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

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Abstract: In this paper we present the asymmetric hydrogenation of α-keto esters with platinum nanoparticles homogeneously stabilized in dendritic core-multishell architectures. The main focus lies on recycling and metal leaching, because little is reported so far about these aspects. It is shown that the stabilizing polymer allows for the efficient modification of the Pt surface with the chiral alkaloid cinchonidine, thereby inducing enantioselectivity and enhancing the reaction rate in the asymmetric hydrogenation of ethyl pyruvate. After optimization of the reaction conditions 63% *ee* for (*R*)-ethyl lactate was obtained. During recycling it was found that this value could even be increased upon ultrafiltration of the catalyst prior to use. Recycling was accomplished for 10 cycles with stable activity and enantioselectivity (~73% *ee*) in the first eight runs. Aggregation of the initially well dispersed nanoparticles was observed by transmission electron microscope (TEM) analysis, leading to reduced conversion after the 8th cycle, but metal leaching into the product has been observed only in the very first run.

Keywords: asymmetric catalysis; chiral modification; dendritic; hydrogenation; nanoparticles; recycling

Introduction

The chiral modification of metal surfaces is a powerful means to expand the range of heterogeneous metal catalysts.[1,2] One of the most successful reactions in this area is the asymmetric hydrogenation of α-keto esters over chirally modified Pt catalysts which was first reported by Orito and co-workers[3–5] and widely studied since then.[6–9] Nowadays, *Cinchona* alkaloid-modified Pt/Al_2O_3 catalysts are applied in industry for asymmetric hydrogenation reactions.[9]

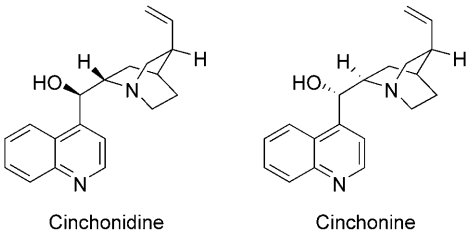
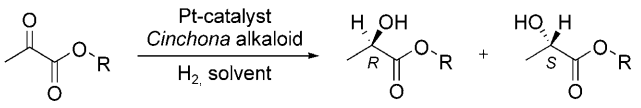


Figure 1. Pseudo-enantiomers cinchonidine and cinchonine; chiral modifiers for the asymmetric hydrogenation of α-keto esters over Pt catalysts.

Cinchona alkaloids (Figure 1) are referred to as "privileged ligands,"[10] because they catalyze a variety of enantioselective transformations[11] and not only induce enantioselectivity in the hydrogenation of α-keto esters (Scheme 1) but also a significant rate enhancement compared to the reaction with non-modified Pt catalyst.[12]

In spite of the wide applicability of heterogeneous metal catalysts, they suffer from certain drawbacks like high metal leaching,[13] less defined catalytic sites, and partial passivation of the metal surface by the solid support. Therefore, homogeneously stabilized metal nanoparticles have become more and more important.[14–16]

For the asymmetric hydrogenation of α-keto esters several examples of homogeneously stabilized Pt nanoparticles have been reported, e.g., stabilized by solvent,[17] polyvinylpyrrolidone,[18,19] surfactant,[20] or



Scheme 1. Asymmetric hydrogenation of α-keto esters over chirally modified Pt catalysts.

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the chiral alkaloid itself.[21] However, to the best of our knowledge, the recycling has only been reported in one case for three consecutive runs,[20] and neither has any data for metal leaching into the products been reported, although such values are of vast importance for industrial applications.

With the help of soluble polymeric stabilizers the best features of homogeneous and heterogeneous catalysis can be combined. They are higher reaction rates and/or selectivity, absence of diffusion phenomena, and simplified purification, including the potential for recycling and application in continuous processes.[15,22,23] Dendritic polymers are widely used as soluble stabilizers of metal nanoparticles for catalysis,[24,25] because they allow control of the size, composition and solubility of nanoparticles and prevent aggregation. At the same time the active sites are not passivated[14] and the encapsulated nanoparticles are easily recyclable with methods developed for polymers, e.g., membrane filtration techniques or precipitation/centrifugation.[22,26]

We recently reported the successful stabilization of Au nanoparticles immobilized in dendritic core-multishell architectures.[27] It was shown that the obtained Au nanoparticles are stable against aggregation induced by changing pH or ionic strength and that they can be easily transferred to various organic solvents. Here we present the asymmetric hydrogenation of pyruvate esters over Pt nanoparticles that have been homogeneously stabilized by dendritic core-multishell architectures and the repetitive recycling of this catalyst by ultrafiltration.

Results and Discussion

The dendritic polymer architectures used in this work consist of hyperbranched polyglycerol as hydrophilic core, alkanedioic acid as the inner hydrophobic shell, and mono-methylated poly(ethylene glycol) (mPEG) as the outer hydrophilic shell and are named **hPG_x-C_n-$mPEG_y$**.[28] These polymers can be prepared with a double or single shell (Figure 2).

The nanoparticles are obtained *via* reduction of an aqueous solution of the respective polymer and $H_2PtCl_6 \cdot 6H_2O$ with sodium borohydride. After 24 h they were modified with cinchonidine and used without further treatment.

Since the adsorption of the modifier on the Pt surface is crucial for the selectivity and rate enhancement,[6] we wanted to compare the outcome of the catalytic reaction with and without addition of cinchonidine (Figure 1) as chiral modifier. The unmodified **$Pt@hPG_{6000}$-C_{18}-$mPEG_{750}$** gave racemic product and only 22% conversion, while the modified catalyst achieved 47% *ee* and full conversion after the same reaction time.[29] These results show that the polymeric stabilizer does not block the nanoparticles surface against modification with cinchonidine and encouraged us to optimize the reaction conditions, because it is well known from the literature that the outcome of the catalytic reaction is quite sensitive towards pressure, solvent, and nanoparticle size.[8]

The first parameter was the treatment of the catalyst prior to reaction. Cinchonidine can be added directly to the reaction mixture or the Pt catalyst can be treated with the modifier for a certain time prior to use to achieve a maximum adsorption of the alkaloid on the metal surface. Upon direct addition, 45% *ee* and 73% conversion were achieved. When the catalyst **$Pt@hPG_{6000}$-C_{18}-$mPEG_{750}$** was stirred with cinchonidine for 2, 24, or 48 h the enantiomeric excess increased slightly to 48% and full conversion was obtained in all cases. Therefore, the catalysts were modified with the chiral alkaloid for two hours in the following experiments.[29]

In order to test the influence of the polymer core size, the presence or absence and length of the inner hydrophobic alkyl chain and the length of the outer mPEG chain, five different polymers were chosen (see Table 1). They were used to prepare Pt nanoparticles at a ratio of 0.5 g/g Pt/polymer and after chiral modification used as catalysts.

In Table 1 it can be seen that different core sizes, the length of the inner alkyl chain or its absence, and the length of the mPEG chain do not significantly influence the obtained enantioselectivity. Regarding the catalyst activity, the length of the outer mPEG-shell as well as the length of the inner alkyl chain have only little influence. An increase of the turnover frequency (TOF) is observed when the polymer core size is decreased (*cf.* Table 1, entry 3 and 4). This suggests that the higher flexibility of the smaller polymer core enables better access to the nanoparticle surface. This is supported by the observed increase in enantioselectivity which indicates a more efficient adsorption of cinchonidine on the metal surface. The absence of the inner alkyl chain does not influence the TOF (*cf.* Table 1, entry 4 and 5), indicating that the hydrophobic alkyl chain is not involved in the adsorption process. However, it was observed that the inner alkyl chain is beneficial for a long-term stability of the Pt nanoparticles. For commercially available Pt/Al_2O_3 a slightly higher enantiomeric excess and similar activity were observed.

Due to the small range of observed *ee* values, it is supposed that the dendritic structure has no influence on the selectivity. Its sole role is the efficient stabilization of the nanoparticles without passivating their surface. Considering the recycling potential, we have chosen **$Pt@hPG_{3000}$-C_{18}-$mPEG_{750}$** for further experiments, because it shows a very good long-term stability and the highest *ee*.

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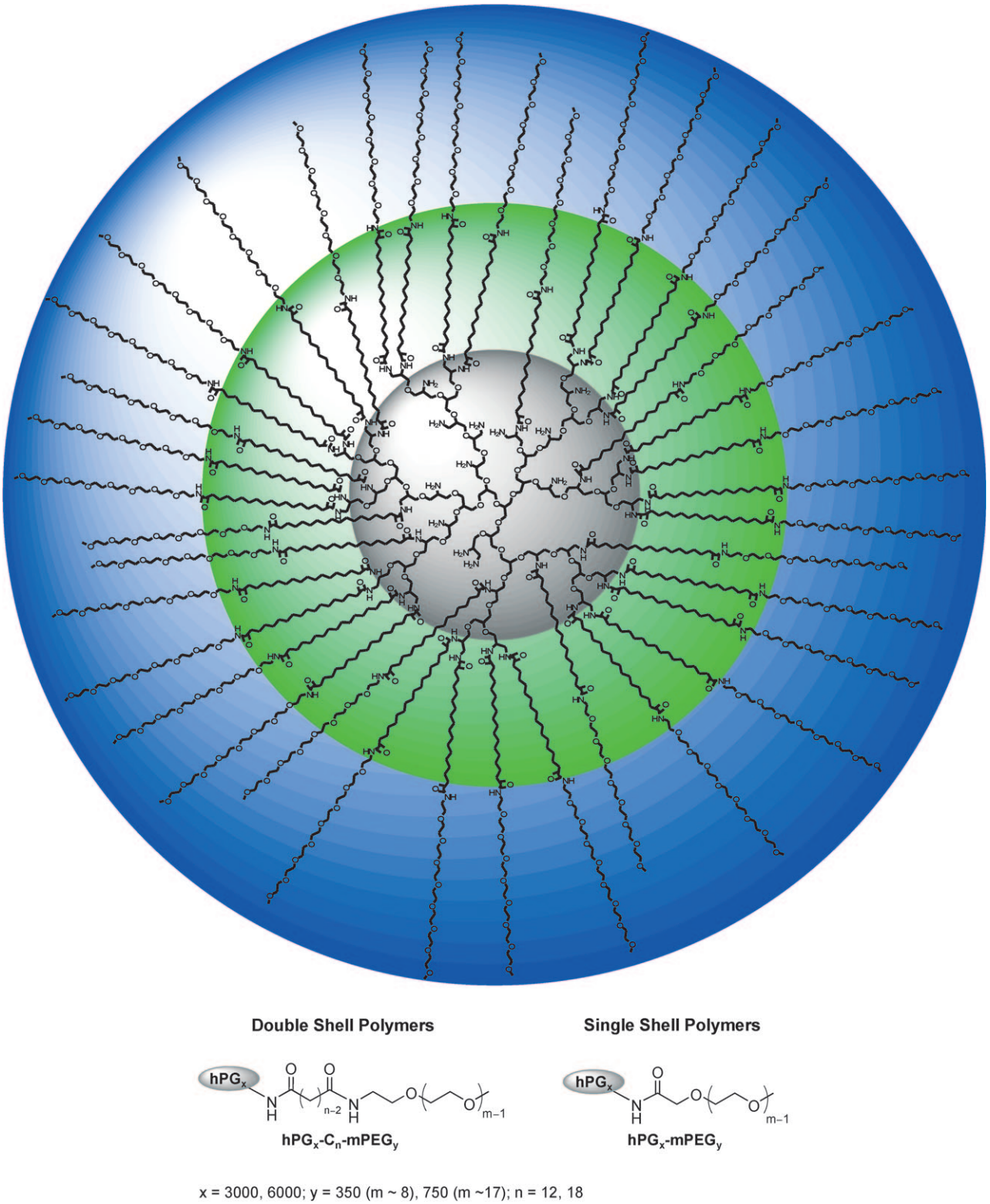

Figure 2. Schematic representation of dendritic double-shell polymer and general structures of dendritic core-multishell architectures.

As reported in several publications[6,30] the obtained enantiomeric excess depends on the hydrogen pressure and a similar behavior was observed here (Figure 3). The enantioselectivity reaches a plateau of 61% *ee* at high hydrogen pressures of around 70 bar

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Table 1. Comparison of catalytic results for Pt nanoparticles stabilized by core-shell architectures and the commercial heterogeneous catalyst in the asymmetric hydrogenation of ethyl pyruvate.[a]

Entry	Catalyst	TOF [h^{-1}]	*ee* [%][b,c]
1	**Pt@hPG$_{6000}$-C$_{12}$-mPEG$_{350}$**	2970	50
2	**Pt@hPG$_{6000}$-C$_{12}$-mPEG$_{750}$**	3110	50
3	**Pt@hPG$_{6000}$-C$_{18}$-mPEG$_{750}$**	3020	46
4	**Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$**	3540	52
5	**Pt@hPG$_{3000}$-mPEG$_{750}$**	3330	49
6	Pt/Al_2O_3	3190	56

[a] *Reaction conditions:* Pt/polymer 0.5 g g^{-1}, solvent: water/acetic acid 2:1, S/C/modifier 1000/1/1, 20 bar H_2 pressure, modification 2 h.
[b] Determined by gas chromatography.
[c] Measured after full conversion.

and no more improvement is obtained for higher pressure.

The best solvents known for this reaction are acetic acid and toluene.[8] Additionally, we tested mixtures of both solvents and as well mixtures of water with acetic acid due to the fact that the nanoparticles are synthesized in water. The results are presented in Table 2.

In pure toluene **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$** was not soluble, but as soon as acetic acid was added, the catalyst solubilized completely. The solubilized catalysts were then preconditioned by two-hour treatment with cinchonidine and after addition of ethyl pyruvate used at a hydrogen pressure of 70 bar. Table 2 shows that the highest TOFs were obtained for reactions

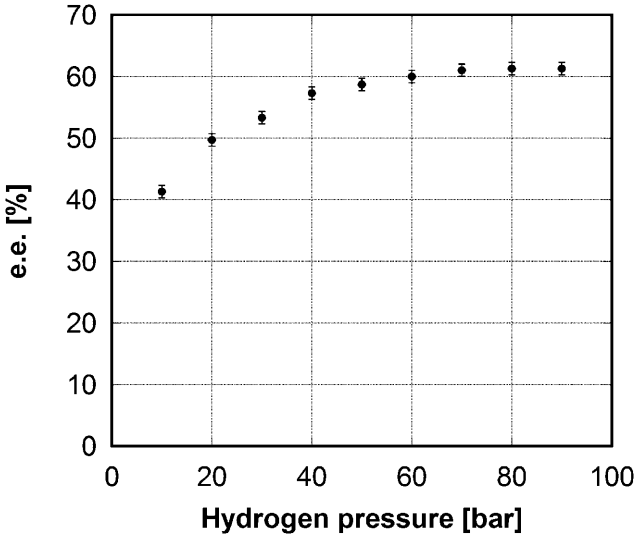

Figure 3. Pressure dependence of the enantiomeric excess in the asymmetric hydrogenation of ethyl pyruvate over cinchonidine modified **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$**. (*Reaction conditions:* Pt/polymer 0.5 g g^{-1}, water/acetic acid 2:1, S/C/modifier 1000/1/1, 1 h, modification 2 h).

Table 2. Solvent optimization for the asymmetric hydrogenation of ethyl pyruvate over cinchonidine-modified **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$**.[a]

Entry	Solvent	Mixture	TOF [h^{-1}][b]	*ee* [%][a,d]
1	water		2000	45
2	water/acetic acid	3:1	3530	55
3	water/acetic acid	1:1	4650	62
4	water/acetic acid	1:3	4010	57
5	acetic acid		2370	46
6	toluene/acetic acid	3:1	1250	60
7	toluene/acetic acid	1:1	2150	58
8	toluene/acetic acid	1:3	2350	56
9	toluene		insoluble	

[a] *Reaction conditions:* Pt/polymer 0.5 g g^{-1}, H_2 gas, S/C/modifier 1000/1/1, solvent 1 mL, modification 2 h.
[b] Determined at 20 bar H_2 pressure.
[c] Determined by gas chromatography.
[d] Determined after full conversion at 70 bar H_2 pressure.

performed in mixtures of water/acetic acid, with a less significant correlation between TOF and *ee*. The highest selectivity was also found in this series in the 1:1 water/acetic acid mixture (62% *ee*, entry 3). In toluene/acetic acid the highest *ee* was obtained for the 3:1 mixture (60% *ee*, entry 6). For further experiments the 1:1 water/acetic acid mixture was used (entry 3).

Prior reports stated that nanoparticle sizes below 4 nm in heterogeneous systems impinge upon the catalytic outcome,[31,32] where others show that with homogeneously stabilized Pt catalysts the reaction is insensitive towards the particles size.[19] With the polymeric stabilizer applied here, we are able to control the size of Pt nanoparticles to a certain extent by changing the Pt/polymer ratio used for the preparation. The lower the amount of Pt per gram of polymer, the smaller the particles are. The synthesized particles were analyzed by transmission electron microscopy (TEM) and had sizes between 2.3 and 2.8 $\pm$ 0.5 nm with relatively low standard deviations of around 20% (Table 3).

The preparation of bigger particles is achieved by using a higher ratio of Pt/polymer but results in an ineffective stabilization with precipitation after a few days. It can be seen that with increasing particle size only a slightly higher enantioselectivity can be observed with 64% *ee* for the sample with the biggest particles (Table 3, entry 5). No clear dependence of catalytic activity on the nanoparticle size is observed. The highest TOF and *ee* are obtained for the biggest particles which could indicate that bigger particles are more efficiently covered by cinchonidine. Due to the fact that catalysts with small Pt/polymer ratios are stable for a much longer time, a ratio of 0.5 g/g was used for the recycling experiment.

The amount of modifier is also known to influence the obtained enantioselectivity and several ratios of

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Table 3. Comparison of catalytic results for the asymmetric hydrogenation of ethyl pyruvate depending on the Pt nanoparticle size.[a]

Entry	Pt/polymer [g g^{-1}]	NP size [nm][b]	TOF [h^{-1}][c]	*ee* [%][d,e]
1	0.25	2.3 ± 0.5	4300	61
2	0.50	2.4 ± 0.5	4650	62
3	0.75	2.5 ± 0.5	3250	62
4	1.00	2.7 ± 0.5	4070	62
5	1.25	2.8 ± 0.5	5170	64

[a] *Reaction conditions:* **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$**, solvent water/acetic acid 1:1, S/C/modifier 1000/1/1, H_2 gas.
[b] Determined by TEM measurements.
[c] Determined at 20 bar H_2 pressure.
[d] Determined by gas chromatography.
[e] Determined after full conversion at 70 bar H_2 pressure.

modifier to Pt were investigated. Starting with 0.25 equivalents of cinchonidine, the amount was increased to 0.5, 1.0, 1.5, and 3.0 equivalents with respect to Pt. For 0.25 and 0.5 equivalents full conversion could not be obtained and the *ee*s were 29 and 42%, respectively. For 1.0, 1.5, and 3.0 equivalents of cinchonidine full conversion and *ee*s of 62, 63, and 62% were obtained. We conclude that an equimolar amount of modifier is necessary to fully cover the surface of the Pt nanoparticles, but higher amounts do not have a negative influence on the outcome of the reaction.

After optimization of the reaction conditions, comparison of **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$** with commercially available Pt/Al_2O_3 shows that both catalysts perform equally well, achieving full conversion and *ee*s of 63% and 64%, respectively, under the same reaction conditions. With a TOF of 5000 h^{-1}, the modified Pt/Al_2O_3 catalyst is similarly active (*cf.* Table 3, entry 2).

In the literature only one publication[20] was found reporting the reuse of homogeneously stabilized Pt catalysts for three consecutive runs with a stable *ee* of 55%. Given that recycling is the most important aspect of catalyst immobilization, we focused on this facet.

Experiments under optimized reaction conditions[33] were performed. In the first test it turned out that further stabilization of the catalyst is necessary to avoid precipitation of Pt during ultrafiltration after a few runs. Therefore, polymer was added to the catalyst which was prepared before with a particle size of 2.6 ± 0.5 nm (Figure 4a). The addition of extra polymer to the finished nanoparticles until a Pt/polymer ratio of 0.1 g/g does not change the size of the Pt particles which was proven by TEM measurements (Figure 4b).

For recycling the catalyst was dissolved in a 1:1 mixture of water and acetic acid. After a two-hour modification with cinchonidine, ethyl pyruvate was added and the solution was subjected to hydrogenation for 30 min at 70 bar hydrogen pressure. After each run the mixture was diluted with methanol and transferred to an ultrafiltration cell for separation of catalyst and product. After separation the catalyst was again treated with cinchonidine and subjected to the next cycle. The addition of modifier in each run is necessary because the modifier decomposes during hydrogenation as soon as the substrate is used up.[34,35]

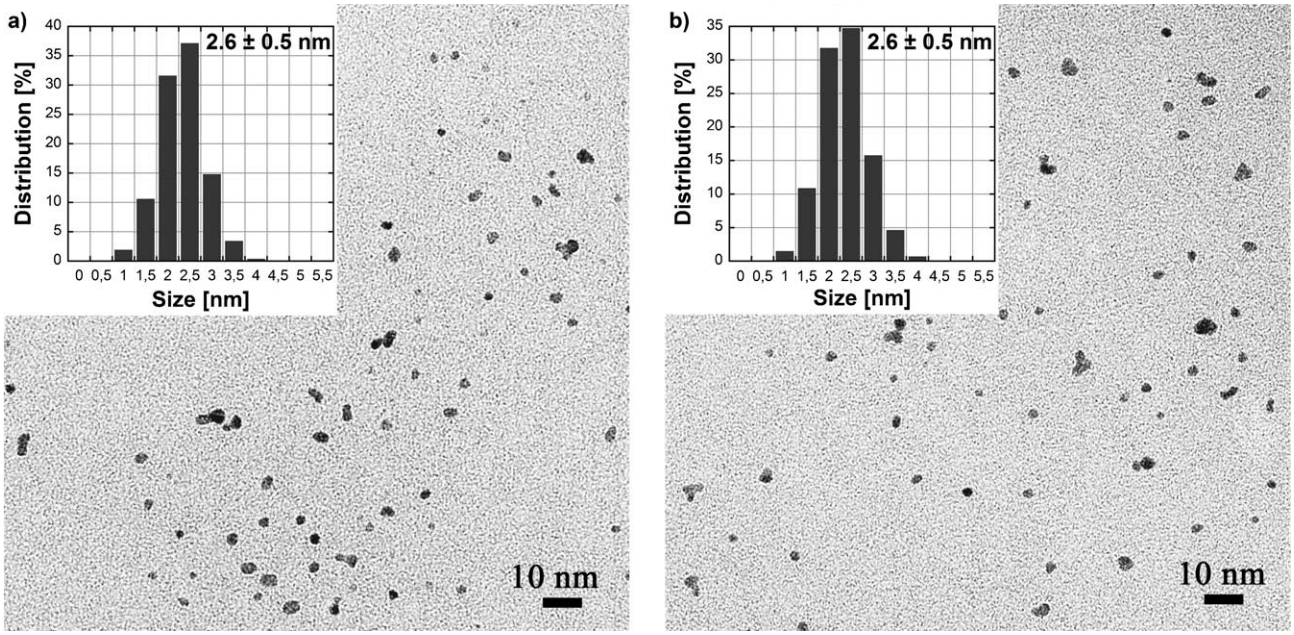

Figure 4. TEM micrographs and particles size distributions of samples (**a**) after preparation of Pt nanoparticles at Pt/polymer 0.5 g g^{-1} and (**b**) after addition of extra polymer to obtain 0.1 g g^{-1}.

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The recycling results are shown in Figure 5. Reuse was accomplished for ten runs with a stable performance for eight runs. The *ee* increased from the 1st to the 2nd run by around 10% to 71%, reached a maximum of 75% *ee* in the 5th run, and then remained stable at around 73% for all runs which accomplished full conversion. This increase in *ee* is assigned to catalyst purification during ultrafiltration which is accompanied by a relatively high metal leaching of 204 ppm into the product as determined by ICP-MS (inductively coupled plasma mass spectrometry) measurements. It is assumed that this metal leaching accounts to a fraction of very small particles that are not detectable by TEM and which cannot be efficiently modified with cinchonidine. When a previously ultrafiltrated catalyst was used, 71% *ee* was already obtained in the 1st cycle and metal leaching into the product was not detectable.

In comparison to results reported for other homogeneous catalyst systems, our system is more efficient than Pt colloids stabilized by solvent[17] or surfactant.[20] Pt nanoparticles stabilized with protonated dihydrocinchonidine[21] reached similar *ee*s of 76% while the reported results for PVP-stabilized Pt colloids are as yet inconclusive since the reported *ee*s range from 43–90%.[18,19,36,37]

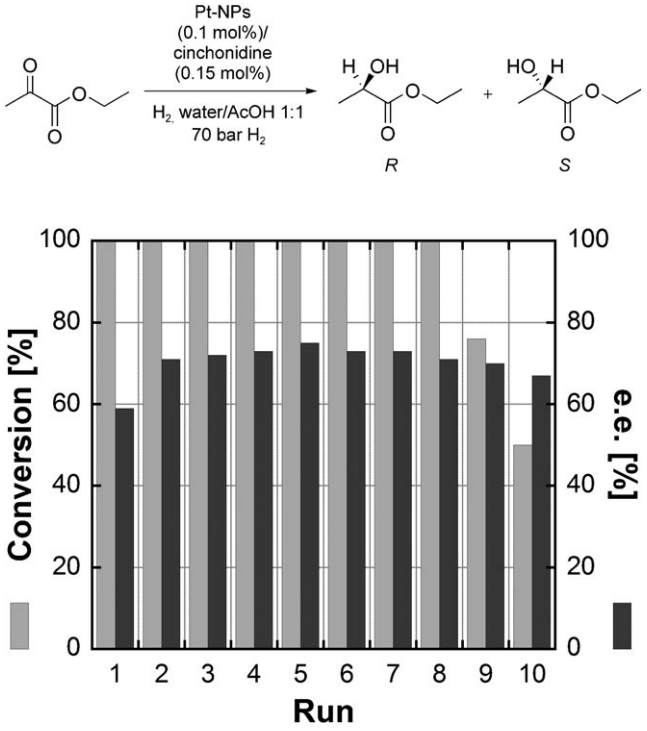

Figure 5. Recycling of homogeneously stabilized Pt nanoparticles in the asymmetric hydrogenation of ethyl pyruvate for 10 consecutive runs achieving a total turnover number of 9300 (conversion and *ee* were determined by gas chromatography).

A first precipitation of Pt on the ultrafiltration membrane was observed during work-up after the 7th and then in each following run. This precipitate can be easily removed from the membrane, which makes it possible to use the same membrane throughout the whole experiment. After the 10th run, the experiment was stopped when only 50% conversion was obtained and a significant amount of platinum was precipitated on the membrane.

To the best of our knowledge, this is the first time that homogeneously stabilized and chirally modified nanoparticles have been recycled in the asymmetric hydrogenation of ethyl pyruvate for more than three cycles[20] with such a high enantioselectivity. Recycling increased the total turnover number of the catalyst from 1000 for a single run to almost 9300 for the reused catalyst. When one aims for a turnover number of 5000 in a single run a significant reduction of the enantioselectivity to 53% *ee* is obtained after 1 h reaction time (77% conversion). Particularly interesting is the fact that after the high metal leaching in the first run (204 ppm), platinum was not detectable in the crude product after the 2nd, 3rd, and 6th runs.

To investigate the stability of the catalyst during the recycling process, TEM measurements were performed after the 1st and 5th run (Figure 6). After the 1st run a negligible decrease of the particle size occurs and the dispersion of the particles on the TEM grid is still very good. A slight increase to 2.7 ± 0.4 nm can be observed after the 5th cycle, but it can be stated that the particle size is stable throughout the experiment within the experimental error. Nevertheless, formation of aggregates can be observed. This aggregation does not lead to a significant enlargement of the nanoparticles itself, but could be due to formation of polymer aggregates with embedded Pt nanoparticles. This kind of polymer aggregates has been reported by our group for similar core-multishell architectures which were applied for the transport of dyes and drugs.[38,39] It shows that the polymer is able to inhibit Ostwald ripening which would lead to the formation of large particles, but at the same time larger aggregates form which – in the end – lead to precipitation during ultrafiltration.

Since an increase in *ee* was observed upon prior purification of the catalyst, we decided to repeat the pressure optimization with the other reaction parameters constant. It turned out that 30 bar hydrogen pressure are already enough to obtain the maximum enantioselectivity using ethyl pyruvate. When methyl pyruvate was tested as substrate, an enantiomeric excess of 67% was obtained for (*R*)-methyl lactate, where Pt/Al_2O_3 performed equally well and reached 68% *ee*.

One of the advantages of surface modification is the versatility of the catalyst because for the same catalyst different modifiers can be used, e.g., other

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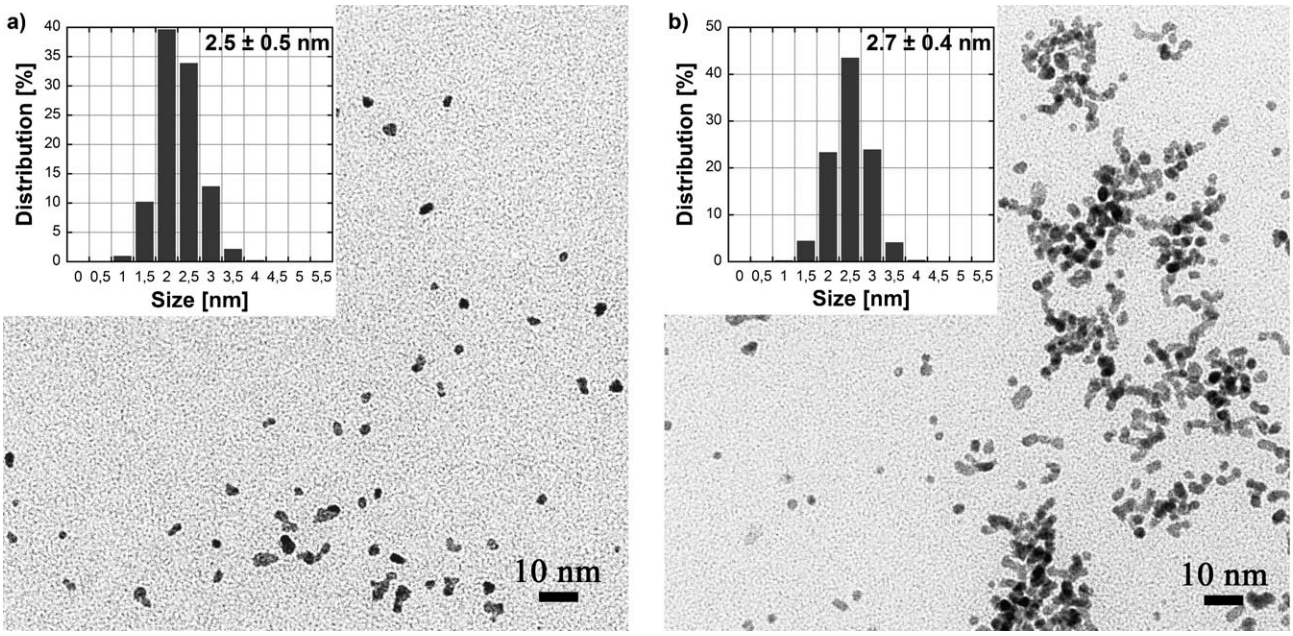

Figure 6. TEM micrographs and particle size distributions of Pt nanoparticles (**a**) after the 1st run and (**b**) after the 5th run.

chiral alkaloids which induce the formation of the other enantiomer of the product. Cinchonine, the pseudo-enantiomer of cinchonidine (see Figure 1), was used for the asymmetric hydrogenation of ethyl pyruvate. Under optimized reaction conditions 47% *ee* of (*S*)-ethyl lactate was obtained with **Pt@hPG$_{3000}$-C$_{18}$-mPEG$_{750}$** as well as with Pt/Al_2O_3. The previously ultrafiltrated nanoparticulate catalyst even gave 53% *ee* at only 30 bar hydrogen pressure which was not achieved with the heterogeneous catalyst.

Conclusions

We have presented here the asymmetric hydrogenation of ethyl pyruvate with chirally modified Pt nanoparticles that were homogeneously stabilized in dendritic core-shell architectures. We were able to show that the polymer does not disturb the chiral modification of the nanoparticles surface and allows for the favorable orientation of modifier and substrate on the nanoparticles surface thereby achieving *ee*s of up to 75%. It was demonstrated that recycling can be easily performed by ultrafiltration for at least eight cycles with stable enantioselectivity and conversion and non-detectable metal leaching after a first purification step. During the recycling experiment we observed the formation of larger polymer aggregates with embedded Pt nanoparticles by TEM, which probably leads to the final precipitation of the catalyst on the ultrafiltration membrane. It is noteworthy that after aggregation the Pt nanoparticles are still separated by the polymer shell. The homogeneous nature of the catalyst makes it also possible to use a continuously operating membrane reactor. This would avoid drying of the catalyst after separation between consecutive runs, thereby reducing stress on the catalyst to further improve its lifetime.

Experimental Section

General

^{1}H NMR and ^{13}C NMR spectra were recorded on an ECX 400 instrument (400 MHz for ^{1}H and 100 MHz for ^{13}C). Calibration was performed using the chloroform peak at 7.26 ppm for ^{1}H and 77.0 ppm for ^{13}C. IR spectra were recorded on KBr plates on a Nicolet Avator 320 FT-IR spectrometer or Jasco FT/IR 6200 spectrometer. Analytical GPC was performed on an Agilent 1100 Series equipped with a UV and RI detector and three Supremalux-columns from PSS (100, 1000, 3000 Å) in water (flow 1 mL min^{-1}); a Pullulan standard was used for calibration. Microscopy was performed on a Philips CM12 transmission electron microscope (FEI, Oregon, USA) using the low-dose protocol of the microscope at a magnification of 60,000× and 200,000× and an accelerating voltage of 100 kV (LaB6 illumination). Samples were prepared by adding droplets of the nanoparticle solution onto 400 mesh copper grids covered with a colloid/carbon film, which had been hydrophilized before use by 60 s plasma treatment at 8 W in a Baltec Med 020 device. At least 1000 particles were measured (WCIF ImageJ) for the calculation of mean diameter and standard deviation. Gas chromatography was performed on a Varian CP-3800 equipped with a test column (CP-Sil B CB; 15 m, 0.25 mm, 0.25 μm), a chiral column (CP-Chirasil-Dex CB; 25 m, 0.25 mm, 0.25 μm) and a Varian Autosampler CP-8400. The

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ee values were reproducible within 1%. ICP-MS measurements were carried out on an Element 2 system (Thermo Fisher) at low resolution (sample gas 0.863 L min^{-1}; plasma power 1350 Watt). Column chromatography was performed on silica gel 60 (230–400 mesh). Hydrogenations were carried out in an autoclave from Roth equipped with a magnetic stirrer. Ultrafiltration was performed with a 300-mL solvent-resistant stirred cell with regenerated cellulose membranes (molecular weight cut-off 5000, 10000 g mol^{-1}), both from Millipore. Ethyl and methyl pyruvates were freshly distilled prior to use. All other reagents and solvents were purchased from Acros, Fluka or Aldrich and used as received.

The general synthesis of double- and single-shell building blocks (**mPEG$_y$-C$_{n-1}$-COOH** and **mPEG$_y$-COOH**) as well as core-shell polymers (**hPG$_x$-C$_n$-mPEG$_y$** and **hPG$_x$-mPEG$_y$**) will be described elsewhere, including analytical data for **mPEG$_{750}$-C$_{17}$-COOH**, **hPG$_{3000}$-C$_{18}$-mPEG$_{750}$** and **hPG$_{3000}$-mPEG$_{750}$**.

Double Shell Building Blocks

mPEG$_{350}$-C$_{11}$-COOH: Yield: 91%. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 6.30$ (m, 1H, N*H*), 3.70–3.32 (m, PEG-backbone), 3.32 (s, 3H, mPEG-O*Me*), 2.25 (t, 2H, CH_2CH_2COOH), 2.13 (t, 2H, CH_2CH_2CONH), 1.56 (m, 4H, CH_2CH_2COOH, CH_2CH_2CONH), 1.22 [m, 12H, -$(CH_2)_6$-]; ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 177.4$, 173.5, 71.7, 70.4, 70.3, 70.0, 69.7, 58.8, 39.0, 36.4, 33.9, 29.2–28.7, 25.5, 24.6; IR (KBr): $\nu = 3336$, 2925, 2857, 1727, 1649, 1550, 1457, 1350, 1287, 1249, 1199, 1106 cm^{-1}.

mPEG$_{750}$-C$_{11}$-COOH: Yield: 91%. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 6.25$ (m, 1H, N*H*), 3.70–3.33 (m, PEG-backbone), 3.30 (s, 3H, mPEG-O*Me*), 2.22 (t, 2H, CH_2CH_2COOH), 2.10 (t, 2H, CH_2CH_2CONH), 1.53 (m, 4H, CH_2CH_2COOH, CH_2CH_2CONH), 1.19 [m, 12H, -$(CH_2)_6$-]; ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 177.0$, 173.4, 71.7, 70.6, 70.5–69.3, 58.7, 38.9, 36.3, 33.8, 29.1–28.7, 25.4, 24.5; IR (KBr): $\nu = 3506$, 3362, 2921, 2889, 1728, 1651, 1541, 1456, 1349, 1297, 1249, 1199, 1107, 949 cm^{-1}.

Double Shell Polymers

hPG$_{6000}$-C$_{12}$-mPEG$_{350}$: Yield: 51%. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 6.48$ (br s, NH), 3.80–3.32 (m, hPG- and PEG-backbone), 3.34 (s, 3H, mPEG-O*Me*), 2.13 [t, 4H, CH_2CH_2CONH(hPG), CH_2CH_2CONH], 1.55 (m, 4H, CH_2CH_2COOH, CH_2CH_2CONH), 1.22 [m, 12H, -$(CH_2)_6$-]; ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 173.4$, 71.8, 71.4–69.0, 58.9, 39.0, 36.5, 29.5–28.7, 25.7; IR (KBr): $\nu = 3289$, 3077, 2924, 2857, 2100, 1648, 1546, 1458, 1350, 1250, 1104 cm^{-1}; GPC: $M_n = 75700$ g mol^{-1}, $M_w = 91400$ g mol^{-1}.

hPG$_{6000}$-C$_{12}$-mPEG$_{750}$: Yield: 56%. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.85$–3.35 (m, hPG- and PEG-backbone), 3.34 (s, 3H, mPEG-O*Me*), 2.13 [m, 4H, CH_2CH_2CONH(hPG), CH_2CH_2CONH], 1.56 [m, 4H, CH_2CH_2CONH(hPG), CH_2CH_2CONH], 1.24 [m, 12H, -$(CH_2)_6$-]; ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 175.8$, 173.5, 71.8, 71.6–69.4, 58.9, 39.0, 36.5, 29.6–28.4, 25.7; IR (KBr): $\nu = 3304$, 3072, 2923, 2865, 2100, 1718, 1654, 1648, 1544, 1458, 1349, 1250, 1107 cm^{-1}. GPC: $M_n = 87200$ g mol^{-1}, $M_w = 136100$ g mol^{-1}.

hPG$_{6000}$-C$_{18}$-mPEG$_{750}$. Yield: 45%. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 6.43$ (br s, NH), 3.90–3.33 (m, hPG- and PEG-backbone), 3.32 (s, 3H, mPEG-O*Me*), 2.11 [t, 4H, CH_2CH_2CONH(hPG), CH_2CH_2CONH], 1.55 [m, 4H, CH_2CH_2CONH(hPG), CH_2CH_2CONH], 1.18 [m, 24H, -$(CH_2)_{12}$-]; ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 173.4$, 71.8, 71.0–69.4, 58.9, 39.0, 36.5, 29.8–28.7, 25.7; IR (KBr): $\nu = 3303$, 2918, 2851, 2100, 1642, 1553, 1466, 1349, 1251, 1111 cm^{-1}; GPC: $M_n = 117000$ g mol^{-1}, $M_w = 261700$ g mol^{-1}.

Synthesis of Pt Nanoparticles in Core-Shell Polymers

Aqueous stock solutions of polymer (10.0 mg/mL) and $H_2PtCl_6 \cdot 6H_2O$ (various concentrations) were prepared and combined according to the desired Pt/metal ratio. The volume was filled up to 500 μL (overall 1 mg Pt/mL) with water and left at room temperature for 24 h. 500 μL of a freshly prepared aqueous $NaBH_4$ solution (containing 3 equiv. $NaBH_4$ according to Pt) were added at once, upon which the solution turned dark brown to black. After another 24 h at room temperature the water was removed under vacuum and appropriate solvent was added.

Hydrogenation Procedure

The catalyst was dissolved in the appropriate solvent and the respective amount of chiral alkaloid in acetic acid (0.1 mmol/mL) was added. The mixture was stirred for 2 h, ethyl pyruvate (285 μL, 2.6 mmol, S/C 1000/1) or methyl pyruvate (232 μL, 2.6 mmol, S/C 1000/1) was added and the homogeneous mixture was conducted to hydrogenation for 1 hour. A sample was taken, filtered through a small plug of silica gel with ethyl acetate and subjected to GC analysis.

Ethyl pyruvate: conversion: test column, flow 0.7 mL min^{-1}, 40 to 70 °C with 10 °C min^{-1}, hold 1 min, to 100 °C with 20 °C min^{-1}; ethyl pyruvate 2.95 min, ethyl lactate 3.12 min; enantiomeric excess: chiral column, flow 2.5 mL min^{-1}, 40 to 100 °C with 10 °C min^{-1}; (*R*)-ethyl lactate 3.96 min, (*S*)-ethyl lactate 4.17 min.

Methyl pyruvate: chiral column, flow 2.5 mL min^{-1}, 40 to 80 °C with 10 °C min^{-1}; methyl pyruvate 3.50 min, (*R*)-methyl lactate 4.25 min, (*S*)-methyl lactate 4.45 min.

Recycling *via* Ultrafiltration

The catalyst with 3 mg Pt nanoparticles in water/acetic acid (1/1, 6 mL) was modified with cinchonidine (catalyst/modifier 1/1.5) and ethyl pyruvate (1710 μL, 15.4 mmol, S/C 1000/1) was added. After hydrogenation at 70 bar the mixture was diluted with methanol, transferred to the ultrafiltration cell and 3–5 filtration cycles were performed until the catalyst is removed from the cell, dried under vacuum and redissolved in water/acetic acid before the next run was performed.

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[29] *Reaction conditions:* catalyst: **Pt@hPG_{6000}-C_{18}-$mPEG_{750}$**, Pt/polymer 0.5 g g^{-1}, substrate/catalyst (S/C)/modifier 1000/1/1, water/acetic acid 2:1, 20 bar H_2 pressure, 1 h; modification for 24 h if not otherwise stated.
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