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Dendritic Nanoreactor Encapsulating Rh Complex Catalyst for Hydroformylation

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A Rh phosphine complex was encapsulated within the surface alkylated poly(propylene imine) dendrimers through ionic interactions. The resulting dendrimer complexes functioned as nanoreactors for hydroformylation of olefins. The congested surface of dendrimers with long alkyl chains favored hydroformylation of higher olefins. One-pot three reactions composed of hydroformylation, the Knoevenagel reaction, and hydrogenation proceeded within the dendritic nanoreactor.

Immobilization of catalycally active species within dendrimers has been a recent research focus because the dendrimers afford a specific nanoenvironment in which active species can reside to confer unique catalysis.[1,2] Characteristic of dendrimers is the host–guest chemistry within the internal cavities of the dendrimers.[3] When active species are introduced to the interior spaces, it is possible to construct nanoreactors.[4] Recently, we have reported on a dendrimer-encapsulated Pd complex catalyst which is bound within the dendrimer cavity through ionic bonds, and have shown that the encapsulated complex acts as a unique nanoreactor for the Heck reactions and allylic aminations.[4b] Here, we report the encapsulation of a Rh(I) complex within the poly(propylene imine) (PPI) dendrimer and describe application of the dendritic nanoreactor to hydroformylation and one-pot three reactions.

Peripheral amino groups on the third generation of the PPI dendrimer were modified with decanoyl chloride or palmitoyl chloride to give the alkylated dendrimers **1a** and **1b**, respectively (Figure 1).[5] 4-Diphenylphosphinobenzoic acid (**2**) was used as the phosphine ligand to fix the Rh complex inside the dendrimer through ionic bonds between the carboxyl group and internal amino groups of the PPI dendrimers.[4b,6]

^{1}H NMR spectra ($CDCl_3$, 30 °C) of **1a** with **2** showed a downfield shift of the α-methylene protons of the tertiary amino groups from 2.29 to 2.40 ppm, which can be explained as protonation of the amino groups of the dendrimer **1a** by **2**.[4b] Encapsulation of the Rh(I) complex was achieved by treatment of $[RhCl(cod)]_2$ with **1a** and **2** (Figure 1). The α-methylene proton signal of the tertiary amino group of **1a** remained at about 2.40 ppm even after complexation. In the case of P/Rh = 1, a characteristic doublet signal at 31.6 ppm ($J_{\text{Rh-P}} = 150$ Hz) appeared in the $^{31}P\{^1H\}$ NMR spectrum ($CDCl_3$, 30 °C). With increasing the P/Rh ratio, the doublet signal broadened and a broad resonance at −4 ppm due to metal-free ligand **2** was also observed, which implies the fast exchange of phosphine ligands within the dendrimer.[7] It is considered that the Rh complex is encapsulated through ionic bonds between the carboxyl group of **2** and amino groups within the dendrimer.

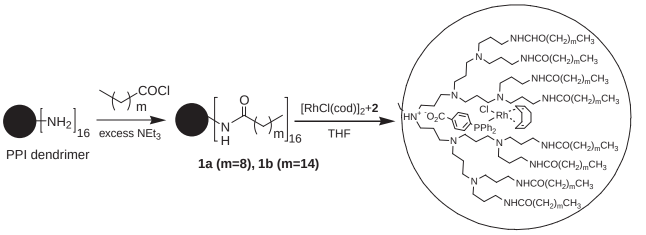
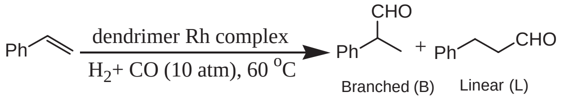


Figure 1. Synthesis of dendrimer-encapsulated Rh(I) complex.

The catalytic performance of the Rh complex encapsulated within the dendrimer **1a** was examined in the hydroformylation of styrene.[8,9] The reaction proceeded smoothly to give the corresponding aldehydes in high yield (B/L = 88/12) without hydrogenation of styrene (Table 1). Reaction rate was strongly influenced by the molar ratio of ligand **2** to Rh; high catalytic activity was observed for P/Rh = 3 and 4 (Entries 3 and 4). Regioselectivity was not affected for the molar ratio of P/Rh from 1 to 6 (Entries 1–6), giving ca 88:12 for branched to linear aldehyde. The reaction hardly occurred in the absence of the dendrimer under the same conditions (Entry 7); however, addition of triethylamine dramatically increased the catalytic activity (Entry 8). Use of PPh_3 instead of **2** did not give any products (Entry 9). Encapsulation of the Rh complex is essential for high catalytic activity and the internal amino groups accelerate the formation of active Rh hydride species.[10] In this way, the alkylated dendrimers provide a concentrated nanoenvironment around the active Rh species as compared to the homogeneous reaction using triethylamine.

As shown in Table 2, the dendritic nanoreactor could be applied to linear olefins. For 1-octene using **1a** and **1b**, the corre-

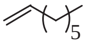
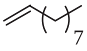
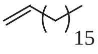
Table 1. Hydroformylation of styrene using dendrimer-encapsulated Rh catalysts[a]



Entry	Ligand	P/Rh[b]	Conv./%[c]	Select./%[c] (B:L)
1	**1a**+**2**	1	20	87:13
2	**1a**+**2**	2	68	88:12
3	**1a**+**2**	3	90	86:14
4	**1a**+**2**	4	91	88:12
5	**1a**+**2**	5	80	88:12
6	**1a**+**2**	6	77	89:11
7	**2**	3	trace	—
8[d]	NEt_3+**2**	3	65	91:9
9	PPh_3	3	trace	—
10[d]	NEt_3+PPh_3	3	19	94:6

[a]Reaction conditions: styrene 1 mmol, $[RhCl(cod)]_2$ 0.0025 mmol, **1a** 0.005 mmol, THF 2 mL, CO 5 atm, H_2 5 atm, 1 h. [b]According to the P/Rh ratio, amount of phosphine ligand was varied. [c]Determined by GC. [d]NEt_3 0.070 mmol.

Table 2. Hydroformylation of linear olefins catalyzed by dendrimer-Rh complexes[a]

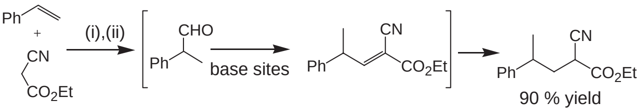
Entry	Olefins	Ligand	Time /h	Conv. /%[b]	Select. /%[b] (B : L)
1	 (**3**)	**1a**	1	73	25 : 75
2		**1b**	1	79	26 : 74
3		**1b**	4	96	26 : 74
4[c]		NEt_3	1	19	26 : 74
5	 (**4**)	**1a**	1	49	26 : 74
6		**1b**	1	63	26 : 74
7		**1b**	4	98	27 : 73
8[c]		NEt_3	1	9	25 : 75
9	 (**5**)	**1a**	1	45	31 : 69
10		**1b**	1	60	28 : 72
11		**1b**	4	96	28 : 72
12[c]		NEt_3	1	14	26 : 74
13[d]	**3** + **5**	**1a**	6	44/43[e]	1.0[f]
14[d]		**1b**	5	14/26[e]	1.9[f]
15[c,d]		NEt_3	12	27/28[e]	1.0[f]

[a] Reaction conditions: substrate 1 mmol, $[RhCl(cod)]_2$ 0.0025 mmol, **2** 0.015 mmol, THF 2 mL, CO 5 atm, H_2 5 atm, 60 °C. [b] Determined by GC. [c] NEt_3 0.07 mmol. [d] 1-Octene 0.5 mmol, 1-octadecene 0.5 mmol, 40 °C. [e] Conversions of olefins (**3**/**5**). [f] Ratio of conversions of **3** to **5**.

sponding aldehydes were formed as main products (B/L = 25/75) in high yield with traces of isomerization products (Entries 1 and 2). On the other hand, for the higher olefins of 1-decene and 1-octadecene, the dendritic nanoreactor using **1b** showed higher catalytic activity than **1a** (Entries 5, 6, 9, and 10). The above phenomenon was not observed when using triethylamine instead of the dendrimers (Entries 4, 8, and 12). Regioselectivity of the products was almost constant among dendrimers **1a**, **1b** and NEt_3. Intermolecular competitive hydroformylations between 1-octene and 1-octadecene were carried out with the dendrimers **1a** and **1b** at 40 °C. Notably, the relative reaction rate of 1-octene over 1-octadecene increased by a factor of 1.9 using dendrimer **1b**. The congested surface alkyl groups on the dendrimer **1b** might have stronger affinity for 1-octadecene than 1-octene giving preferential penetration of 1-octadecene into the dendrimer.

The internal amino groups within the dendrimer acted as a base catalyst for the Knovenagel condensation. For example, the reaction between benzaldehyde and ethyl cyanoacetate using dendrimer **1** afforded (*E*)-ethyl 2-cyanocinnamate in 99% yield. The combined action of the active Rh species and the base sites of the dendritic catalyst could be applied to a one-pot synthesis (Scheme 1). Treatment of styrene and methyl cyanoacetate under the hydroformylation conditions afforded directly ethyl 2-cyano-4-phenylpentanoate, a valuable intermediate of glutarimide, in 90% yield.[11] The Rh complex and tertiary amino groups within the dendrimer participate in three sequential reactions: hydroformylation, the Knoevenagel condensation, and hydrogenation.[12]

In summary, we report the encapsulation of Rh complexes within surface alkylated PPI dendrimers through ionic interactions. The congested surface of dendrimers with long alkyl chains favors hydroformylation of higher olefins. The specific nanoenvironment created by the dense amino groups inside the dendrimers can act not only as a promoter and anchor of the active Rh species but also as a base catalyst, promoting one-pot three reactions within the dendrimers.



Scheme 1. One-pot reaction using the dendritic nanoreactor. Reaction conditions:styrene 0.5 mmol, ethyl cyanoacetate 0.75 mmol, $[RhCl(cod)]_2$ 0.0025 mmol, **1a** 0.005 mmol, **3** 0.015 mmol, THF 2 mL, CO 5 atm, H_2 5 atm. (i) 40 °C, 9 h. (ii) 60 °C, 24 h.

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References and Notes

1 For a book on dendrimers, see: "Dendrimers and Other Dendritic Polymers," ed. by J. M. J. Fréchet and D. A. Tomalia, Wiley & Sons, New York (2001).
2 For recent reviews on dendritic catalysts, see: a) D. Astruc and F. Chardac, *Chem. Rev.*, **101**, 2991 (2001). b) R. van Heerbeek, P. C. J. Kamer, P. W. N. M. van Leeuwen, and J. N. H. Reek, *Chem. Rev.*, **102**, 3717 (2002).
3 a) J. F. G. A. Jansen, E. M. M. de Brabander-van den Berg, and E. W. Meijer, *Science*, **266**, 1226 (1994). b) S. Hech and J. M. J. Fréchet, *Angew. Chem., Int. Ed.*, **40**, 74 (2001).
4 For several examples of dendrimer-encapsulated metal catalysts, see: Ru complex a) Q.-H. Fan, Y.-M. Chen, X.-M. Chen, D.-Z. Jiang, F. Xi, and A. S. C. Chan, *Chem. Commun.*, **2000**, 789. Pd complex b) M. Ooe, M. Murata, T. Mizugaki, K. Ebitani, and K. Kaneda, *J. Am. Chem. Soc.*, **126**, 1604 (2004). Pd nanoparticles c) Y. Niu, L. K. Yeung, and R. M. Crooks, *J. Am. Chem. Soc.*, **123**, 6840 (2001). d) M. Ooe, M. Murata, T. Mizugaki, K. Ebitani, and K. Kaneda, *Nano Lett.*, **2**, 999 (2002).
5 A. P. H. J. Schenning, C. Elissen-Romn, J. W. Weener, M. W. P. L. Baars, S. J. van der Gaast, and E. W. Meijer, *J. Am. Chem. Soc.*, **120**, 8199 (1998).
6 Immobilization of metal complexes on dendrimers by electrostatic interactions, see: a) U. Boas, A. J. Karlsson, B. F. M. de Waal, and E. W. Meijer, *J. Org. Chem.*, **66**, 2136 (2001). b) R. van de Coevering, M. Kuil, R. J. M. K. Gebink, and G. van Koten, *Chem. Commun.*, **2002**, 1636.
7 E. Monflier, H. Bricout, F. Hapiot, S. Tilley, A. Aghmiz, and A. M. Masdeu-Bultó, *Adv. Synth. Catal.*, **346**, 435 (2004).
8 C. D. Frohling and C. W. Kohlpaintner, in "Applied Homogeneous Catalysts with Organometallic Compounds," ed. by B. Cornils and W. A. Herrmann, Wiley-VCH, Weinheim (1996), p 27.
9 Recent example of hydroformylation catalyzed by self-assembled Rh complex, see: V. F. Slagt, P. C. J. Kamer, P. W. N. M. van Leeuwen, and J. N. H. Reek, *J. Am. Chem. Soc.*, **126**, 1526 (2004).
10 Formation of Rh hydride species is facilitated in the presence of amine: see, P. S. Hallman, D. Evans, J. A. Osborn, and G. Wilkinson, *J. Chem. Soc., Chem. Commun.*, **1967**, 305.
11 R. R. Goehring, T. D. Greenwood, G. C. Nwokogu, J. S. Pisipati, T. G. Rogers, and J. F. Wolfe, *J. Med. Chem.*, **33**, 926 (1990).
12 Use of NEt_3 instead of **1a** could also promote the sequencial reactions to give the corresponding product in almost the same yield.