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Noncovalent Anchoring of Homogeneous Catalysts to Silica Supports with Well-Defined Binding Sites

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Abstract: The efficient reversible functionalization of silica with catalytic sites using noncovalent interactions is described. We prepared silica materials with well-defined binding sites that selectively bind guest molecules that are equipped with the complementary binding motif, with the interaction between the two components being based on either hydrogen bonds or metal−ligand interactions. Several phosphine ligands functionalized with glycine-urea groups, required for hydrogen bond formation to the complementary host on the silica, have been prepared. The resulting noncovalently immobilized complexes have been used as a ligand system in the Pd-catalyzed allylic substitution and Rh-catalyzed hydroformylation of 1-octene. The supramolecular interaction between the transition-metal catalyst and the binding site located at the support is sufficiently strong to enable efficient catalyst recycling. In addition, the nature of the support facilitates the de- and refunctionalization of support, allowing the recycling of both homogeneous catalysts and the functionalized support. A rhodium catalyst based on a functionalized xantphos ligand was used in the hydroformylation of 1-octene in 11 consecutive reactions without showing catalyst deterioration or metal leaching.

Introduction

The efficient separation and subsequent recycling of homogeneous transition-metal catalysts remains a topic that not only constitutes scientific challenges but also is of commercial relevance. The practical use of the ever-increasing number of tailor-made transition-metal catalysts[1] is indeed limited by the cumbersome separation from the product phase, especially for application in the fine-chemical industry.[2] For bulk chemicals, several simple unit operations are applied, such as distillation, extraction, filtration, and two-phase catalysis.[3] So far, several strategies for advanced catalyst recycling have been explored, including supported aqueous phase catalysis,[4] fluorous phase catalysis,[5] and the use of ionic liquids[6] and supercritical fluids.[7] A widely studied approach to facilitate catalyst−product separation is the attachment of homogeneous catalysts to dendritic,[8] polymeric organic, inorganic, or hybrid supports.[9,10] Unfortunately, the holy grail in this research area, a single solution to the separation problem, does not exist, and especially, problems, such as solubility of different components, catalyst instability, and metal leaching, during the recycling procedure strongly limit the utility of some of the concepts. For example, aqueous phase catalysis is limited to substrates that are soluble in water. Immobilization of inorganic materials, such as silica, has advantages due to the physical strength and chemical inertness, but the activity is generally lower than that of the homogeneous system. A decrease in activity does not necessarily occur for catalysts attached to dendrimers and (hyperbranched) soluble polymeric supports, but here, the availability of suitable membrane materials complicates the practical use.

In most supported catalysts reported so far, the catalyst has been covalently linked to the support. An interesting alternative

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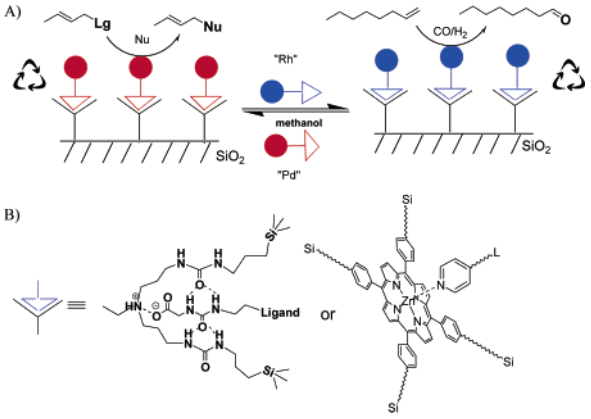
approach is the noncovalent anchoring of the catalyst to the support. Only a few examples have been reported so far, and most examples involve the immobilization via ionic interactions. Cationic transition-metal catalysts have been immobilized on heteropolyacids[11] and silica supports[12] via ion pairing. This appeared to be a viable approach for cationic rhodium catalysts that are active in hydrogenation reactions, but the concept is obviously limited to charged catalysts. In a similar approach, Mecking and Schwab immobilized NaTPPTS to a polyelectrolyte providing a polymer-bound, soluble hydroformylation catalyst that was recovered via ultrafiltration.[14] Bianchini introduced the so-called supported hydrogen-bonded catalysts in which sulfonated phosphine-based ligands are tethered to a silica surface via hydrogen bonds between the silanols and the sulfonate groups.[13] In this approach, the noncovalent interaction is established between the support and the ligand, which makes it applicable to a broader range of catalysts. Indeed, such rhodium and ruthenium complexes have been used for (enantioselective) hydrogenation[13c] and hydroformylation reactions.[13a]

Here, we report a new approach in which well-defined binding sites, based on different binding motifs, are immobilized on silica that can be noncovalently functionalized with catalysts that have ancillary ligands with the complementary motif (Scheme 1). This offers a high level of control and flexibility since, in this approach, the noncovalent anchoring is independent of the type of support and the transition metal. The reversible nature of this type of anchoring allows controlled de- and refunctionalization of the support, which enables the simple reuse of the support ultimately leading to a modular multipurpose system, and simplifies the variation of catalyst loading even during catalysis. Furthermore, the noncovalent approach simplifies the preparation of multicomponent catalysts by using different orthogonal binding motifs in a modular fashion, which can be interesting for tandem reactions. To ultimately reach this goal, we have investigated the immobilization of two well-defined binding sites on the support to which tailor-made transition-metal catalysts, with a complementary binding motif, have been assembled (Scheme 1). One binding motif is based on hydrogen bonds and ionic interactions, an interaction that was previously used to functionalize dendrimers,[15] and the other motif is based on metal−ligand interactions,[16] and in principle, these interactions are orthogonal.

Scheme 1. General Concept of Supramolecular Anchoring of Catalysts Using Binding Sites that are Immobilized on Silica Support (A), and the Two Binding Motifs Explored in this Paper (B)



Experimental Section

Materials. Amorphous silica powder (silica 60, 70−200 μm, surface area = 550 m^2/g) was obtained from Fluka and dried under vacuum at 110 °C overnight before being used. 1-Octene was purified over neutral alumina prior to its use. All other chemicals were purchased commercially and used without further purification. Solvents were dried prior to their use. Hexane, pentane, diethyl ether, THF, and toluene were distilled from sodium. Dichloromethane and triethylamine were distilled under nitrogen from calcium hydride/benzophenone. All solutions and solvents not stated above were degassed under argon prior to their use. All experiments were performed using standard Schlenk techniques under an argon atmosphere.

A. Analytical Techniques. NMR spectra were recorded on a Varian mercury 300 or Inova 500 spectrometer. ^{31}P and ^{13}C spectra were measured ^{1}H decoupled. TMS was used as a standard for ^{1}H and ^{13}C NMR, and 85% H_3PO_4 in H_2O was used for ^{31}P NMR. Mass spectra

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(FAB) were recorded on a JEOL JMS SX/SX102A instrument. Elemental analysis was carried out by Kolbe, Microanalytische Laboratorium, Mülheim. The amounts of palladium and rhodium were determined with induced coupled argon plasma-atomic emission spectrometry (ICP-AES). The ICP-AES measurements were determined with a sequential Jarrell Ash upgraded (model 25) atomscan model 2400 ICP scanning monochromator and a Perkin-Elmer Optima 3000 XL instrument. Gas chromatography was performed on an Interscience HR GC Mega 2 apparatus (split/splitless injector, J & W Scientific, DB1 = 30 m column, film thickness = 3.0 mm, carrier gas = 70 kPa He, F. I. D. detector). FT-IR spectra were obtained on a Bio-Rad FTS-7 spectrophotometer. UV−vis spectroscopy experiments were performed on an HP 8453 UV−visible system. Melting points were determined on a Gallenkamp MFB-595 melting point apparatus in open capillaries and were reported uncorrected.

Synthesis of 1. DAB-dendr-$(NH_2)_4$ (0.12 g, 0.38 mmol) was dissolved in 5 mL of dichloromethane. 3-Triethoxysilylpropylisocyanate (0.42 g, 1.70 mmol) was added, and the mixture was stirred for 3 h at room temperature. The mixture was precipitated by addition to a stirred diethyl ether solution (20 mL), and the pure white solid was collected by filtration, which yielded 0.42 g (85%). Mp 91−92 °C dec. ^{1}H NMR (500 MHz, $CDCl_3$): δ 5.87 (br, 2 H), 5.52 (br, 2 H), 3.83 (q, J = 6.5 Hz, 8 H), 3.24 (br t, 8 H), 3.18 (br, 8 H), 2.40 (br, 12 H), 1.59−1.64 (m, 12 H), 1.24 (t, J = 6.5 Hz, 12 H), 0.66 (br, 12 H). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 159.5 (s), 58.6 (s), 53.6 (s), 51.7 (s), 43.1 (s), 38.8 (s), 27.9 (s), 24.8 (s), 24.0 (s), 18.5 (s), 7.9 (s). FT-IR (KBr): 3338, 1629 cm^{-1}. HRMS (FAB$^+$) m/z calcd for $C_{56}H_{124}N_{10}O_{16}Si_4$ [M + H] 1305.8352. Found 1305.8368. Anal. Calcd for $C_{56}H_{124}N_{10}O_{16}Si_4$: C, 51.50; H, 9.57; N, 10.73. Found: C, 51.75; H, 9.77; N, 10.78.

Synthesis of 2. A quantity of 100 mg (0.13 mmol) of zinc(II) tetra-4-aminophenylporphyrin was dissolved into 20 mL of dry DMF. After 132.8 mg (0.56 mmol) of 3-triethoxysilylpropylisocyanate was added, the mixture was stirred at 80 °C for 5 h. The solvent and excess of the reagent were removed under high vacuo to afford the pure product, which yielded 200 mg (90%). ^{1}H NMR (DMSO): δ 8.80 (s, 8 H), 8.01 (d, J = 7.5 Hz, 8 H), 7.79 (d, J = 8.4 Hz, 8 H), 6.40 (s, 4 H), 5.80 (s, 4 H), 3.77 (q, J = 7.2 Hz, 24 H), 3.19 (t, J = 7.2 Hz, 8 H), 1.58 (m, 8 H), 1.13 (t, J = 6.9 Hz, 36 H), 0.63 (t, J = 7.2 Hz, 8 H). ^{13}C NMR (75.5 MHz, DMSO): δ 159.5 (s), 155.1 (s), 153.3 (s), 140.5 (s), 136.5 (s), 135.8 (s), 126.2 (s), 117.6 (s), 63.1 (s), 47.2 (s), 28.7 (s), 23.9 (s), 12.7 (s). FT-IR (KBr): 3360, 1635, 1618 cm^{-1}. MS (FAB$^+$) m/z calcd for $C_{84}H_{116}N_{12}O_{16}Si_4Zn$ [M + H] 1728.7. Found 1728.7. Anal. Calcd for $C_{84}H_{116}N_{12}O_{16}Si_4Zn$: C, 58.40; H, 6.77; N, 9.73. Found: C, 58.51; H, 6.73; N, 9.82.

Synthesis of 5. At −78 °C, 8.5 mL of *n*-butyllithium (1.64 M in pentane, 13.90 mmol) was added dropwise to a stirred solution of 4,5-dibromo-2-(5-bromopentyl)-7-hexyl-9,9-dimethylxanthene (4.0 g, 6.64 mmol) in 200 mL of Et_2O. The resulting suspension was stirred for another 2 h at −78 °C. Next, a solution of 2.55 mL of chlorodiphenylphosphine (13.9 mmol) in 10 mL of ether was added, and the reaction mixture was slowly warmed to room temperature and stirred overnight. A quantity of 20 mL of 4 M hydrochloric acid was then added to quench the reaction mixture. The water layer was removed, and the organic layer was dried with $MgSO_4$. The solvents were removed in vacuo, and the residual white solid was washed with pentane and purified by flash column chromatography (eluent: 10% dichloromethane in light petroleum ether), which yielded 2 g (37%). Mp 140−141 °C dec. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.19−7.22 (m, 24 H), 3.45 (t, J = 6.9 Hz, 2 H), 3.32 (t, J = 6.9 Hz, 2 H), 2.41 (t, J = 7.5 Hz, 2 H), 1.76 (q, J = 7.2 Hz, 2 H), 1.62 (s, 2 H), 1.45−1.17 (m, 4 H), 0.84 (t, J = 6.6 Hz, 3 H). ^{31}P NMR (121.4 MHz, $CDCl_3$, versus H_3PO_4): δ −17.2. ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 150.2 (t, J = 10.0 Hz), 137.5 (s), 136.8 (s), 134.1 (t, J = 10.2 Hz), 132.2 (s), 132.1 (s), 129.9 (s), 129.6 (s), 128.5 (s), 128.4 (s), 128.3 (s), 126.6 (s), 45.1 (s), 35.5 (s), 35.2 (s), 33.9 (s), 32.7 (s), 32.0 (s), 31.8 (s), 31.4 (s), 30.5 (s), 28.8 (s), 27.6 (s), 22.7 (s), 14.2 (s). FT-IR (KBr): 2957, 2925, 2854, 1421 cm^{-1}. MS (FAB$^+$) m/z calcd for $C_{50}H_{53}BrOP_2$ [M + H]$^+$ 811.2. Found 811.2. Anal. Calcd for $C_{50}H_{53}BrOP_2$: C, 73.98; H, 6.58. Found: C, 73.77; H, 6.51.

Synthesis of 6. A quantity of 0.50 g (0.61 mmol) of **5** was dissolved into 15 mL of THF. Under argon, the solution was transferred into an autoclave (100 mL). After addition of 20 mL of liquid NH_3, the mixture in the autoclave was stirred and heated at 70 °C for 16 h. THF was removed in vacuo, and the residue was dissolved in 20 mL of dichloromethane and washed with 10 mL of water. The organic layer was separated and dried over $MgSO_4$. A white solid was obtained after purification after flash column chromatography (eluent: 30% dichloromethane in light petroleum ether), which yielded 0.41 g (89%). Mp 131−132 °C dec. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.24 (m, 24 H), 6.35 (br s, 2 H), 2.64 (t, J = 6.50 Hz, 2 H), 2.43(m, 4 H), 1.67 (s, 6 H), 1.41 (m, 6 H), 1.26−1.21 (m, 8 H), 0.87 (t, J = 6.5 Hz, 3 H). ^{31}P{^{1}H} NMR (121.4 MHz, $CDCl_3$, versus H_3PO_4): δ −16.6. ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 150.8 (t, J = 12.3 Hz), 137.6 (t, J = 5.9 Hz), 137.1 (s), 136.8 (s), 133.8 (t, J = 10.9 Hz), 131.8 (s), 129.6 (s), 129.4 (s), 128.0 (s), 126.1 (s), 125.0 (s), 42.0 (s), 35.2 (s), 34.4 (s), 33.4 (s), 31.8 (s), 31.5 (s), 31.2 (s), 31.0 (s), 28.5 (s), 26.1 (s), 22.5 (s), 14.0 (s). FT-IR (KBr): 3453, 3053, 2961, 2854 cm^{-1}. MS (FAB$^+$) m/z calcd for $C_{50}H_{55}NOP_2$ [M + H]$^+$ 748.4. Found 748.5. Anal. Calcd for $C_{50}H_{55}NOP_2$: C, 80.29; H, 7.41; N, 1.87. Found: C, 80.38; H, 7.46; N, 1.84.

Synthesis of 7. To a solution of 0.25 g (0.33 mmol) of **6** in 10 mL of dichloromethane was added 0.038 mL (0.35 mmol) of ethylisocyanatoacetate. After the mixture was stirred overnight at room temperature, the solvent was evaporated. The product was recrystallized from dichloromethane/pentane and obtained as a white solid, which yielded 0.25 g (85%). Mp 85−86 °C dec. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.29−7.18 (m, 24 H), 6.34 (s, 1 H), 6.33 (s, 1 H), 4.21 (q, J = 7.5 Hz, 2 H), 3.98 (s, 2 H), 3.11 (t, J = 7.0 Hz, 2 H), 2.41 (t, J = 7.5 Hz, 4 H), 1.64 (s, 6 H), 1.43 (m, 6 H), 1.29 (t, J = 7.0 Hz, 3 H), 1.25−1.20 (m, 8 H), 0.86 (t, J = 6.5 Hz, 3H). ^{31}P NMR (121.4 MHz, $CDCl_3$, versus H_3PO_4): δ −17.3. ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 171.4 (s), 158.3 (s), 137.8 (m), 137.7 (s), 137.4 (s), 136.9 (s), 134.0 (m), 132.2 (m), 132.1 (m), 131.9 (s), 129.8 (s), 129.7 (s), 128.2 (br s), 126.4 (s), 61.5 (s), 42.4 (s), 40.7 (s), 35.5 (s), 34.7 (s), 32.0 (s), 31.8 (s), 31.4 (s), 30.1 (s), 28.8 (s), 26.4 (s), 22.7 (s), 14.3 (s), 14.2 (s). FT-IR (KBr): 3364, 3051, 2930, 2856, 1751, 1637 cm^{-1}. MS (FAB$^+$) m/z calcd for $C_{55}H_{62}N_2O_4P_2$ [M + H]$^+$ 877.4. Found 877.5. Anal. Calcd for $C_{55}H_{62}N_2O_4P_2$: C, 75.32; H, 7.13; N, 3.19. Found: C, 75.26; H, 7.06; N, 3.17.

Synthesis of 8. A solution of 15.0 mg of NaOH (0.37 mmol) in 4 mL water was added to a solution of 0.27 g (0.31 mmol) of **7** in 5 mL of THF. After the mixture was stirred overnight, the THF was evaporated and the reaction mixture was neutralized by addition of 2 mL of 0.40 M aqueous HCl. The solvent was decanted, and the crude product was washed with water. After recrystallization from chloroform, a white powder was obtained, which yielded 0.13 g (49%). Mp 95−96 °C dec. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.28−7.17 (m, 24 H), 6.35 (s, 1 H), 6.33 (s, 1 H), 3.91 (s, 2 H), 3.46 (t, J = 7.5 Hz, 2 H), 2.41 (t, J = 7.5 Hz, 4 H), 1.65 (s, 6 H), 1.43 (m, 6 H), 1.29−1.20 (m, 8 H), 0.86 (t, J = 6.5 Hz, 3 H). ^{31}P NMR (121.4 MHz, DMSO, versus H_3PO_4): δ −13.43. ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 171.3 (s), 151.1 (t, J = 13.7 Hz), 137.8 (m), 137.7 (s), 137.4 (s), 136.8 (s), 134.1 (m), 132.3 (m), 132.0 (m), 131.9 (s), 129.8 (s), 129.7 (s), 128.2 (br s), 126.4 (s), 46.4 (s), 38.8 (s), 35.5 (s), 34.7 (s), 32.0 (s), 31.7 (s), 31.4 (s), 30.9 (s), 28.8 (s), 26.3 (s), 22.7 (s), 14.2 (s). FT-IR (KBr): 3386, 3051, 2927, 2855, 1773, 1654, 1565 cm^{-1}. HRMS (FAB$^+$) m/z calcd for $C_{53}H_{58}N_2O_4P_2$ [M − OH]$^+$ 831.4. Found 831.4. Anal. Calcd for $C_{53}H_{58}N_2O_4P_2$: C, 74.98; H, 6.89; N, 3.30. Found: C, 74.62; H, 6.77; N, 3.21.

B. Synthesis of Silica-Immobilized Host Material: Si-I, Si-II, and Si-III. Si-I. A quantity of 1.0 g of silica was dried at 180 °C under reduced pressure for 2 h. To a suspension of the silica in 15 mL of toluene was added 0.1 g (0.0767 mmol) of **1**, and the resulting mixture

was refluxed for 5 h. The silica was isolated by filtration, washed with toluene, and dried under vacuo. Analysis of the solution showed that all of the host material **1** was attached to the silica. The subsequent silica modification was performed by refluxing a mixture of 1 g of the modified silica and 1 mL of dimethoxydimethylsilane in 15 mL of toluene for 2 h. The resulting Si-I was washed with toluene, dried under reduced pressure, and stored under argon.

Si-II. A quantity of 0.1 g of **1** (0.0767 mmol) was dissolved in 3 mL of THF. One milliliter of H_2O and 1 mL of $Si(OMe)_4$ were subsequently added. Gelation took place within 1 h. After 36 h, the gel was carefully dried under reduced pressure. The dried gel was made into a powder and thoroughly washed with MeOH, THF, and Et_2O. The resulting silica was further modified by refluxing with 1 mL of dimethoxydimethylsilane in 15 mL of toluene for 2 h. The resulting Si-II was washed with toluene, dried under reduced pressure, and stored under argon.

Si-III. To a suspension of the silica (1.55 g, predried at 180 °C under vacuo for 2 h) in 15 mL of toluene was added 0.15 g (0.0868 mmol) of **2**, and the resulting mixture was refluxed for 5 h. The silica was washed with toluene and dried under vacuo. Subsequently, silica modification was carried out by refluxing a mixture of 1 g of silica and 1 mL of dimethoxydimethylsilane in 15 mL of toluene for 2 h. The resulting Si-III was washed with toluene, dried under reduced pressure, and stored under argon.

Determination of Binding Constants Using ^{1}H NMR Titrations. ^{1}H NMR titration experiments were performed to determine the association constants (K_1 and K_2) related to the binding of the first and the second guest ligand in the two binding pockets of **1**, respectively.

$$H + G \overset{K_1}{\rightleftharpoons} HG$$

$$HG + G \overset{K_2}{\rightleftharpoons} HG_2$$

The ^{1}H NMR titrations were carried out on an Inova 500 spectrometer (500 MHz). For a typical experiment, stock solution A, containing 1.05 mM of **1** [14.692 mg of **1** in 10 mL of CD_3Cl (dry and free of acid)], and stock solution B, containing 2.90 mM of guest **3** and 1.05 mM of **1** (5.684 mg of **3** (or **4**) in 5 mL of stock solution A), were prepared. Twelve 5-mm NMR tubes were filled to a total volume of 0.6 mL by the addition of different volumes of stock solutions A and B. All titrations were performed at 298 K. Typically, the chemical shift of the CH_2 next to the amine of **1** and the urea protons was monitored, and ^{1}H NMR titration curves were analyzed with a fitting program developed by Hunter et al., which details the equations given in the paper.[21]

Determination of Adsorption Constants. The adsorption constants were determined according to a procedure analogous to that described previously.[22] A stock solution of 0.97 mM of **4** in dichloromethane (4.817 mg of **4** in 10 mL of dried CH_2Cl_2) was prepared. For each data point, a different volume of stock solution (100−500 μl) was transferred into a UV cuvette and then diluted into 5 mL of solution. After different amounts of silica−I (1.0−7.0 mg) were added to this solution, the mixture was shaken at room temperature for 2 h. The concentration of guest **4** in free solution was determined by UV−vis spectroscopy experiments using an HP 8453 UV−visible system. Analysis of the data with a nonlinear regression program led to a value of $K = 2 \times 10^4$ M^{-1} and a binding site of 17×10^{-5} (mol/g silica).

C. Catalytic Procedures. Allylic Amination Using Noncovalently Immobilized Palladium Catalysts. At room temperature and under argon, a mixture of 5×10^{-6} mol of $[Pd(croty)Cl]_2$, 1×10^{-5} mol of ligand **4**, and 250 mg of the Si-I was stirred in 5 mL of dichloromethane for 30 min. After the catalyst was washed with dichloromethane, catalysis began with the addition of 1.0 mmol of crotyl acetate and 2.0 mmol of freshly distilled piperidine in 5 mL of dichloromethane. The reaction mixture was monitored in time by quenching samples in DBA/Et_2O (DBA is dibenzylideneacetone) and analyzed by GC for the conversion and product distribution. Subsequent catalytic runs were performed after the products were removed and the noncovalently anchored catalyst was washed with dichloromethane.

Allylic Alkylation Using Noncovalently Immobilized Palladium Catalysts. A mixture of 5×10^{-6} mol of $[Pd(allyl)Cl]_2$, 1×10^{-5} mol of ligand **6**, and 140 mg of Si-III in 5 mL of CH_2Cl_2 was stirred for 30 min. After the catalyst was washed with CH_2Cl_2, catalysis began with the addition of 5 mL of CH_2Cl_2, 1.0 mmol of crotyl acetate, 2.0 mmol of diethyl-2-methylmalonate, 2.0 mmol of BSA [*N*,*O*-bis(trimethylsilyl)-acetamide], and a catalytic amount of KOAc (1.5 mg). The reaction mixture was monitored by taking samples from the reaction mixture that, after an aqueous workup, were analyzed by GC using decane as the internal standard. Subsequent catalytic runs were performed after the products were removed and the supported catalyst was washed with CH_2Cl_2.

Hydroformylation of 1-Octene. A typical catalysis experiment included the following: a stainless steel 50 mL autoclave, equipped with a mechanical stirrer, a substrate vessel, and a cooling spiral. A sample outlet was charged with 1×10^{-5} mol of $Rh(acac)(CO)_2$, 1×10^{-4} mol of ligand **4**, **6**, or **8**, 1.2 g of Si-I or Si-III, and 20 mL of toluene. The suspension was incubated for 1 h at 80 °C under 20 bar CO/H_2 (1:1). A mixture of 1 mL of 1-octene and 1 mL of decane was added, and the CO/H_2 pressure was brought to 50 bar. The mixture was stirred for 20 h. The autoclave was cooled to 10 °C, and the pressure was reduced to 1.8 bar. With this small overpressure, the liquid was slowly removed from the catalyst with a 1.2-mm syringe. After the catalyst was washed with 5 mL of toluene, 20 mL of toluene was added and the pressure was brought to 20 bar. Finally, the mixture was heated to 80 °C, and the second cycle was performed.

Results and Discussion

Synthesis of Binding Motifs and Guest Ligands. The binding site previously used to anchor the catalyst to the periphery of dendrimers comprises two urea groups and a basic amine, and binding is based on four hydrogen bonds between three urea groups and a proton transfer from the guest acid function to the amine base of the dendrimer host. Since the binding in this motif was compatible with the catalytic reaction conditions and resulted in binding sufficiently strong to enable catalyst recycling, we decided to immobilize a similar binding motif on silica. For this purpose, we used the first generation DBA dendrimer, which was reacted with 3-triethoxysilylpropylisocyanate to give host **1** as a white powder in one step in 85% yield (Scheme 2).

Porphyrin molecules are frequently used building blocks in supramolecular chemistry, and we recently showed that as-

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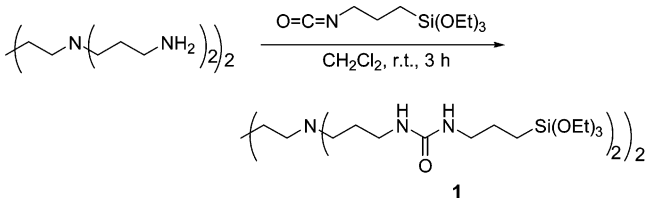
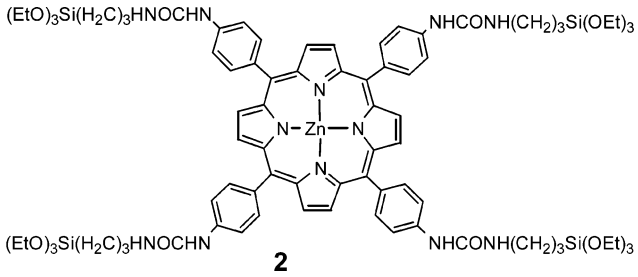
(18) Bettelheim, A.; White, B. A.; Raybuck, S. A.; Murray, R. W. *Inorg. Chem*. **1987**, *26*, 1009−1017.
(19) Bronger, R. P. J.; Kamer, P. C. J.; Reek, J. N. H.; van Leeuwen, P. W. N. M. *Organometallics* **2003**, *22*, 5358−5369.
(20) (a) Deschler, U.; Kleinschmit, P.; Panster, P. *Angew. Chem*. **1986**, *98*, 237−253. (b) Wieland, S.; Panster, P. *Catal. Org. React*. **1995**, *62*, 383−392.
(21) We have analyzed the titration curves with a fitting program developed by Hunter et al.: Bisson, A. P.; Hunter, C. A.; Carlos, J. *Chem.−Eur. J*. **1998**, *4*, 845−851.
(22) Jang, B. B.; Lee, K. P.; Min, D. H.; Suh, J. *J. Am. Chem. Soc*. **1998**, *120*, 12008−12016.

Scheme 2. Synthesis of Host Molecule **1** in One Step from Commercially Available Compounds



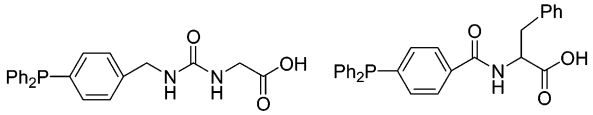
1

semblies based on axial pyridine coordination to zinc porphyrins are stable under catalytic conditions, as tested in various reactions.[16] In addition, this interaction is orthogonal to that of **1** since pyridines and amines do not bind to **1** and glycine-urea functional groups have no significant interaction with **2**. Therefore, we decided to also investigate the use of such metal−ligand interactions as a means to noncovalently anchor transition-metal catalysts. To this end, we immobilized zinc porphyrins as binding sites on silica material, which could be used as noncovalent support for phosphine-based transition-metal complexes equipped with a nitrogen donor for the anchoring process.[17] For this purpose, we functionalized the *para*-tetraamino zinc(II) porphyrin with trialkoxysilane groups using 3-triethoxysilylpropylisocyanate, giving building block **2** in 90% yield.[18]



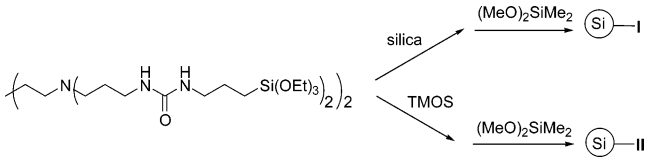
2

Catalysts that can be noncovalently anchored to the binding site of **1** are those functionalized with the complementary binding motif (i.e., a glycine-urea group). We have prepared phosphines **3** and **4** according to the procedures previously reported.[15c] Note that guest phosphine **4** is functionalized with an amide function instead of a urea group, and complexation with the host material will be based on three hydrogen bonds. In addition, the molecule contains an extra phenyl group to improve solubility in apolar organic solvents.



3 **4**

Scheme 4. Two Different Routes for Preparing Silica-Immobilized Host Materials



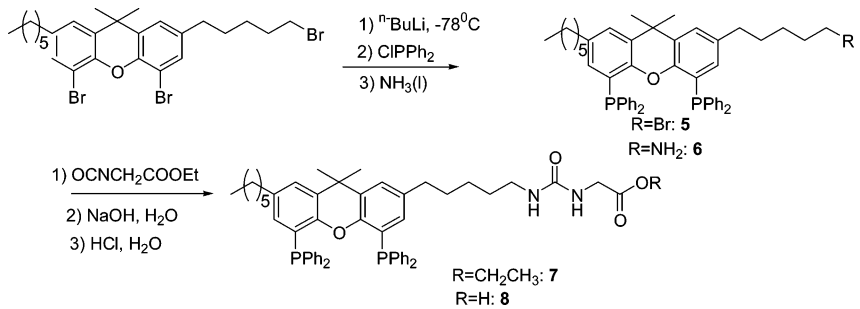
From previous work in this area, we know that certain bidentate phosphine ligands[10b,10c] lead to metal−ligand interactions sufficiently strong to suppress metal leaching; so, we decided to functionalize a xantphos analogue with the required binding motifs. To this end, 4,5-dibromo-2-(5-bromopentyl)-7-hexyl-9,9-dimethylxanthene[19] was converted to the dilithio derivative by treatment with *n*-BuLi, and subsequent reaction with chlorodiphenylphosphine afforded the bromo derivative **5** (37% yield), which was further transferred into derivative **6** in 89% yield with liquid ammonia at elevated temperatures. Reaction of **6** with the commercially available ethylisocyanatoacetate yielded ester derivative **7** in 85% yield. After hydrolysis of the ester and recrystallization from chloroform, pure **8** was isolated in 49% yield as a white powder. Diphosphine guest **8** is thus prepared using four standard reactions (Scheme 3).

Immobilization of the Host Molecules of 1 and 2 on Silica. Host molecule **1** was immobilized on silica by grafting it to commercially available silica and by using the sol−gel technique[20] (Scheme 4). Both methodologies are based on straightforward experimental procedures. Si-I was obtained after a suspension of **1** (0.1 g) and silica (1.0 g) in toluene was refluxed for 5 h, leading to quantitative grafting of the host material. The sol−gel procedure involved the overnight stirring of a solution of **1** and tetramethyl orthosilicate (TMOS) in THF/H_2O. The resulting gel was dried and crushed into free-flowing silica, resulting in **1** being immobilized on a polysilicate support. The surfaces of the silica materials were modified by reaction with dimethoxydimethysilane in order to cap the free acidic silanols. To this end, a suspension of either Si-I or Si-II was refluxed for 2 h in toluene in the presence of dimethoxydimethylsilane.

Si-III was prepared by refluxing a suspension of Zn porphyrin **2** (0.15 g) and 1.0 g of commercially available silica in toluene for 5 h. Again, the remaining free acidic silanols on the surfaces of the silica were modified by reaction with dimethoxydimethysilane.

Binding of Guest Ligands to Silica Host Materials. The binding of guest ligands **3** and **4** into the binding sites of **1** was first studied in solution by NMR spectroscopy. Upon the addition of **3**, the protons of the urea groups of **1**, as well as the CH_2 groups next to the amine, shifted downfield in a fashion

Scheme 3. Synthesis of Glycine-Urea-Modified Xantphos Diphosphine **8** in Four Steps



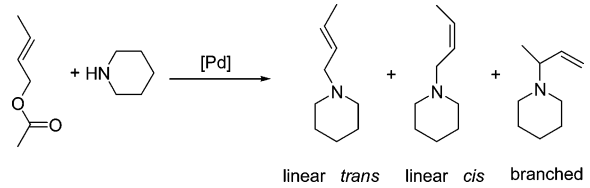
similar to that previously observed, with the binding into the dendrimers functionalized with the same binding sites.[15] The binding constants were determined by fitting the titration curves and by assuming that K_1 and K_2 are not equal.[21] A negative cooperative effect was observed; for guest **3**, we found that K_2 (3×10^3 M^{-1}) is an order of magnitude lower than K_1 (8×10^4 M^{-1}), and for guest **4**, a similar effect was observed (K_1 and K_2 are 3×10^4 and 3×10^2 M^{-1}, respectively). This effect is very likely due to the proximity of the two basic functions of the host. As expected, the binding constant of **4** is lower than that of **3** since only three hydrogen bonds are involved in the binding process and the benzyl group might induce some steric hindrance. In general, the binding of the first guest is higher compared to that of the second one, and the exchange of bound and free guests is fast on the NMR time scale under the conditions applied (500 MHz, room temperature).

To compare the binding behavior of the guests in the silica-immobilized binding sites with that of **1** in free solution, we have measured the adsorption constant of **4** to Si-I.[22] We monitored the concentration of **4** in dichloromethane solution using UV−vis spectroscopy in the presence of various amounts of Si-I. From the analysis of the titration curve, we found that 17×10^{-5} (mol/g silica) binding sites for guest **4** are available, with an adsorption constant of $K = 2 \times 10^4$ M^{-1}. This is consistent with the numbers from the experimental procedure, which shows that we immobilized 9×10^{-5} mol of host **1** onto the surface of 1 g of silica, which indicates that almost all of the binding sites of **1** are accessible and able to bind two guests.

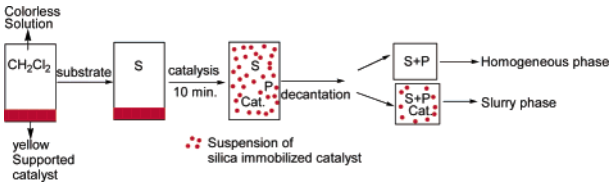
We performed an additional experiment to determine the binding efficiency with respect to the recycling procedures of guest ligand **4** being anchored to Si-I or Si-II. A precise amount of Si-I and 2 equiv of guest **4** were added to a dichloromethane solution, and the suspension was stirred for 20 min. Subsequently, we filtered the solution and washed the silica with dichloromethane (eight times) to simulate the recycling procedure. The filtrate was concentrated to recover unbound guest **4**. Next, the silica layer was washed with methanol several times, and the filtrate was concentrated to afford guest **4**, which remained bound to Si-I during the previous "recycling procedures". We found that approximately 1 equiv of the guest was bound sufficiently strong to the silica during the washing with dichloromethane, which is in line with the difference in the binding constant observed for the first and the second guest molecule ($K_2 = 300$ M^{-1}, which is insufficient). The guest molecules that remained bound during the dichloromethane washing procedure were recovered quantitatively after washing with methanol, indicating that the binding is fully reversible and controllable by choosing the proper solvent. When the ester of guest **4**, a ligand that does not significantly bind to the binding site of host molecule **1**, was subjected to the same experimental procedure, we found that nothing remained on the silica during the washing procedure with dichloromethane. In addition, guest **4** was found to have no interaction with the capped silica material, indicating that the binding site is, indeed, essential in these systems.

Similar experiments with Si-II showed that slightly less than 1 equiv remained on the silica during the washing process with dichloromethane. Probably, part of the host molecules **1** become inaccessible as a result of the sol−gel procedure[20] because they are situated in the narrow pores of the material. Therefore, we decided to use Si-I for the subsequent catalytic reactions.

Scheme 5. Palladium-Catalyzed Allylic Amination of Crotyl Acetate Using Piperidine as the Nucleophile



Scheme 6. Schematic Representation of the Control Experiment that Proves Catalysis Takes Place at the Noncovalently Functionalized Support



Compound **6** contains a primary amino group, which is a functional group that can be used for noncovalent anchoring to Zn porphyrin functionalized silica material. The binding constant of **6** to Zn porphyrin **2** in toluene solution was determined via titrations monitored by UV−vis spectroscopy and was found to be in the expected range ($K_{ass} = 2.2 \times 10^4$). The adsorption constant of guest **6** to Si-III was determined in a way similar to that described above and was found to be around 1.0×10^5. The number of binding sites available (7.4×10^{-5} mol/g silica) was, again, in line with that expected based on the experimental procedure (8.7×10^{-5} mol of host **1** was grafted to the surface of 1 g of silica), which indicates that nearly all binding sites are accessible and able to bind to guest ligand **6**.

Catalysis. Allylic Amination Using a Palladium Catalyst Immobilized via Hydrogen Bonds. We studied the Pd-catalyzed allylic amination[23,24] as a model reaction using crotyl acetate and piperidine as the substrate molecules (Scheme 5) and ligand **4** assembled to silica support Si-I. The ligand was preassembled on the silica material, and when the slurry was stirred in the presence of $[Pd(crotyl)Cl]_2$, the silica material turned yellow, indicating that the supported catalyst was formed [(guest **4**)$_2$Pd(crotyl)(Cl)]−Si-I. After the slurry had been washed with dichloromethane to remove the potentially unbound catalyst, the reaction began by the addition of the substrates. Samples were withdrawn from the reaction mixture and analyzed by GC to determine the conversion and product distribution.

The first experiment was carried out to show that catalysis takes place at the heterogeneous phase and not in the homogeneous phase (Scheme 6). To this end, a slurry reaction mixture was stirred and monitored for 10 min, after which a part of the homogeneous solution containing the substrate and the product solvent was decanted. This mixture was transferred into another Schlenk flask, and both the supernatant and the slurry residue were stirred again under reaction conditions; the reaction progress was further monitored. The results displayed in Figure 1A clearly show that the reaction continued only in the vessel containing the heterogeneous phase. In a similar experiment using the ester of ligand **4**, a ligand that does not sufficiently

(23) Johannsen, M.; Jørgensen, K. A. *Chem. Rev.* **1998**, *98*, 1689−1708.

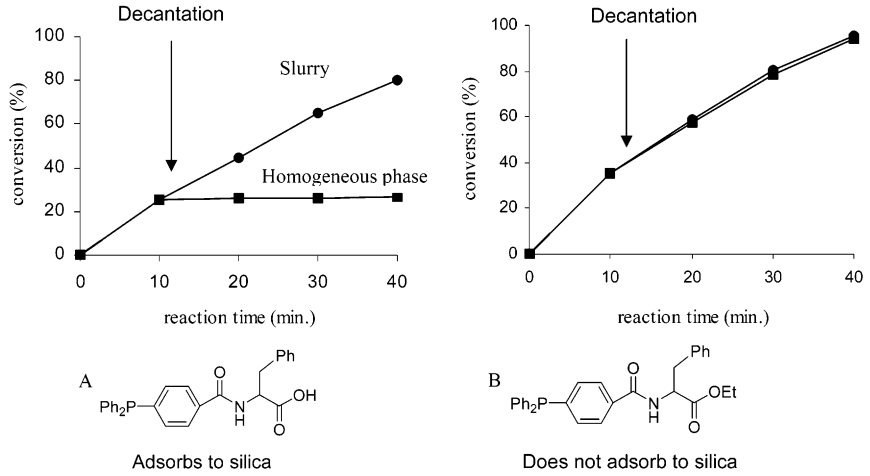


Figure 1. Conversion in the allylic amination reaction using guest **4** supported on silica (A) as the ligand and the ester of **4** (B); see text and Scheme 6 for explanation.

Table 1. Palladium-Catalyzed Allylic Amination Using the Supported Ligand (**4**−Si-I) Studied in Four Consecutive Reactions and Compared with the Homogeneous System[a]

entry	cycle	catalyst	time (min)	conv (%)	linear *trans* (%)	linear *cis* (%)	branched (%)
1	HOM	Pd(guest **4**)$_2$(crotyl)Cl	5	92.2	54.1	11.2	34.7
2	HOM[b]	Pd(guest **4**)$_2$(crotyl)Cl	5	92.0	54.3	11.2	34.5
3	1	(**4**−Si-I)$_2$Pd(crotyl)Cl	30	90.5	53.2	11.7	35.1
4	2	(**4**−Si-I)$_2$Pd(crotyl)Cl	30	85.6	54.5	10.5	35.0
5	3	(**4**−Si-I)$_2$Pd(crotyl)Cl	30	84.9	53.4	11.1	35.5
6	4	(**4**−Si-I)$_2$Pd(crotyl)Cl	30	72.8	53.7	10.9	35.4

[a] With 5 mL of CH_2Cl_2, [crotyl acetate] = 0.2 M, [piperidine] = 0.4 M, ligand/Pd = 2, [Pd] = 0.002 M, room temperature. [b] Capped silica (250 mg) was added to the solution.

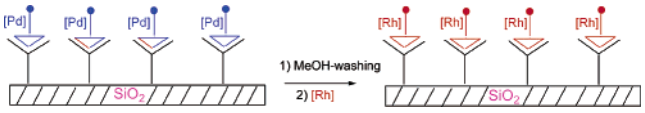
bind to the host molecule, the reactions in both vessels proceeded with the same rate (Figure 1B). These experiments clearly show that if the catalyst is noncovalently anchored to the binding sites of the silica, the reaction indeed takes place at the heterogeneous phase. In line with this, we observed that during the catalytic experiment the silica remained yellow, whereas the organic solvent was colorless. The homogeneous phase was analyzed by atomic emission spectroscopy, confirming that this phase indeed does not even contain traces of palladium (<0.1%).

We subsequently compared the catalytic properties of the noncovalently anchored catalyst with the homogeneous catalysts, and we studied the recycling properties of the systems (Table 1). In addition, a control experiment was carried out in which the homogeneous reaction was performed in the presence of capped SiO_2 silica material (Table 1, entry 2). The yields and the product distribution are the same as those of the homogeneous reaction (entry 1), indicating that the solid phase does not interfere with the reaction. Moreover, the organic phase was yellow, while the silica material remained white, clearly showing that the capped silica does not adsorb the metal complex.

The noncovalently anchored catalyst was less active than the homogeneous catalyst, as is commonly found for heterogenized catalysts; 90% conversion was reached in 30 min (5 min for the homogeneous reaction).[25] The product distribution is the same as that in the homogeneous phase, suggesting that the catalytically active species is a similar palladium complex. The noncovalently anchored catalyst was separated by a simple

(24) Trost, B. M.; van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395−422.

Scheme 7. Defunctionalization and Subsequent Refunctionalization of Si-I



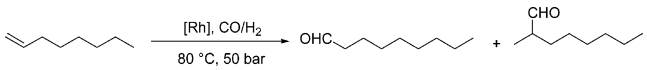
filtration step and could be recycled. In four consecutive reactions, the selectivity did not change at all, while the activity decreased slightly. Since there is no Pd leaching into the homogeneous phase during the recycling process as determined by ICP-AES (<0.1%), this decrease is attributed to the catalyst decomposition, as is commonly observed for palladium catalysts.

Hydroformylation Using Rhodium Catalysts Immobilized via Hydrogen Bonds. To demonstrate the potential of the concept of supramolecular anchoring, we decided to use the same silica material as was used for the support for the rhodium-catalyzed hydroformylation[26] of 1-octene. To this end, the palladium catalyst was removed from the Si-I surface by washing it with methanol until the silica was completely white and the eluent became colorless (Scheme 7). The absence of palladium on the support was confirmed by ICP-AES analysis of the silica material (<0.1%).

After the mixture was dried, the silica material was used as a supramolecular support for the rhodium-catalyzed hydroformylation. Guest ligand **4**, Rh(acac)(CO)$_2$, 20 mL of toluene, and the Si-I were added to a stainless steel 50-mL autoclave, equipped with a mechanical stirrer and a substrate vessel. The suspension was heated for 1 h at 80 °C under 20 bar CO/H_2 (1:1) to allow catalyst formation before a mixture of 1 mL of 1-octene and 1 mL of decane (internal standard) was added, and the CO/H_2 pressure was raised to 50 bar. The mixture was stirred for 20 h, after which the autoclave was cooled to 10 °C and the pressure reduced to 1.8 bar. With this small overpressure, the liquid was slowly removed from the supported catalyst via a syringe while keeping the catalyst under a syngas atmosphere, thereby suppressing catalyst decomposition. Subsequently, the silica material was washed with 5 mL of toluene, making the system ready for the next catalytic cycle. Using this procedure,

(25) A control experiment showed that the reaction did not proceed in the absence of the palladium catalyst.
(26) *Rhodium Catalyzed Hydroformylation*; van Leeuwen, P. W. N. M., Claver, C., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2000.

Table 2. Rhodium-Catalyzed Hydroformylation of 1-Octene Using the Supported Ligand (**4**−Si-I) Studied in Eight Consecutive Reactions[a]



cycle	conv (%)	linear aldehyde (%)	branched aldehyde (%)	isomers (%)	l/b ratio
1	90.4	64.5	32.2	3.3	2.0
2	90.0	62.5	33.2	4.3	1.9
3	86.6	66.8	30.4	2.8	2.2
4	85.1	60.8	33.8	5.4	1.8
5	81.1	61.4	33.8	4.8	1.8
6	80.5	63.4	33.4	3.2	1.9
7	80.0	67.1	30.5	2.4	2.2
8	79.9	67.3	30.7	2.0	2.2

[a] With 1.2 g of Si-I, 0.01 mmol of $Rh(acac)(CO)_2$, ligand/Rh = 10, 1 mL of 1-octene, 1 mL of decane, and 20 mL of toluene; 80 °C, 50 bar of CO/H_2, 20 h.

Table 3. Rhodium-Catalyzed Hydroformylation of 1-Octene Using the Supported Ligand (**8**−Si-I) Studied in 13 Consecutive Reactions under Various Conditions[a]

entry	cycle	conv (%)	TOF (h^{-1})	linear aldehyde (%)	branched aldehyde (%)	isomers (%)	l/b ratio
1	1	39.4	17.0	87.7	3.4	8.9	25.9
2	2	39.9	17.1	87.7	3.6	8.7	24.4
3	3	39.0	16.9	87.4	3.5	9.1	25.0
4	4	40.0	17.1	87.9	3.5	8.6	25.0
5	5	39.6	17.0	87.4	3.6	9.0	24.3
6	6	39.0	16.9	87.4	3.4	9.2	25.7
7	7[b]	42.2	17.7	86.1	3.7	10.2	23.3
8	8[c]	41.4	18.4	87.5	3.3	9.2	26.5
9	9[d]	45.3	20.4	87.9	3.1	9.0	27.9
10	10[e]	54.6	19.2	65.6	2.5	31.9	25.9
11	11[f]	40.5	17.1	86.1	3.9	10.0	22.2
12	12[g]	62.9	28.7	79.5	5.3	15.2	15.0
13	13[h]	86.2	29.4	42.4	13.3	44.3	3.2
14	Rh−A[i]	24	8	85.5	4.5	9.9	19
15	Rh−B[i]	19[j]	283	93.3	2.9	3.7	32

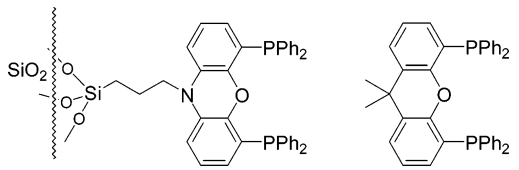
[a] With 1.2 g of Si-I, 0.01 mmol of $Rh(acac)(CO)_2$, ligand/Rh = 10, 1 mL of 1-octene, 1 mL of decane, and 20 mL of toluene; 80 °C, 50 bar of CO/H_2. [b] At 40 bar of CO/H_2. [c] At 30 bar of CO/H_2. [d] At 20 bar of CO/H_2. [e] At 10 bar of CO/H_2. [f] At 50 bar of CO/H_2. [g] At 100 °C. [h] At 120 °C. [i] Data extracted from ref 10c. [j] After 2 h.

we performed eight consecutive reaction experiments. The results are depicted in Table 2.

The chemo- and regioselectivities (linear/branched ratio (l/b) ∼ 2) of the reaction are typical of bistriphenylphosphine-based rhodium complexes.[26] All reactions had 80−90% conversion, and the activity of the catalyst was only modest (average TOF ∼ 30 mol·mol^{-1}·h^{-1}). However, the results show clearly that the catalyst can be recycled at least eight times with only a slight loss in activity. This decrease in activity is a result of small amounts of rhodium that leached from the ligand (Rh leaching was determined by ICP-AES analysis) during the recycling process, which has been observed previously for systems based on covalently anchored monodentate phosphine ligands applied in this reaction.[10i] We anticipated that the use of bidentate ligands would suppress rhodium leaching and, in addition, would afford systems that give rise to higher regioselectivity. Indeed, when Xantphos-type ligand **8** was noncovalently anchored to Si-I, a rhodium catalyst that gave a high regioselectivity (l/b = 25, 87% linear aldehyde; see Table 3) was obtained. Also, metal leaching was suppressed completely; for 11 consecutive runs, no loss in either activity or selectivity was observed and no rhodium was detected by ICP-AES analysis of the organic phase (<0.5%). Compared to those of the homogeneous system, the silica-anchored xantphos showed a decrease in both activity and selectivity. Similar effects were observed previously for covalently anchored Nixantphos on silica (Rh−A).[10c] Interestingly, higher activity and selectivity for the linear aldehyde are observed for the noncovalently anchored ligand compared to those of the covalently anchored Nixantphos, while in the homogeneous phase, these Nixantphos and Xantphos ligands show similar activity and selectivity.[28] The difference in spacer length might be the reason for this slight improvement as the active site is located further from the silica support. We previously reported the coexistence of cationic and neutral rhodium species upon using covalently anchored Nixantphos,[10c] which resulted in a hydrogenation side reaction, which could be suppressed by adding a base or by modifying the silica surface. The current system does not show this behavior because the surface was modified in order to obtain selective binding to the binding sites.

We decided to study the influence of syngas pressure on the catalytic performance. A decrease in syngas pressure to 20 bar resulted in a slightly higher turnover frequency up to a maximum of 20.4 mol^{-1}·h^{-1} (aldehyde or rhodium). At this pressure, a maximum in the l/b ratio was obtained, while the amount of isomerization is not changed (Table 3, entry 9). These results are in line with a partial negative order in *p*-CO and with a zero order in *p*-H_2, commonly found for Rh−diphosphine catalyst systems.[27] A further decrease of syngas pressure to 10 bar leads to both a decreased activity and a decreased regioselectivity. The rate of isomerization is suddenly affected and increases 3-fold to more than 30%. To test whether this was due to catalyst decomposition, catalysis using the same conditions of the first six catalyst experiments was performed (Table 3, entry 11). Similar results were obtained, indicating that no decomposition had taken place.

At 100 °C, the activity of the catalyst was higher at the expense of a small decrease in selectivity. Catalysis performed at higher temperatures (120 °C) resulted in catalyst decomposition (Table 3, entry 13), as was clear from the large decrease in selectivity (the high conversions of entries 12 and 13 do not allow comparison of the TOF with other entries). In addition, the product phase was yellow, and significant amounts of rhodium in the product phase were detected by ICP-AES analysis (1.6% of the total amount of rhodium was leached to the organic phase).

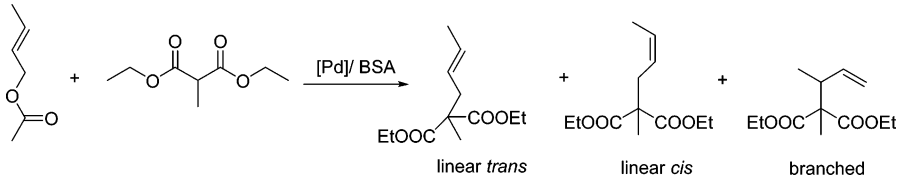


A B

Allylic Alkylation Using Palladium Catalysts Immobilized via Metal−Ligand Interactions. To investigate the use of

(27) (a) Lazzaroni, R.; Uccello-Barretta, G.; Benetti, M. *Organometallics* **1989**, *8*, 2323−2327. (b) Casey, C. P.; Petrovich, L. M. *J. Am. Chem. Soc.* **1995**, *117*, 6007−6014.
(28) van der Veen, L. A.; Keeven, P. H.; Schoemaker, G. C.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Lutz, M.; Spek, A. L. *Organometallics* **2000**, *19*, 872−883.

Table 4. Palladium-Catalyzed Alkylation of Crotyl Acetate and Diethyl-2-methylmalonate Using the Supported Ligand (**6**−Si-III) Studied in Three Consecutive Reactions and Compared with the Homogeneous System[a]



cycle	catalyst	time (h)	conv (%)	linear *trans* (%)	linear *cis* (%)	branched (%)
	(guest **6**)$_2$Pd(allyl)Cl	0.5	78.9	65.5	9.2	25.3
	(guest **6**)$_2$Pd(allyl)Cl[b]	0.5	77.5	65.4	9.5	25.1
1	(**6**−Si-III)$_2$Pd(allyl)Cl	6	21.7	66.1	9.6	24.3
2	(**6**−Si-III)$_2$Pd(allyl)Cl	6	20.1	65.8	9.7	24.5
3	(**6**−Si-III)$_2$Pd(allyl)Cl	6	16.8	66.3	9.0	24.7

[a] With 5 mL of CH_2Cl_2, [Pd] = 0.002 M, ligand/Pd = 2, [crotyl acetate] = 0.2 M, [diethyl-2-methylmalonate] = 0.4 M, [BSA] = 0.4 M, room temperature. [b] In the presence of Zn tetraphenyl porphyrin **2**.

metal−ligand interactions as a means for the noncovalent anchoring of catalysts, we studied ligand **6**, attached to Si-III, as the supported ligand for the palladium-catalyzed alkylation[24] of crotyl acetate using the diethyl-2-methylmalonate anion as the nucleophile. In a typical experiment, 5 μmol of [Pd(allyl)(Cl)]$_2$, 20 μmol of ligand **6**, and the proper amount of Si-III were dissolved in 5 mL of dichloromethane, and the mixture was stirred at room temperature for 15 min. Subsequently, the silica material was washed to remove the nonbound catalyst, and the reaction began by the addition of crotyl acetate, diethyl-2-methylmalonate, BSA (*N*,*O*-bis(trimethylsilyl)acetamide), and a catalytic amount of KOAc dissolved in 5 mL of dichloromethane. The results of the catalytic reactions are shown in Table 4. For comparison, we also performed the reaction with the unsupported ligand in the absence and presence of zinc porphyrin **2**.[25] This control experiment shows that in the homogeneous phase, the assembly of the porphyrin does not change the catalytic performance of the palladium catalyst; both the selectivity and the activity are similar in the presence and absence of **2**. Comparing the noncovalently anchored catalyst with the homogeneous analogue, we observed, as expected, a small decrease in activity, but the selectivity remains the same throughout all of the experiments. The catalyst was separated by a simple filtration step and recycled. In three consecutive reactions, the selectivity did not change at all, while the activity decreased slightly, which again is attributed to catalyst decomposition during the recycling process.

Similar to the experiments with the hydrogen-bonded system, we decided to use the same silica material as the support for the rhodium-catalyzed hydroformylation. Again, the support was washed with methanol to remove all of the palladium complexes, and we "uploaded" fresh ligand **6** to Si-III. The experimental details are similar to those for the hydrogen-bonded system, and the results are summarized in Table 5. Interestingly, the activity of the supported catalyst is identical to that of the hydrogen-bonded system, but the selectivity of the catalyst system is slightly higher and more comparable to that of the homogeneous analogue. Much to our surprise, we found that, in contrast to the result with **8**, the activity decreased upon reusing the recycled catalyst. With the Xantene-based bidentate diphosphine, we found previously[10b,c] that the metal−ligand interaction is sufficiently strong to suppress rhodium leaching, and the origin of the decrease must therefore be either leaching of the whole complex or catalyst deactivation. Also, the results

Table 5. Rhodium-Catalyzed Hydroformylation of 1-Octene Using the Supported Ligand (**6**−Si-III) Studied in Four Consecutive Reactions[a]

cycle	conv (%)	TOF (h^{-1})	linear aldehyde (%)	branched aldehyde (%)	isomers (%)	l/b ratio
1	69.1	16.8	94.2	2.2	3.6	43.2
2	59.6	14.2	93.9	2.4	3.7	40.0
3	53.4	13.7	93.2	2.3	4.5	40.5
4	44.3	10.7	93.8	2.5	3.7	36.7

[a] With 1.4 g of Si-III, 0.01 mmol of Rh(acac)(CO)$_2$, ligand/Rh = 10, 1 mL of 1-octene, 1 mL of decane, and 20 mL of toluene; 80 °C, 50 bar of CO/H_2, 20 h.

with ligand **8** show that the metal−ligand interaction is sufficiently strong, and that the catalyst is very stable. The binding of ligand **6** to the support is as equally strong as that of ligand **8** to Si-I, and the equal activity observed for both systems suggests that during the reaction, the ligand remains on the support. We therefore reasoned that the product formed must interfere with the binding process. From UV−vis titrations of Zn(TPP) with butylamine performed in toluene in the presence of nonanal (10%), the aldehyde produced during the hydroformylation reaction, we know that the product formed has no effect on the binding strength ($K = 5 \times 10^4$ M^{-1} in the presence and absence of aldehyde). Most likely, nonanal, formed during the process, reacts with the primary amine of ligand guest **6** giving the corresponding imine, which results in a reduced affinity for the zinc porphyrin.[29] Indeed, in a control experiment. we found that under hydroformylation conditions, 60% of *n*-butylamine (1 equiv was added with respect to the ligand) was converted into the corresponding imine,[30] making this the most plausible explanation for the drop in activity observed in consecutive reactions.

Conclusions

We have introduced a new strategy for immobilizing transition-metal catalysts on silica supports that involves the use of well-defined binding sites that are immobilized on silica material. These binding sites can be reversibly functionalized with homogeneous catalysts equipped with the complementary

(29) The binding constants of 1-butylamine and 1-butylimine with the Zn−TPP complex are 5.4×10^4 and 1.9×10^3 M^{-1}, respectively.

(30) A control hydroformylation experiment was carried out in the presence of 1 mL of 1-butylamine (and 1 mL of 1-octene, 1×10^{-5} mol Rh(acac)(CO), 1×10^{-4} mol Xantphos) at 80 °C and 50 bar of H_2/CO for 20 h. The reaction mixture was analyzed by GC−MS, showing the conversion of 60% of the 1-butylamine into 1-butylnonylimine.

binding motif. The two binding motifs explored in the current contribution are based on hydrogen bonds, in combination with acid−base protonation, and on metal−ligand interactions. These binding motifs are, in principle, orthogonal and can potentially be used in one system. The host−guest binding behavior of the silica-supported systems was found to correspond well with the analogous systems in solution.

The supported transition-metal catalysts have been studied in the palladium-catalyzed allylic substitution and the rhodium-catalyzed hydroformylation. In general, the noncovalently immobilized catalyst system shows an activity lower than that of the homogeneous analogues, commonly observed for heterogenized catalysts, and importantly, the selectivity was retained. Using the current noncovalent interactions, the catalyst was bound to the support sufficiently strong to enable efficient separation and reuse of the catalyst. Interestingly, the silica material could be quantitatively defunctionalized by washing it with methanol, and consequently, the support could be used in different reactions (i.e., we first applied the systems in allylic substitution and then in rhodium-catalyzed hydroformylation). When noncovalently bound diphosphine **8** was used, the rhodium catalyst was reused in 11 consecutive runs without any noticeable deterioration of the catalyst. Employing the concept of noncovalent anchoring clearly opens the way to modular multipurpose systems since the catalyst and support can be reused after separation. In this view, it is important to stress that the catalysts used in this study can also be noncovalently anchored to the dendritic materials previously reported.[15c]

Acknowledgment. We are grateful to the NRSC-C for financial support, and L. Hoitinga is kindly acknowledged for performing rhodium and palladium analyses.

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