with low leaching.[171]

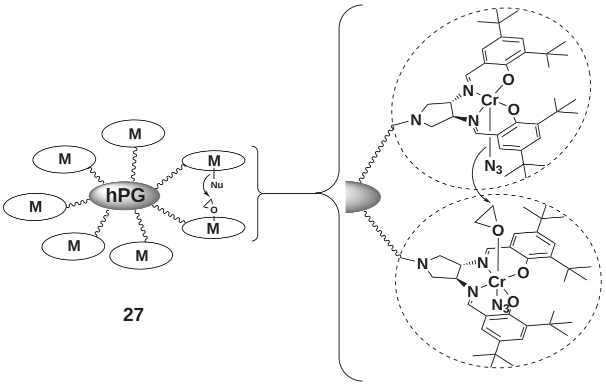
2 Scientific Goals

As outlined in the introduction, the efficient recovery and reuse of transition metal catalysts is a major objective in this research project. Thereby, catalyst immobilization on soluble polymeric supports is especially attractive because it permits to combine homogeneous reaction conditions with facilitated separation. The aim of this work is the application of hyperbranched polyglycerol **1** as support for various transition metal catalysts. Its versatile applicability should be demonstrated with two different approaches: (1) homogeneous metal complex conjugation and (2) stabilization of catalytically active metal nanoparticles. Major focus will be on the recyclability of the developed systems as well as the influence of immobilization on the catalytic performance.

2.1 Covalent Immobilization of Chiral Transition Metal Complexes on Dendritic Polyglycerol

For the covalent attachment of metal complexes to a support, an efficient synthesis strategy with a tunable linker is desirable to avoid loss of the precious ligand during catalyst synthesis and to facilitate investigations on the influence of linker type or length on the catalytic performance.

The first subproject is concerned with the immobilization of salen ligands onto hyperbranched polyglycerol **1**. As described in the introduction, salen(Cr^{III}) or salen(Co^{III}) complexes are powerful catalysts for asymmetric ring opening reactions of epoxides. Since the immobilization of asymmetric salen ligands suffers from low yields and ill-defined species on the support, a symmetrical salen ligand based on pyrrolidine shall be immobilized via attachment of a linker at the pyrrolidine moiety (Figure 20).

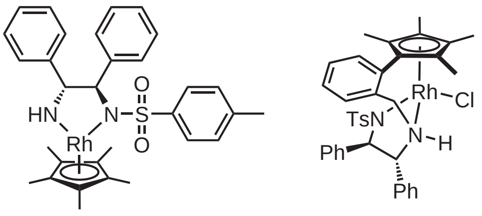


27

Figure 20. Schematic representation of hPG-supported pyrrolidine salen(Cr^{III}) catalyst **27**.

The application of the salen(Cr^{III}) catalyst **27** in the asymmetric ring opening of *meso* epoxides shall be used to investigate the influence of the linker on the catalytic performance. As already outlined in the introduction, this reaction proceeds via a bimetallic cooperative mechanism and the achieved enantioselectivity strongly depends on the orientation of the catalytic units to one another. Attachment of salen(Cr^{III}) to hPG **1** via the pyrrolidine backbone should first of all lead to an enhancement of the reaction rate and the obtained enantiocontrol is expected to be strongly dependent on the length of the linker between the pyrrolidine salen(Cr^{III}) complex and hPG **1**.

In the second subproject an efficient immobilization strategy for a tethered TsDPEN-Rh^{III} catalyst **28** (Figure 21) shall be developed that enables the attachment to various amine functionalized supports.



29 **28**

Figure 21. Original TsDPEN Rh^{III} catalyst **29** and tethered variant **28** for asymmetric transfer hydrogenation reactions.

The tethered variant of TsDPEN[252] shall be immobilized onto hPG **1** and is supposed to be significantly more stable than immobilized versions of the original catalyst **29**. In cooperation with the group of Prof. Schomäcker (Technical University Berlin) and PolyAn GmbH, the tethered variant of **28** should also be immobilized onto different solid supports to compare the performance of soluble and solid supported catalysts.

2.2 Homogeneous Stabilization of Metal Nanoparticles and Application to Catalysis

For the synthesis and stabilization of metal nanoparticles in solution, an efficient stabilizer is required which is suitable for the synthesis of various transition metal nanoparticles and enables size control, extended storage, and transfer to organic solvents. Concurrently, for catalytic purposes the adsorption of stabilizer on the metal surface should not be too strong in order to avoid reduction of the catalytic activity.

Core-multishell architectures composed of a hydrophilic core, hydrophobic inner shell, and hydrophilic outer shell (Figure 22) have been initially developed in our group for the solubilization and transport of drugs and dyes[253,254] and shall now be tested for the homogeneous stabilization of catalytically active metal nanoparticles.

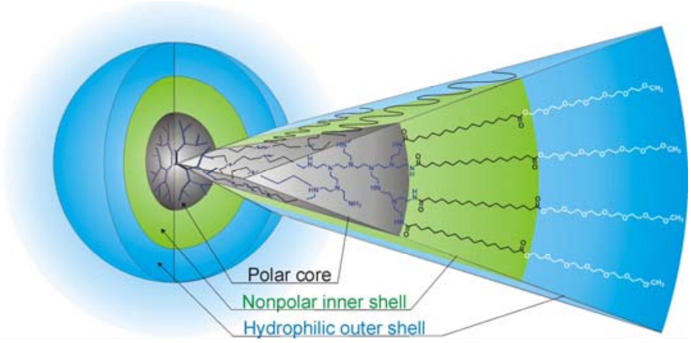


Figure 22. Schematic representation of PEI-based core-multishell architecture developed by Haag and coworkers.[253]

The first objective is to establish the applicability of those core-shell architectures to metal nanoparticle synthesis and stabilization. For this purpose the known systems (Figure 22) will be used for the synthesis of gold nanoparticles, whose formation and aggregation can be easily followed by UV/Vis.

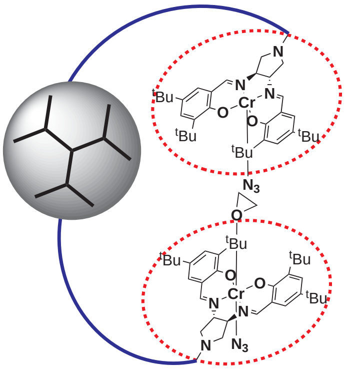
For catalytic applications, the PEI core might be problematic because amine groups are known to coordinate strongly to metals which can reduce the catalytic activity. Therefore, hPG **1** based core-multishell structures should be used whose properties can be further adjusted by modularly changing the shell building blocks. Initially, simple hydrogenation reactions with catalytically active Pt nanoparticles are envisioned to test the accessibility of the metal surface for hydrogen and substrates, and to establish a recycling procedure based on membrane filtration. In cooperation with the group of Prof. Schomäcker, the recycling via phase separation and the catalytic activity in consecutive cycles should be investigated.

Another interesting question that shall be addressed is the chiral modification of the nanoparticles surface to achieve asymmetric hydrogenation with a formerly unselective catalyst. Does the core-multishell stabilizer allow for an efficient modification of the metal surface with the chiral cinchona alkaloids? Since the asymmetric hydrogenation of α-keto esters is known to be strongly dependent on the reaction conditions a detailed optimization of the reaction conditions should be performed and the applicability of the formerly developed recycling procedure should be investigated.

3 Publications and Manuscripts

3.2 Covalent Immobilization of Chiral Metal Catalysts

3.2.1 Intramolecular Acceleration of Asymmetric Epoxide Ring-Opening by Dendritic Polyglycerol Salen–Cr^{III} Complexes

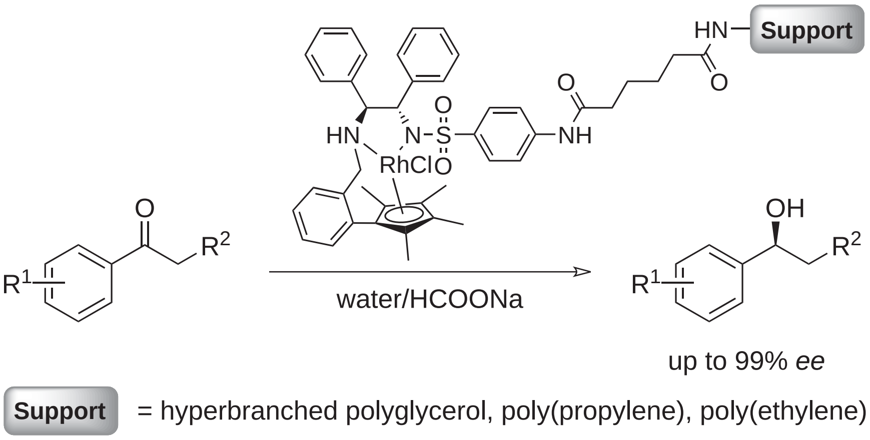


This chapter was published in the following journal:

J. Keilitz, R. Haag, *Eur. J. Org. Chem.* **2009**, 3272-3278 (DOI: 10.1002/ejoc.200900241).

http://onlinelibrary.wiley.com/doi/10.1002/ejoc.200900241/abstract

3.2.2 Immobilization of a Tethered Rh^{III}-TsDPEN Catalyst on Soluble and Solid Polymeric Supports and Successful Application to Asymmetric Transfer Hydrogenation of Ketones



This chapter was published in the following journal:

J. Dimroth, J. Keilitz, U. Schedler, R. Schomäcker, R. Haag, *Adv. Synth. Catal.* **2010**, *in print* (DOI: 10.1002/adsc.201000340).

http://onlinelibrary.wiley.com/doi/10.1002/adsc.201000340/abstract

3.3 Homogeneous Stabilization of Catalytically Active Metal Nanoparticles

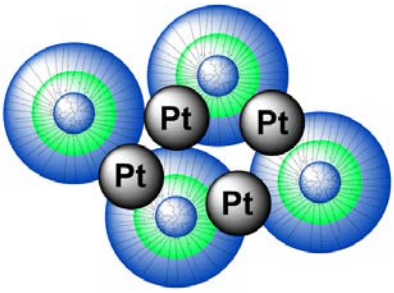
3.3.1 Dendritic Polymers with a Core-Multishell Architecture: A Versatile Tool for the Stabilization of Nanoparticles

This chapter was published in the following journal:

J. Keilitz, M. R. Radowski, J.-D. Marty, R. Haag, F. Gauffre, C. Mingotaud, *Chem. Mater.* **2008**, *20*, 2423-2425 (DOI: 10.1021/cm8002639).

http://pubs.acs.org/doi/abs/10.1021/cm8002639

3.3.2 Homogeneous Stabilization of Pt Nanoparticles in Dendritic Core-Multishell Architectures: Application in Catalytic Hydrogenation Reactions and Recycling

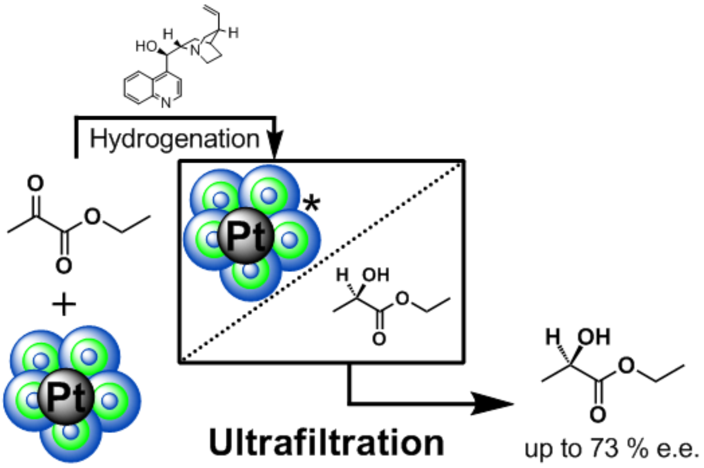


This chapter was published in the following journal:

J. Keilitz, M. Schwarze, S. Nowag, R. Schomäcker, R. Haag, *ChemCatChem* **2010**, *2*, 863-870 (DOI: 10.1002/cctc.201000013).

http://onlinelibrary.wiley.com/doi/10.1002/cctc.201000013/abstract

3.2.3 Chirally Modified Platinum Nanoparticles Stabilized by Dendritic Core-Multishell Architectures for the Asymmetric Hydrogenation of Ethyl Pyruvate



This chapter was published in the following journal:

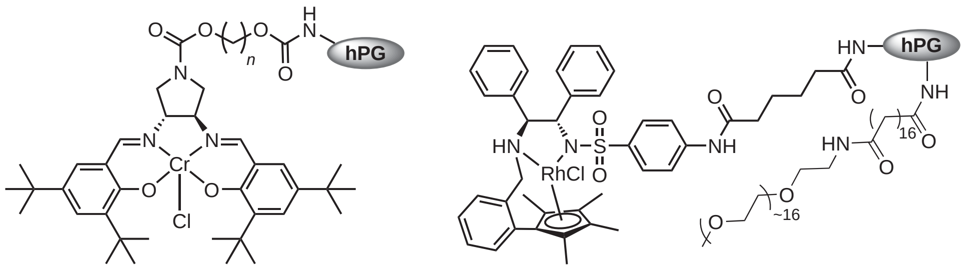
J. Keilitz, S. Nowag, J.-D. Marty, R. Haag, *Adv. Synth. Catal.* **2010**, *352*, 1503-1511 (DOI: 10.1002/adsc.201000128).

http://onlinelibrary.wiley.com/doi/10.1002/adsc.201000128/abstract

4 Summary and Conclusion

In this work, hyperbranched polyglycerol **1** was evaluated as soluble support for the immobilization of various catalytic systems. Two major approaches have been investigated: (1) the covalent immobilization of chiral metal complexes and (2) the non-covalent stabilization of catalytically active metal nanoparticles.

In the first part it was shown that hPG **1** is a suitable support for the covalent attachment of chiral metal complexes, as demonstrated with the successful synthesis of pyrrolidine salen(Cr^{III}) catalyst **30** and a tethered TsDPEN-Rh^{III} catalyst **31** (Figure 23).

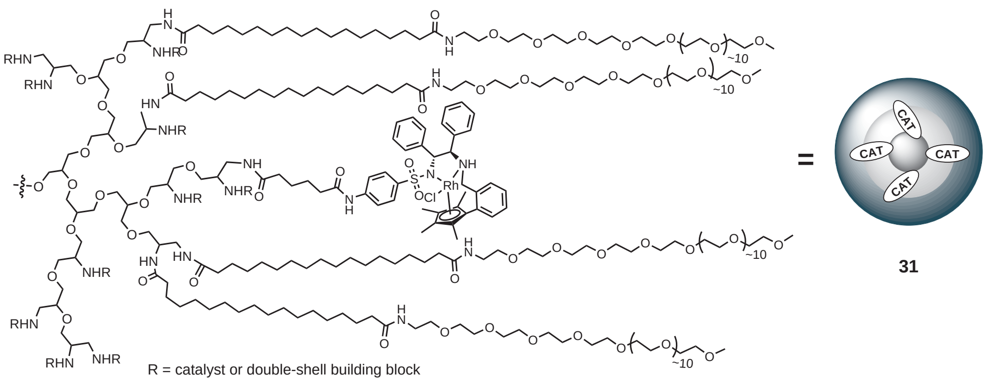


30a-d (n = 0, 6, 10, 18)

31

Figure 23. Structures of hPG **1** supported catalysts: pyrrolidine salen(Cr^{III}) **30** and tethered TsDPEN-Rh^{III} complex **31**.

For pyrrolidine salen(Cr^{III}) catalyst **30**, a positive dendritic effect with regard to the reaction rate was observed in the asymmetric ring opening of *meso* epoxides with TMSN$_3$. This reaction proceeds via a cooperative bimetallic mechanism. The observed rate enhancement proves that attachment to hPG **1** leads to a higher local concentration of catalytic units and therefore promotes cooperative interaction. It becomes apparent that perfect dendrimers as catalyst supports can be efficiently replaced by hyperbranched polymers without loosing the beneficial properties. The enantioselective outcome of the investigated reaction is known to depend on the orientation of two cooperating salen units to one another. With catalyst **30a** only the unfavorable orientation is obtained, leading to low enantioselectivities of 22 % *ee* (1 mol% catalyst loading). The introduction of linkers of different length (C$_6$, C$_{10}$, and C$_{18}$) allowed a bigger fraction of favorable interactions via backfolding and the *ee* could be increased to 48 % with catalyst **30c** (C$_{10}$). Additionally, efficient recovery by dialysis and reuse for four runs with low metal leaching was demonstrated with catalyst **30a**. A slight decrease of activity and an increase of enantioselectivity from 20 to 30 % *ee* was observed.



31

R = catalyst or double-shell building block

Figure 24. Fragment of hPG-supported TsDPEN-Rh^{III} catalyst **31**.

The hPG-supported tethered TsDPEN-Rh^{III} catalyst **31** (Figure 24) was designed such that a water-soluble catalyst was obtained. Therefore, amphiphilic chains were introduced at the polymer periphery to generate a double shell with an outer layer of water-soluble mPEG. Catalyst **31** showed high activities and enantioselectivities of up to 99 % *ee* in the asymmetric hydrogenation of various prochiral ketones in water with sodium formate as hydrogen donor. Recovery was easily achieved by ultrafiltration, however, upon recycling a significant drop of activity was observed. Furthermore, during separation the catalyst precipitated and remained insoluble after the third run. Interestingly, the selectivity remained high throughout all three runs.

The second part of this work concentrated on the homogeneous stabilization of metal nanoparticles and their recovery after catalytic reactions. It was demonstrated that dendritic core-multishell architectures based on poly(ethylene imine) or hPG **1** are efficient stabilizers for Au and Pt nanoparticles in aqueous solution. The polymer architecture allows to control the particle size during synthesis and the transfer of the nanoparticles to a variety of organic solvent was demonstrated.

The catalytic activity of Pt nanoparticles was demonstrated for the hydrogenation of methyl crotonate. Stabilized Pt nanoparticles showed a similar activity compared to Pt/C, indicating that the polymer does not passivate the metal surface. Recycling was achieved by ultrafiltration for nine runs and very low metal leaching into the product was observed. For the hydrogenation of isophorone a high selectivity for C=C versus C=O hydrogenation (> 99:1) was achieved.

Polymer stabilized Pt nanoparticles were chirally modified with cinchonidine and the resulting catalyst was successfully applied to the asymmetric hydrogenation of pyruvate esters. The influence of polymer, pressure, solvent, and nanoparticle size was investigated and after optimization of the reaction conditions *ee*’s of up to 75 % were obtained.

Recycling was easily achieved by ultrafiltration for 10 cycles with stable activity and enantioselectivity for eight runs.

In conclusion, it could be shown that dendritic hPG **1** is a versatile support for the efficient recovery and recycling of transition metal catalysts. In case of immobilized metal complexes, one can make use of dendritic effects, e.g., when a high local concentration of catalyst is advantageous for the desired reaction. The properties of the final catalyst can be easily changed by attachment of additional functional groups to the polymer periphery, e.g., the introduction of solubilizing moieties. hPG-based core-multishell architectures were found to be extremely versatile and generally applicable stabilizers for catalytically active metal nanoparticles. They enable size control during synthesis, transfer to various solvents, long term storage, efficient stabilization under various reaction conditions, and are easily separable. Most importantly, they do not passivate the nanoparticles surface which can participate in catalytic reactions and can even be modified with chiral alkaloids for asymmetric transformations.

5 Outlook

Since hyperbranched polyglycerol was shown to be a suitable support for chiral transition metal complexes, one could envision the immobilization of other precious chiral catalysts. However, further improvement of the stability of the polymer supported metal complexes is required in order to make them suitable for the application in continuously operating membrane reactors. This could be achieved by using bigger polymer cores which facilitates and accelerates separation, and by the introduction of bigger shielding moieties which could improve the long-term stability of the catalytic units by creating a protective “microenvironment” around the catalyst.

The core-multishell architectures presented in this work for the stabilization of Au and Pt nanoparticles could be further investigated with regard to the synthesis of other metal nanoparticles, e.g. Pd nanoparticles and their application in selective hydrogenation, oxidation, or C–C coupling reactions. Additionally, the synthesis of bimetallic nanoparticles is of great interest, because they are known to have significantly different catalytic properties compared to their monometallic analogues. Improvement of the long-term stability and application in continuously operating systems is also necessary and could be achieved by tuning the polymer structure with regard to composition and size of the core and the double shell.

6 Zusammenfassung

In der vorliegenden Arbeit wurde die Anwendbarkeit von hochverzweigtem Polyglycerol (hPG) als löslicher Träger für die Immobilisierung von verschiedenen Katalysatorsystemen an zwei größeren Themengebiete untersucht: (1) die kovalente Anbindung chiraler Metallkomplexe und (2) die nicht-kovalente Stabilisierung katalytisch aktiver Metallnanopartikel.

Im ersten Teil konnte gezeigt werden, dass hPG ein sehr gut geeigneter Träger für die kovalente Anbindung chiraler Metallkomplexe ist. Dies wurde erfolgreich an der Synthese von Pyrrolidin-Salen(Cr^{III})-Komplexen und einem TsDPEN-Rh^{III}-Komplex demonstriert.

Im Fall des geträgerten Pyrrolidin-Salen(Cr^{III})-Katalysators konnte in der asymmetrischen Ringöffnung von *meso*-Epoxiden ein positiver dendritischer Effekt beobachtet werden. Diese Reaktion verläuft nach einem kooperativen bimetallischen Mechanismus und die beobachtete Beschleunigung beweist, dass die Anbindung des Katalysators an hochverzweigtes Polyglycerol zu einer erhöhten lokalen Katalysatorkonzentration führt und somit kooperative Interaktion begünstigt. Hiermit konnte gezeigt werden, dass perfekte Dendrimere durch hochverzweigte Polymere ersetzt werden können, ohne dass die positiven Effekte der dendritischen Struktur verloren gehen. Es ist bekannt, dass die erzielten Enantiomerenüberschüsse stark von der Orientierung zweier Katalysatormoleküle zueinander abhängen. Durch den Einbau von längeren verbindenden Ketten zwischen Katalysator und polymerem Träger, konnte die Enantioselektivität von 22 % *ee* auf 48 % *ee* gesteigert werden. Diese Steigerung ist darauf zurückzuführen, dass ein längerer Linker ein Zurückfalten von Katalysatormolekülen ermöglicht und dadurch die günstigere Anordnung erreicht werden kann, die zu hohen Enantiomerenüberschüssen führt. Der polymergeträgerte Katalysator konnte mittels Dialyse erfolgreich von der Reaktionsmischung abgetrennt und viermal mit sehr geringem Metallverlust wieder verwendet werden. Dabei wurde eine stabile Aktivität und steigende Selektivität beobachtet (von 20 % auf 30 % *ee*).

Der hPG-geträgerte TsDPEN-Rh^{III}-Katalysator wurde als wasserlösliches System konzipiert. Dazu wurden amphiphile Ketten in die Polymerperipherie eingeführt, die eine Doppelschale mit einer äußeren Schale aus wasserlöslichem mPEG bilden. Der erhaltene Katalysator wurde in der asymmetrischen Transferhydrierung von verschiedenen prochiralen Ketonen in Wasser getestet und zeigte eine gute Aktivität und hohe

Selektivität von bis zu 99 % *ee* bei Verwendung von Natriumformiat als Wasserstoffquelle. Der Katalysator konnte leicht durch Ultrafiltration abgetrennt werden, aber bei der Wiederverwendung trat ein erheblicher Aktivitätsverlust auf. Während der Abtrennung nach dem dritten Katalysezyklus setzte sich der Katalysator auf der Ultrafiltrationsmembran ab und konnte nicht wieder gelöst werden. Interessanterweise blieb die hohe Enantioselektivität während des ganzen Recyclingexperiments erhalten.

Der zweite Teil dieser Arbeit beschäftigte sich mit der homogenen Stabilisierung von Metallnanopartikeln und ihrer Wiedergewinnung nach katalytischen Reaktionen. Es konnte gezeigt werden, dass dendritische Kern-Multischalen-Architekturen, basierend auf Poly(ethylenimin) oder hochverzweigtem Polyglycerol, sehr gut für die Synthese und Stabilisierung von Au- und Pt-Nanopartikeln in wässriger Lösung geeignet sind. Das Polymer erlaubt dabei die Kontrolle der Partikelgröße und den Transfer der Metallnanopartikel von Wasser in organische Lösungsmittel.

Die katalytische Aktivität der Pt-Nanopartikel wurde anhand der Hydrierung von Methylcrotonat demonstriert. Beim Vergleich von polymerstabilisierten Pt-Nanopartikeln mit Pt/C konnte eine ähnliche Aktivität festgestellt werden. Das zeigt, dass der polymere Stabilisator die Metalloberfläche nicht passiviert. Die Pt-Nanopartikel konnten per Ultrafiltration neun Mal wieder verwendet werden, wobei es nur einen sehr geringen Metallverlust gab. In der selektiven Hydrierung der C=C gegen die C=O Bindung von Isophoron erreichten die polymerstabilisierten Nanopartikel eine sehr hohe Selektivität von über 99:1.

Die chirale Modifizierung der Pt-Nanopartikel wurde mit dem Alkaloid Cinchonidin erreicht und der resultierende Katalysator erfolgreich in der asymmetrische Hydrierung von Pyruvatester eingesetzt. Der Einfluss des Polymers, des Druckes, des Lösungsmittels und der Nanopartikelgröße auf das Resultat der Reaktion wurde untersucht und nach Optimierung der Reaktionsbedingungen wurden Enantiomerenüberschüsse von bis zu 75 % erreicht. Die Pt-Nanopartikel konnten auch hier erfolgreich wieder verwendet werden. Insgesamt wurden zehn Reaktionszyklen durchgeführt, von denen die ersten acht konstante Aktivität und Selektivität aufwiesen.

Zusammenfassend kann festgestellt werden, dass dendritisches hPG ein vielseitiges Trägermaterial ist, das effiziente Wiedergewinnung und Recycling ermöglicht. Im Fall von immobilisierten Metallkomplexen können dendritische Effekte ausgenutzt werden, z. B. wenn eine hohe lokale Katalysatorkonzentration vorteilhaft für eine angestrebte

Reaktion ist. Die Eigenschaften des polymergeträgerten Katalysators können leicht den Erfordernissen angepasst werden, z. B. durch Anbindung lösungsvermittelnder Gruppen in der Polymerperipherie.

hPG-basierte Kern-Multischalen-Architekturen sind sehr vielseitig und allgemein anwendbare Stabilisatoren für katalytisch aktive Metallnanopartikel. Sie ermöglichen während der Herstellung die Kontrolle der Nanopartikelgröße, den Transfer in verschiedene Lösungsmittel, Langzeitlagerung und Stabilisierung unter verschiedenen Reaktionsbedingungen. Am bedeutendsten ist, dass das Polymer die Metalloberfläche der Nanopartikel nicht passiviert. Diese ist für katalytische Reaktionen zugänglich und kann für asymmetrische Synthesen mit chiralen Alkaloiden modifiziert werden.

7 References

[1] R. Noyori, ed., *Asymmetric Catalysis in Organic Synthesis*. 1994, Wiley: New York.

[2] E. N. Jacobsen, A. Pfaltz, H. Yamamoto, eds. *Comprehensive Asymmetric Catalysis*. 1999, Springer: New York.

[3] I. Ojima, ed. *Catalytic Asymmetric Synthesis*. 2nd ed. 2000, Wiley-VCH: New York.

[4] H.-U. Blaser, E. Schmidt, eds. *Asymmetric catalysis on industrial scale*. 2004, Wiley-VCH: Weinheim.

[5] I. Agranat, H. Caner, J. Caldwell, *Nat. Rev. Drug Discovery* **2002**, *1*, 753-768.

[6] D. J. Pollard, J. M. Woodley, *Trends Biotechnol.* **2006**, *25*, 66-73.

[7] H. Caner, E. Groner, L. Levy, I. Agranat, *Drug Discovery Today* **2004**, *9*, 105-110.

[8] M. Breuer, K. Ditrich, T. Habicher, B. Hauer, M. Keßeler, R. Stürmer, T. Zelinski, *Angew. Chem. Int. Ed.* **2004**, *43*, 788-824.

[9] S. Bertelsen, K. A. Jorgensen, *Chem. Soc. Rev.* **2009**, *38*, 2178-2189.

[10] H.-U. Blaser, M. Studer, *Heterogeneous Catalysis*, in *Comprehensive Asymmetric Catalysis*, E. N. Jacobsen, A. Pfaltz, H. Yamamoto, eds. 1999, Springer: New York. p. 1353-1366.

[11] T. Mallat, E. Orglmeister, A. Baiker, *Chem. Rev.* **2007**, *107*, 4863-4890.

[12] D. J. Cole-Hamilton, *Science* **2003**, *299*, 1702-1706.

[13] J. M. Hawkins, T. J. N. Watson, *Angew. Chem. Int. Ed.* **2004**, *43*, 3224-3228.

[14] D. E. De Vos, I. F. J. Vankelecom, P. A. Jacobs, *Chiral Catalyst Immobilization and Recycling*. Weinheim, Wiley-VCH, 2000.

[15] Q.-H. Fan, Y.-M. Li, A. S. C. Chan, *Chem. Rev.* **2002**, *102*, 3385-3466.

[16] R. van Heerbeek, P. C. J. Kamer, P. W. N. M. van Leeuwen, J. N. H. Reek, *Chem. Rev.* **2002**, *102*, 3717-3756.

[17] N. End, K.-U. Schöning, *Top. Curr. Chem.* **2004**, *242*, 241–271.

[18] R. Haag, S. Roller, *Polymeric Supports for the Immobilisation of Catalysts*, in *Top. Curr. Chem.*, A. Kirschning, ed. 2004, Springer-Verlag: Berlin, Heidelberg. p. 1-42.

[19] L. H. Gade, Editor, *Dendrimer Catalysis*. Top. Organomet. Chem. Vol. 20, Springer, 2006. 189 pp.

[20] A. F. Trindade, P. M. P. Gois, C. A. M. Afonso, *Chem. Rev.* **2009**, *109*, 418-514.

[21] B. Helms, J. M. J. Fréchet, *Adv. Synth. Catal.* **2006**, *348*, 1125-1148.

[22] N. Madhavan, C. W. Jones, M. Weck, *Acc. Chem. Res.* **2008**, *41*, 1153-1165.

[23] B. Pugin, *J. Mol. Catal. A: Chem.* **1996**, *107*, 273-279.

[24] C. E. Song, J. S. Lim, S. C. Kim, K.-J. Lee, D. Y. Chi, *Chem. Commun.* **2000**, 2415-2416.

[25] D. A. Annis, E. N. Jacobsen, *J. Am. Chem. Soc.* **1999**, *121*, 4147-4154.

[26] R. Breinbauer, E. N. Jacobsen, *Angew. Chem. Int. Ed.* **2000**, *39*, 3604-3607.

[27] T. Belser, E. N. Jacobsen, *Adv. Synth. Catal.* **2008**, *350*, 967-971.

[28] C. E. Song, S.-g. Lee, *Chem. Rev.* **2002**, *102*, 3495-3524.

[29] M. Heitbaum, F. Glorius, I. Escher, *Angew. Chem. Int. Ed.* **2006**, *45*, 4732-4762.

[30] C. Hajji, R. Haag, *Top. Organomet. Chem.* **2006**, *20*, 149-176.

[31] J. M. Fraile, J. I. Garcia, J. A. Mayoral, *Chem. Rev.* **2009**, *109*, 360-417.

[32] J. Lu, P. H. Toy, *Chem. Rev.* **2009**, *109*, 815-838.

[33] D. E. Bergbreiter, J. Tian, C. Hongfa, *Chem. Rev.* **2009**, *109*, 530-582.

[34] U. Kragl, C. Dreisbach, *Angew. Chem. Int. Ed.* **1996**, *35*, 642-644.

[35] J. Wöltinger, K. Drauz, A. S. Bommarius, *Appl. Catal. A* **2001**, *221*, 171-185.

[36] P. Hodge, *Chem. Soc. Rev.* **1997**, *26*, 417-424.

[37] H. Yang, L. Zhang, W. Su, Q. Yang, C. Li, *J. Catal.* **2007**, *248*, 204-212.

[38] I. F. J. Vankelecom, D. Tas, R. F. Parton, V. Van de Vyver, P. A. Jacobs, *Angew. Chem. Int. Ed.* **1996**, *35*, 1346-1348.

[39] R. F. Parton, I. F. J. Vankelecom, D. Tas, K. B. M. Janssen, P.-P. Knops-Gerrits, P. A. Jacobs, *J. Mol. Catal.* **1996**, *113*, 283-292.

[40] T. Welton, *Chem. Rev.* **1999**, *99*, 2071-2083.

[41] P. Wasserscheid, W. Keim, *Angew. Chem. Int. Ed.* **2000**, *39*, 3772-3789.

[42] R. Sheldon, *Chem. Commun.* **2001**, 2399-2407.

[43] J. Dupont, R. F. de Souza, P. A. Z. Suarez, *Chem. Rev.* **2002**, *102*, 3667-3691.

[44] V. I. Pârvulescu, C. Hardacre, *Chem. Rev.* **2007**, *107*, 2615-2665.

[45] L. P. Barthel-Rosa, J. A. Gladysz, *Coord. Chem. Rev.* **1999**, *190-192*, 587-605.

[46] C. C. Tzschucke, C. Markert, W. Bannwarth, S. Roller, A. Hebel, R. Haag, *Angew. Chem. Int. Ed.* **2002**, *41*, 3964-4000.

[47] G. Pozzi, I. Shepperson, *Coord. Chem. Rev.* **2003**, *242*, 115-124.

[48] P. G. Jessop, T. Ikariya, R. Noyori, *Chem. Rev.* **1999**, *99*, 475-493.

[49] C. P. Mehnert, *Chem. Eur. J.* **2005**, *11*, 50-56.

[50] F. Zhao, S.-i. Fujita, M. Arai, *Curr. Org. Chem.* **2006**, *10*, 1681-1695.

[51] R. Haag, *Chem. Eur. J.* **2001**, *7*, 327-335.

[52] R. Haag, A. Hebel, J.-F. Stumbé, in *Handbook of Combinatorial Chemistry*, R. Hanko, K. C. Nicolaou, W. Hartwig, eds. 2002, Wiley-VCH: Weinheim. p. 24-58.

[53] H. P. Dijkstra, G. P. M. van Klink, G. van Koten, *Acc. Chem. Res.* **2002**, *35*, 798-810.

[54] R. Haag, S. Roller, *Dendritic Polymers as High-Loading Supports for Organic Synthesis and Catalysis*, in *Polymeric Materials in Organic Synthesis and Catalysis*, M. R. Buchmeiser, ed. 2003, Wiley-VCH: Weinheim. p. 305-344.

[55] T. J. Dickerson, N. N. Reed, K. D. Janda, *Soluble Polymers as Catalyst and Reagent Platforms: Liquid-Phase Methodologies*, in *Polymeric Materials in Organic Synthesis and Catalysis*, M. R. Buchmeiser, ed. 2003, Wiley-VCH: Weinheim. p. 241-276.

[56] D. E. Bergbreiter, J. Li, *Top. Curr. Chem.* **2004**, *242*, 113-176.

[57] D. E. Bergbreiter, B. L. Case, Y.-S. Liu, J. W. Caraway, *Macromolecules* **1998**, *31*, 6053-6062.

[58] D. E. Bergbreiter, L. Zhang, V. M. Mariagnanam, *J. Am. Chem. Soc.* **1993**, *115*, 9295-9296.

[59] D. E. Bergbreiter, J. W. Caraway, *J. Am. Chem. Soc.* **1996**, *118*, 6092-6093.

[60] D. E. Bergbreiter, Y.-S. Liu, *Tetrahedron Lett.* **1997**, *38*, 3703-3706.

[61] R. Haag, A. Sunder, A. Hebel, S. Roller, *J. Comb. Chem.* **2002**, *4*, 112-119.

[62] C. Müller, M. G. Nijkamp, D. Vogt, *Eur. J. Inorg. Chem.* **2005**, 4011-4021.

[63] Membrane Extraction Technology, London, UK, http://www.membrane-extraction-technology.com.

[64] Koch Membrane Systems, Wilmington, USA, http://www.kochmembrane.com.

[65] C. Linder, M. Nemas, M. Perry, R. Katraro, US Patent no. 5,265,734.

[66] M. K. Koukou, N. Papayannakos, N. C. Markatos, M. Bracht, H. M. Van Veen, A. Roskam, *J. Membr. Sci.* **1999**, *155*, 241-259.

[67] E. L. V. Goetheer, A. W. Verkerk, L. J. P. van den Broeke, E. de Wolf, B.-J. Deelman, G. van Koten, J. T. F. Keurentjes, *J. Catal.* **2003**, *219*, 126-133.

[68] E. Gibbins, M. D'Antonio, D. Nair, L. S. White, L. M. Freitas dos Santos, I. F. J. Vankelecom, A. G. Livingston, *Desalination* **2002**, *147*, 307-313.

[69] K. De Smet, A. Pleysier, I. F. J. Vankelecom, P. A. Jacobs, *Chem. Eur. J.* **2003**, *9*, 334-338.

[70] M. Gaab, S. Bellemin-Laponnaz, L. H. Gade, *Chem. Eur. J.* **2009**, *15*, 5450-5462.

[71] See http://www.millipore.com.

[72] S. Laue, L. Greiner, J. Wöltinger, A. Liese, *Adv. Synth. Catal.* **2001**, *343*, 711-720.

[73] N. Brinkmann, D. Giebel, G. Lohmer, M. T. Reetz, U. Kragl, *J. Catal.* **1999**, *183*, 163-168.

[74] A. W. Kleij, R. A. Gossage, R. J. M. K. Gebbink, N. Brinkmann, E. J. Reijerse, U. Kragl, M. Lutz, A. L. Spek, G. van Koten, *J. Am. Chem. Soc.* **2000**, *122*, 12112-12124.

[75] G. E. Oosterom, S. Steffens, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. Van Leeuwen, *Top. Catal.* **2002**, *19*, 61-73.

[76] M. Mutter, H. Hagenmaier, E. Bayer, *Angew. Chem. Int. Ed.* **1971**, *10*, 811-812.

[77] E. Bayer, M. Mutter, *Nature* **1972**, *237*, 512-513.

[78] E. Bayer, V. Schurig, *Angew. Chem. Int. Ed.* **1975**, *14*, 493-494.

[79] H. Han, K. D. Janda, *J. Am. Chem. Soc.* **1996**, *118*, 7632-7633.

[80] C. A. McNamara, M. J. Dixon, M. Bradley, *Chem. Rev.* **2002**, *102*, 3275-3299.

[81] D. E. Bergbreiter, C. Li, *Org. Lett.* **2003**, *5*, 2445-2447.

[82] P. H. Toy, K. D. Janda, *Acc. Chem. Res.* **2000**, *33*, 546-554.

[83] D. E. Bergbreiter, *Chem. Rev.* **2002**, *102*, 3345-3384.

[84] E. Schwab, S. Mecking, *Organometallics* **2001**, *20*, 5504-5506.

[85] C. Schlenk, A. W. Kleij, H. Frey, G. van Koten, *Angew. Chem. Int. Ed.* **2000**, *39*, 3445-3447.

[86] A. D. Schlüter, J. P. Rabe, *Angew. Chem. Int. Ed.* **2000**, *39*, 864-883.

[87] B. Helms, J. L. Mynar, C. J. Hawker, J. M. J. Frechet, *J. Am. Chem. Soc.* **2004**, *126*, 15020-15021.

[88] D. Yu, N. Vladimirov, J. M. J. Frechet, *Macromolecules* **1999**, *32*, 5186-5192.

[89] L. A. Connal, R. Vestberg, C. J. Hawker, G. G. Qiao, *Macromolecules* **2007**, *40*, 7855-7863.

[90] T. S. Reger, K. D. Janda, *J. Am. Chem. Soc.* **2000**, *122*, 6929-6934.

[91] W. Wang, L. Wang, J. Wang, Z. Ma, J. Wang, *J. Appl. Polym. Sci.* **2005**, *97*, 1632-1636.

[92] T. Malmström, C. Andersson, *J. Mol. Catal. A: Chem.* **1999**, *139*, 259-270.

[93] T. Malmström, C. Andersson, J. Hjortkjaer, *J. Mol. Catal. A: Chem.* **1999**, *139*, 139-147.

[94] B. Wan, S. Liao, D. Yu, *React. Funct. Polym.* **2000**, *45*, 55-59.

[95] G. E. Oosterom, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Angew. Chem. Int. Ed.* **2001**, *40*, 1828-1849.

[96] N. Hadjichristidis, M. Pitsikalis, S. Pispas, H. Iatrou, *Chem. Rev.* **2001**, *101*, 3747-3792.

[97] H. Gao, K. Matyjaszewski, *Prog. Polym. Sci.* **2009**, *34*, 317-350.

[98] W. R. Dichtel, K.-Y. Baek, J. M. J. Frechet, I. B. Rietveld, S. A. Vinogradov, *J. Polym. Sci. A: Polym. Chem.* **2006**, *44*, 4939-4951.

[99] V. Rodionov, H. Gao, S. Scroggins, D. A. Unruh, A.-J. Avestro, J. M. J. Frechet, *J. Am. Chem. Soc.* **2010**, *132*, 2570-2572.

[100] S. Abraham, C.-S. Ha, I. Kim, *Macromol. Rapid Commun.* **2006**, *27*, 1386-1392.

[101] B. Helms, S. J. Guillaudeu, Y. Xie, M. McMurdo, C. J. Hawker, J. M. J. Frechet, *Angew. Chem. Int. Ed.* **2005**, *44*, 6384-6387.

[102] Y. Chi, S. T. Scroggins, J. M. J. Frechet, *J. Am. Chem. Soc.* **2008**, *130*, 6322-6323.

[103] G. R. Newkome, C. Moorefield, F. Vögtle, *Dendritic Macromolecules: Concepts, Syntheses, Perspectives*. Weinheim, VCH, 1996.

[104] E. Buhleier, W. Wehner, F. Vögtle, *Synthesis* **1978**, 155-158.

[105] G. R. Newkome, C. N. Moorefield, F. Vögtle, *Dendrimers and Dendrons*. Weinheim, Wiley-VCH, 2001.

[106] F. Vögtle, G. Richardt, N. Werner, *Dendrimer Chemistry - Concepts, Syntheses, Properties, Applications*. Weinheim, Wiley-VCH, 2009. 342.

[107] D. Astruc, F. Chardac, *Chem. Rev.* **2001**, *101*, 2991-3023.

[108] R. Kreiter, A. W. Kleij, R. J. M. Klein Gebbink, G. van Koten, *Dendritic catalysts*, in *Top. Curr. Chem.*, F. Vögtle, C. A. Schalley, eds. 2001, Springer: Berlin Heidelberg New York. p. 163-199.

[109] D. Méry, D. Astruc, *Coord. Chem. Rev.* **2006**, *250*, 1965-1979.

[110] A. Berger, R. J. M. Klein Gebbink, G. van Koten, *Transition Metal Dendrimer Catalysts*, in *Dendrimer Catalysis*, L. H. Gade, ed. 2006, Springer: Berlin Heidelberg p. 1-38.

[111] L. J. Twyman, A. S. H. King, I. K. Martin, *Chem. Soc. Rev.* **2002**, *31*, 69–82.

[112] J. N. H. Reek, D. de Groot, G. E. Oosterom, P. C. J. Kamer, P. W. N. M. van Leeuwen, *C.R. Chim.* **2003**, *6*, 1061-1077.

[113] S. A. Chavan, W. Maes, L. E. M. Gevers, J. Wahlen, I. F. J. Vankelecom, P. A. Jacobs, W. Dehaen, D. E. De Vos, *Chem. Eur. J.* **2005**, *11*, 6754-6762.

[114] P. B. Rheiner, D. Seebach, *Chem. Eur. J.* **1999**, *5*, 3221-3236.

[115] M. Kimura, T. Shiba, M. Yamazaki, K. Hanabusa, H. Shirai, N. Kobayashi, *J. Am. Chem. Soc.* **2001**, *123*, 5636-5642.

[116] A. Miedaner, C. J. Curtis, R. M. Barkley, D. L. DuBois, *Inorg. Chem.* **1994**, *33*, 5482-5490.

[117] A. K. Kakkar, *Macromol. Symp.* **2003**, *196*, 145-154.

[118] G. van Koten, J. T. B. H. Jastrzebski, *J. Mol. Catal. A: Chem.* **1999**, *146*, 317-323.

[119] D. Astruc, E. Boisselier, C. Ornelas, *Chem. Rev.* **2010**, ASAP DOI: 10.1021/cr900327d.

[120] F. Ribaudo, P. W. N. M. Van Leeuwen, J. N. H. Reek, *Supramolecular Dendritic Catalysis: Noncovalent Catalyst Anchoring to Functionalized Dendrimers*, in *Dendrimer Catalysis*, L. H. Gade, ed. 2006, Springer: Berlin Heidelberg. p. 39-59.

[121] F. Ribaudo, P. W. N. M. van Leeuwen, J. N. H. Reek, *Isr. J. Chem.* **2009**, *49*, 79-98.

[122] C. R. Yates, W. Hayes, *Eur. Polym. J.* **2004**, *40*, 1257-1281.

[123] A. Hult, M. Johansson, E. Malmström, *Adv. Polym. Sci.* **1999**, *143*, 1-34.

[124] Y. H. Kim, O. W. Webster, *Macromolecules* **1992**, *25*, 5561-5572.

[125] E. Malmström, M. Johansson, A. Hult, *Macromolecules* **1995**, *28*, 1698-1703.

[126] Tradename: Lupasol/Lupamin, http://www.veredlungschemikalien.basf.de.

[127] A. Sunder, R. Hanselmann, H. Frey, R. Mülhaupt, *Macromolecules* **1999**, *32*, 4240-4246.

[128] Y. H. Kim, *Adv. Mater.* **1992**, *4*, 764-766.

[129] A. Sunder, R. Mülhaupt, R. Haag, H. Frey, *Adv. Mater.* **2000**, *12*, 235-239.

[130] R. K. Kainthan, E. B. Muliawan, S. G. Hatzikiriakos, D. E. Brooks, *Macromolecules* **2006**, *39*, 7708-7717.

[131] A. L. Sisson, D. Steinhilber, T. Rossow, P. Welker, K. Licha, R. Haag, *Angew. Chem. Int. Ed.* **2009**, *48*, 7540-7545.

[132] D. Wilms, F. Wurm, J. Nieberle, P. Boehm, U. Kemmer-Jonas, H. Frey, *Macromolecules* **2009**, *42*, 3230-3236.

[133] C. Hajji, S. Roller, M. Beigi, A. Liese, R. Haag, *Adv. Synth. Catal.* **2006**, *348*, 1760-1771.

[134] S. Ricken, P. W. Osinski, P. Eilbracht, R. Haag, *J. Mol. Catal. A* **2006**, *257*, 78-88.

[135] M. Beigi, S. Roller, R. Haag, A. Liese, *Eur. J. Org. Chem.* **2008**, 2135-2141.

[136] M. Beigi, R. Haag, A. Liese, *Adv. Synth. Catal.* **2008**, *350*, 919-925.

[137] M. Meise, R. Haag, *ChemSusChem* **2008**, *1*, 637-642.

[138] R. K. Kainthan, J. Janzen, E. Levin, D. V. Devine, D. E. Brooks, *Biomacromolecules* **2006**, *7*, 703-709.

[139] H. Frey, R. Haag, *Rev. Mol. Biotechnol.* **2002**, *90*, 257-267.

[140] M. Calderón, M. A. Quadir, S. K. Sharma, R. Haag, *Adv. Mater.* **2010**, *22*, 190-218.

[141] D. Wilms, S.-E. Stiriba, H. Frey, *Acc. Chem. Res.* **2010**, *43*, 129-141.

[142] C. Müller, L. J. Ackerman, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. van Leeuwen, *J. Am. Chem. Soc.* **2004**, *126*, 14960-14963.

[143] J. W. J. Knapen, A. W. van der Made, J. C. de Wilde, P. W. N. M. van Leeuwen, P. Wijkens, D. M. Grove, G. van Koten, *Nature* **1994**, *372*, 659-663.

[144] A. W. Kleij, R. A. Gossage, J. T. B. H. Jastrzebski, J. Boersma, G. Van Koten, *Angew. Chem. Int. Ed.* **2000**, *39*, 176-178.

[145] A. Mansour, T. Kehat, M. Portnoy, *Org. Biomol. Chem.* **2008**, *6*, 3382-3387.

[146] K. Heuze, D. Méry, D. Gauss, J.-C. Blais, D. Astruc, *Chemistry* **2004**, *10*, 3936-3944.

[147] K. B. Hansen, J. L. Leighton, E. N. Jacobsen, *J. Am. Chem. Soc.* **1996**, *118*, 10924-10925.

[148] R. G. Konsler, J. Karl, E. N. Jacobsen, *J. Am. Chem. Soc.* **1998**, *120*, 10780-10781.

[149] L. Ropartz, K. J. Haxton, D. F. Foster, R. E. Morris, A. M. Z. Slawin, D. J. Cole-Hamilton, *J. Chem. Soc. Dalton Trans.* **2002**, 4323-4334.

[150] G. Rodriguez, M. Lutz, A. L. Spek, G. Van Koten, *Chem. Eur. J.* **2002**, *8*, 45-57.

[151] H. P. Dijkstra, M. Q. Slagt, A. McDonald, C. A. Kruithof, R. Kreiter, A. M. Mills, M. Lutz, A. L. Spek, W. Klopper, G. P. M. van Klink, G. van Koten, *Eur. J. Inorg. Chem.* **2003**, 830-838.

[152] P. Servin, R. Laurent, L. Gonsalvi, M. Tristany, M. Peruzzini, J.-P. Majoral, A.-M. Caminade, *Dalton Trans.* **2009**, 4432-4434.

[153] M. F. Renehan, H.-J. Schanz, E. M. McGarrigle, C. T. Dalton, A. M. Daly, D. G. Gilheany, *J. Mol. Catal. A: Chem.* **2005**, *231*, 205-220.

[154] Y.-C. Chen, T.-F. Wu, J.-G. Deng, H. Liu, Y.-Z. Jiang, M. C. K. Choi, A. S. C. Chan, *Chem. Commun.* **2001**, 1488-1489.

[155] Y.-C. Chen, T.-F. Wu, J.-G. Deng, H. Liu, X. Cui, J. Zhu, Y.-Z. Jiang, M. C. K. Choi, A. S. C. Chan, *J. Org. Chem.* **2002**, *67*, 5301-5306.

[156] Y.-C. Chen, T.-F. Wu, L. Jiang, J.-G. Deng, H. Liu, J. Zhu, Y.-Z. Jiang, *J. Org. Chem.* **2005**, *70*, 1006-1010.

[157] R. Noyori, S. Hashiguchi, *Acc. Chem. Res.* **1997**, *30*, 97-102.

[158] M. J. Palmer, M. Wills, *Tetrahedron Asymmetry* **1999**, *10*, 2045-2061.

[159] H.-U. Blaser, C. Malan, B. Pugin, F. Spindler, H. Steiner, M. Studer, *Adv. Synth. Catal.* **2003**, *345*, 103-151.

[160] S. Gladiali, E. Alberico, *Chem. Soc. Rev.* **2006**, *35*, 226-236.

[161] X. Wu, J. Xiao, *Chem. Commun.* **2007**, 2449-2466.

[162] T. Ikariya, A. J. Blacker, *Acc. Chem. Res.* **2007**, *40*, 1300-1308.

[163] C. Wang, X. Wu, J. Xiao, *Chem. Asian J.* **2008**, *3*, 1750-1770.

[164] M. Q. Slagt, S.-E. Stiriba, R. J. M. Klein Gebbink, H. Kautz, H. Frey, G. van Koten, *Macromolecules* **2002**, *35*, 5734-5737.

[165] M. Q. Slagt, S.-E. Stiriba, H. Kautz, R. J. M. K. Gebbink, H. Frey, G. Van Koten, *Organometallics* **2004**, *23*, 1525-1532.

[166] S.-E. Stiriba, M. Q. Slagt, H. Kautz, R. J. M. K. Gebbink, R. Thomann, H. Frey, G. Van Koten, *Chem. Eur. J.* **2004**, *10*, 1267-1273.

[167] I. F. J. Vankelecom, P. A. Jacobs, *Catalyst Immobilization on Inorganic Supports*, in *Chiral Catalyst Immobilization and Recycling*, D. E. De Vos, I. F. J. Vankelecom, P. A. Jacobs, eds. 2000, Wiley-VCH: Weinheim.

[168] S. Nishimura, *Handbook of Heterogeneous Catalytic Hydrogenation for Organic Synthesis*. New York, Wiley-VCH, 2001.

[169] P. C. Stair, *J. Chem. Phys.* **2008**, *128*, 182507/1-182507/4.

[170] G. Schmid, Editor, *Nanoparticles: From Theory to Application*, 2004. 434 pp.

[171] A. Roucoux, J. Schulz, H. Patin, *Chem. Rev.* **2002**, *102*, 3757-3778.

[172] D. Astruc, F. Lu, J. R. Aranzaes, *Angew. Chem. Int. Ed.* **2005**, *44*, 7852-7872.

[173] A. Roucoux, K. Philippot, *Handb. Homogeneous Hydrogenation* **2007**, *1*, 217-256.

[174] J. M. Campelo, D. Luna, R. Luque, J. M. Marinas, A. A. Romero, *ChemSusChem* **2009**, *2*, 18-45.

[175] K. D. Hermanson, S. O. Lumsdon, J. P. Williams, E. W. Kaler, O. D. Velev, *Science* **2001**, *294*, 1082-1086.

[176] W. E. Doering, M. E. Piotti, M. J. Natan, R. G. Freeman, *Adv. Mater.* **2007**, *19*, 3100-3108.

[177] R. P. Cowburn, M. E. Welland, *Science* **2000**, *287*, 1466-1468.

[178] J. Gao, H. Gu, B. Xu, *Acc. Chem. Res.* **2009**, *42*, 1097-1107.

[179] R. M. Crooks, M. Zhao, L. Sun, V. Chechik, L. K. Yeung, *Acc. Chem. Res.* **2001**, *34*, 181-190.

[180] B. F. G. Johnson, *Top. Catal.* **2003**, *24*, 147-159.

[181] D. Barkhuizen, I. Mabaso, E. Viljoen, C. Welker, M. Claeys, E. van Steen, J. C. Q. Fletcher, *Pure Appl. Chem.* **2006**, *78*, 1759-1769.

[182] A. Fukuoka, P. L. Dhepe, *Chem. Rec.* **2009**, *9*, 224-235.

[183] L. Durán Pachón, G. Rothenberg, *Appl. Organomet. Chem.* **2008**, *22*, 288-299.

[184] M. E. Labib, *Colloids Surf. A* **1988**, *29*, 293-304.

[185] Y. Lin, R. G. Finke, *J. Am. Chem. Soc.* **1994**, *116*, 8335-8353.

[186] J. D. Aiken, III, Y. Lin, R. G. Finke, *J. Mol. Catal. A: Chem.* **1996**, *114*, 29-51.

[187] S. Sistach, K. Rahme, N. Pérignon, J.-D. Marty, N. Lauth-de Viguerie, F. Gauffre, C. Mingotaud, *Chem. Mater.* **2008**, *20*, 1221-1223.

[188] G. Schmid, R. Pfeil, R. Boese, F. Brandermann, S. Meyer, G. H. M. Calis, J. W. A. Van der Velden, *Chem. Ber.* **1981**, *114*, 3634-3642.

[189] C. Amiens, D. de Caro, B. Chaudret, J. S. Bradley, R. Mazel, C. Roucau, *J. Am. Chem. Soc.* **1993**, *115*, 11638-11639.

[190] A. Duteil, G. Schmid, W. Meyer-Zaika, *J. Chem. Soc. Chem. Commun.* **1995**, 31-32.

[191] L. Wu, Z.-W. Li, F. Zhang, Y.-M. He, Q.-H. Fan, *Adv. Synth. Catal.* **2008**, *350*, 846-862.

[192] M. Brust, M. Walker, D. Bethell, D. J. Schiffrin, R. Whyman, *J. Chem. Soc. Chem. Commun.* **1994**, 801-802.

[193] F. Dassenoy, K. Philippot, T. Ould Ely, C. Amiens, P. Lecante, E. Snoeck, A. Mosset, M.-J. Casanove, B. Chaudret, *New J. Chem.* **1998**, *22*, 703-712.

[194] S. Chen, K. Kimura, *J. Phys. Chem. B* **2001**, *105*, 5397-5403.

[195] G. Schmid, V. Maihack, F. Lantermann, S. Peschel, *J. Chem. Soc. Dalton Trans.* **1996**, 589-595.

[196] A. Rodriguez, C. Amiens, B. Chaudret, M.-J. Casanove, P. Lecante, J. S. Bradley, *Chem. Mater.* **1996**, *8*, 1978-1986.

[197] P. J. Collier, J. A. Iggo, R. Whyman, *J. Mol. Catal. A: Chem.* **1999**, *146*, 149-157.

[198] F. Lu, J. Ruiz, D. Astruc, *Tetrahedron Lett.* **2004**, *45*, 9443-9445.

[199] J. Schulz, A. Roucoux, H. Patin, *Chem. Eur. J.* **2000**, *6*, 618-624.

[200] N. Semagina, E. Joannet, S. Parra, E. Sulman, A. Renken, L. Kiwi-Minsker, *Appl. Catal. A* **2005**, *280*, 141-147.

[201] R. Sablong, U. Schlotterbeck, D. Vogt, S. Mecking, *Adv. Synth. Catal.* **2003**, *345*, 333-336.

[202] J. P. Novak, C. Nickerson, S. Franzen, D. L. Feldheim, *Anal. Chem.* **2001**, *73*, 5758-5761.

[203] R. Abu-Reziq, D. Wang, M. Post, H. Alper, *Adv. Synth. Catal.* **2007**, *349*, 2145-2150.

[204] B. Panella, A. Vargas, A. Baiker, *J. Catal.* **2009**, *261*, 88-93.

[205] J. S. Bradley, B. Tesche, W. Busser, M. Maase, M. T. Reetz, *J. Am. Chem. Soc.* **2000**, *122*, 4631-4636.

[206] R. Narayanan, M. A. El-Sayed, *J. Am. Chem. Soc.* **2003**, *125*, 8340-8347.

[207] M. T. Reetz, E. Westermann, *Angew. Chem. Int. Ed.* **2000**, *39*, 165-168.

[208] A. H. M. de Vries, J. M. C. A. Mulders, J. H. M. Mommers, H. J. W. Henderickx, J. G. de Vries, *Org. Lett.* **2003**, *5*, 3285-3288.

[209] J. G. De Vries, *Dalton Trans.* **2006**, 421-429.

[210] M. B. Thathagar, J. E. ten Elshof, G. Rothenberg, *Angew. Chem. Int. Ed.* **2006**, *45*, 2886-2890.

[211] A. V. Gaikwad, A. Holuigue, M. B. Thathagar, J. E. ten Elshof, G. Rothenberg, *Chem. Eur. J.* **2007**, *13*, 6908-6913.

[212] R. Narayanan, M. A. El-Sayed, *J. Phys. Chem. B* **2004**, *108*, 8572-8580.

[213] R. Narayanan, M. A. El-Sayed, *Langmuir* **2005**, *21*, 2027-2033.

[214] W. Hou, N. A. Dehm, R. W. J. Scott, *J. Catal.* **2008**, *253*, 22-27.

[215] http://worldaccount.basf.com/wa/EU~de_DE/Catalog/Chemicals/pi/BASF/Brand/pluronic/brand_top.

[216] K. Rahme, F. Gauffre, J.-D. Marty, B. Payré, C. Mingotaud, *J. Phys. Chem. C* **2007**, *111*, 7273-7279.

[217] K. Rahme, P. Vicendo, C. Ayela, C. Gaillard, B. Payré, C. Mingotaud, F. Gauffre, *Chem. Eur. J.* **2009**, *15*, 11151-11159.

[218] T. I. Abdullin, O. V. Bondar, Y. G. Shtyrlin, M. Kahraman, M. Culha, *Langmuir* **2010**, *26*, 5153-5159.

[219] T. Azzam, L. Bronstein, A. Eisenberg, *Langmuir* **2008**, *24*, 6521-6529.

[220] S. N. Sidorov, L. M. Bronstein, P. M. Valetsky, J. Hartmann, H. Colfen, H. Schnablegger, M. Antonietti, *J. Colloid Interface Sci.* **1999**, *212*, 197-211.

[221] L. M. Bronstein, D. M. Chernyshov, I. O. Volkov, M. G. Ezernitskaya, P. M. Valetsky, V. G. Matveeva, E. M. Sulman, *J. Catal.* **2000**, *196*, 302-314.

[222] S. Kanaoka, N. Yagi, Y. Fukuyama, S. Aoshima, H. Tsunoyama, T. Tsukuda, H. Sakurai, *J. Am. Chem. Soc.* **2007**, *129*, 12060-12061.

[223] M. Zhao, L. Sun, R. M. Crooks, *J. Am. Chem. Soc.* **1998**, *120*, 4877-4878.

[224] L. Balogh, D. A. Tomalia, *J. Am. Chem. Soc.* **1998**, *120*, 7355-7356.

[225] K. Esumi, A. Suzuki, N. Aihara, K. Usui, K. Torigoe, *Langmuir* **1998**, *14*, 3157-3159.

[226] Y. Niu, R. M. Crooks, *C.R. Chim.* **2003**, *6*, 1049-1059.

[227] R. W. J. Scott, O. M. Wilson, R. M. Crooks, *J. Phys. Chem. B* **2005**, *109*, 692-704.

[228] M. Zhao, R. M. Crooks, *Angew. Chem. Int. Ed.* **1999**, *38*, 364-366.

[229] M. Zhao, R. M. Crooks, *Chem. Mater.* **1999**, *11*, 3379-3385.

[230] M. R. Knecht, M. G. Weir, V. S. Myers, W. D. Pyrz, H. Ye, V. Petkov, D. J. Buttrey, A. I. Frenkel, R. M. Crooks, *Chem. Mater.* **2008**, *20*, 5218-5228.

[231] K. Esumi, A. Kameo, A. Suzuki, K. Torigoe, *Colloids Surf. A* **2001**, *189*, 155-161.

[232] Y. Niu, L. K. Yeung, R. M. Crooks, *J. Am. Chem. Soc.* **2001**, *123*, 6840-6846.

[233] F. Groehn, B. J. Bauer, Y. A. Akpalu, C. L. Jackson, E. J. Amis, *Macromolecules* **2000**, *33*, 6042-6050.

[234] D. Astruc, *Inorg. Chem.* **2007**, *46*, 1884-1894.

[235] S. Mecking, R. Thomann, H. Frey, A. Sunder, *Macromolecules* **2000**, *33*, 3958-3960.

[236] M. Krämer, N. Pérignon, R. Haag, J.-D. Marty, R. Thomann, N. Lauth-de Viguerie, C. Mingotaud, *Macromolecules* **2005**, *38*, 8308-8315.

[237] J.-D. Marty, E. Martinez-Aripe, A.-F. Mingotaud, C. Mingotaud, *J. Colloid Interface Sci.* **2008**, *326*, 51-54.

[238] H.-U. Blaser, H.-P. Jalett, M. Müller, M. Studer, *Catal. Today* **1997**, *37*, 441-463.

[239] A. Baiker, *J. Mol. Catal. A: Chem.* **2000**, *163*, 205-220.

[240] J. U. Köhler, J. S. Bradley, *Catal. Lett.* **1997**, *45*, 203-208.

[241] J. U. Köhler, J. S. Bradley, *Langmuir* **1998**, *14*, 2730-2735.

[242] X. Zuo, H. Liu, M. Liu, *Tetrahedron Lett.* **1998**, *39*, 1941-1944.

[243] X. Zuo, H. Liu, D. Guo, X. Yang, *Tetrahedron* **1999**, *55*, 7787-7804.

[244] V. Mevellec, C. Mattioda, J. Schulz, J.-P. Rolland, A. Roucoux, *J. Catal.* **2004**, *225*, 1-6.

[245] H. Bönnemann, G. A. Braun, *Angew. Chem. Int. Ed.* **1996**, *35*, 1992-1995.

[246] M. F. Dumont, S. Moisan, C. Aymonier, J.-D. Marty, C. Mingotaud, *Macromolecules* **2009**, *42*, 4937-4940.

[247] M. Bartók, T. Bartók, G. Szöllösi, K. Felföldi, *Catal. Lett.* **1999**, *61*, 57-60.

[248] V. Morawsky, U. Prusse, L. Witte, K. D. Vorlop, *Catal. Commun.* **2000**, *1*, 15-20.

[249] J. Lemo, K. Heuze, D. Astruc, *Inorg. Chim. Acta* **2006**, *359*, 4909-4911.

[250] N. Pérignon, A.-F. Mingotaud, J.-D. Marty, I. Rico-Lattes, C. Mingotaud, *Chem. Mater.* **2004**, *16*, 4856-4858.

[251] N. Pérignon, J.-D. Marty, A.-F. Mingotaud, M. Dumont, I. Rico-Lattes, C. Mingotaud, *Macromolecules* **2007**, *40*, 3034-3041.

[252] D. S. Matharu, D. J. Morris, A. M. Kawamoto, G. J. Clarkson, M. Wills, *Org. Lett.* **2005**, *7*, 5489-5491.

[253] M. R. Radowski, A. Shukla, H. von Berlepsch, C. Böttcher, G. Pickaert, H. Rehage, R. Haag, *Angew. Chem. Int. Ed.* **2007**, *46*, 1265-1269.

[254] S. Küchler, M. R. Radowski, T. Blaschke, M. Dathe, J. Plendl, R. Haag, M. Schäfer-Korting, K. D. Kramer, *Eur. J. Pharm. Biopharm.* **2009**, *71*, 243-250.

8 Curriculum Vitae

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

9 Publications and Conference Contributions

Publications

1) Juliane Keilitz, Michal R. Radowski, Jean-Daniel Marty, Rainer Haag, Fabienne Gauffre, Christophe Mingotaud; *Dendritic Polymers with a Core-Multishell Architecture: A Versatile Tool for the Stabilization of Nanoparticles*, Chem. Mater. **2008**, *20*, 2423-2425.
2) Juliane Keilitz, Rainer Haag; *Intramolecular Acceleration of the Asymmetric Epoxide Ring Opening by Dendritic Polyglycerol Salen-Cr^{III} Complexes*, Eur. J. Org. Chem. **2009**, 3272-3278.
3) Manuela Avi, Georg Steinkellner, Juliane Keilitz, Chakib Hajji, Rainer Haag, Karl Gruber, Herfried Griengl; *α- and β-oxygenated aldehydes derived from Diels-Alder reactions as substrates for hydroxylnitrile lyases;* J. Mol. Catal. B: Enzymatic **2009**, *61*, 268-273.
4) Patent Pending, File No.: 10 2009 029 173.3 (DPMA), Application Date 9/3/2009.
5) Juliane Keilitz, Michael Schwarze, Sabrina Nowag, Reinhard Schomäcker, Rainer Haag, *Homogeneous Stabilization of Pt-Nanoparticles in Dendritic Core-Multishell-Architectures: Application in Catalytic Hydrogenation Reactions and Recycling*, ChemCatChem **2010**, *2*, 863-870.
6) Juliane Keilitz, Sabrina Nowag, Jean-Daniel Marty, Rainer Haag, *Chirally Modified Platinum Nanoparticles Stabilized by Dendritic Core-Multishell Architectures for the Asymmetric Hydrogenation of Ethyl Pyruvate*, Adv. Synth. Catal. **2010**, *352*, 1503-1511.
7) Sabrina Nowag, Xi-Sen Wang, Juliane Keilitz, Arne Thomas, Rainer Haag, *Dendritic Core-Multishell-Polymer Templates for the Synthesis of Pt-Nanoparticle Loaded Porous Silica and their Application in Catalysis*, ChemCatChem **2010**, *2*, 807-811.
8) Jonas Dimroth, Juliane Keilitz, Uwe Schedler, Reinhard Schomäcker, Rainer Haag, *Immobilization of a tethered Rh^{III}-TsDPEN catalyst on soluble and solid polymeric supports and successful application to asymmetric transfer hydrogenation of ketones*, Adv. Synth. Catal. **2010**, *in print*.

Poster presentations

1) Makromolekulares Kolloquium, Freiburg, Germany (22-24 February 2007)
Poster: Hyperbranched Polyglycerol as High-Loading Support for Metal-Salen Complexes in Asymmetric Catalysis; *Juliane Keilitz, Chakib Hajji, Sebastian Roller, Rainer Haag*

2) Eighth Tetrahedron Symposium, Berlin, Germany (27-29 June 2007)
Poster: Hyperbranched Polyglycerol as High-Loading Support for Metal-Salen Complexes in Asymmetric Catalysis; *Juliane Keilitz, Chakib Hajji, Sebastian Roller, Rainer Haag*

3) IDS:5 – International Dendrimer Symposium 5, Toulouse, France (28 August - 1 September 2007)
Poster: Hyperbranched Polyglycerol as Support for Metal-Salen Complexes in Asymmetric Catalysis; *Juliane Keilitz, Rainer Haag*
(Poster-Prize Catalysis)

4) ISHC XVI – International Symposium on Homogeneous Catalysis XVI, Florence, Italy (6-11 July 2008)
Poster: Hyperbranched Polyglycerol as Support for Metal-Salen Complexes in Asymmetric Catalysis; *Juliane Keilitz, Rainer Haag*

5) 42. Jahrestreffen Deutscher Katalytiker, Weimar, Germany (11-13 March 2009)
Poster: Quasi-Homogeneous Hydrogenation with Platinum Nanoparticles Supported on Soluble Dendritic Architectures; *Juliane Keilitz, Michael Schwarze, Sabrina Nowag, Reinhard Schomäcker, Rainer Haag*

Oral presentations

1) IDS6 – International Dendrimer Symposium 6, Stockholm, Sweden (14-18 June 2009)
Oral presentation: Homogenization of Heterogeneous Catalysts – Stabilization of Metal Nanoparticles by Soluble Dendritic Architectures and Applications thereof; *Juliane Keilitz, Sabrina Nowag, Jean-Daniel Marty, Christophe Mingotaud, Rainer Haag*

2) ISHHC XIV – International Symposium on the Relations between Homogeneous and Heterogeneous Catalysis XIV, Stockholm, Sweden (13-18 September 2009)
Oral presentation: Homogenization of Heterogeneous Catalysts – The Asymmetric Hydrogenation of Ethylpyruvate on Chirally Modified Pt-Nanoparticles; *Juliane Keilitz, Sabrina Nowag, Jean-Daniel Marty, Christophe Mingotaud, Rainer Haag*

3) APME 2009 – 8th International Conference on Advanced Polymers via Macromolecular Engineering, Dresden, Germany (4-7 October 2009)
Oral presentation: Homogenization of Heterogeneous Catalysts – Stabilization of Metal Nanoparticles by Soluble Dendritic Architectures and Applications Thereof – the Asymmetric Hydrogenation of Ethylpyruvate; *Juliane Keilitz, Sabrina Nowag, Jean-Daniel Marty, Christophe Mingotaud, Rainer Haag*