Supramolecular chiral dendritic monophosphites assembled by hydrogen bonding and their use in the Rh-catalyzed asymmetric hydrogenation†

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A new type of supramolecular chiral dendritic monophosphite ligands has been prepared *via* a hydrogen-bonding assembly. The Rh complexes of these supramolecular ligands have been successfully applied in the asymmetric hydrogenation of enamides and dehydroamino acid derivatives with good enantioselectivities, which are comparable to those obtained from the free monophosphite ligands. The supramolecular catalyst could be easily recycled *via* solvent precipitation.

Introduction

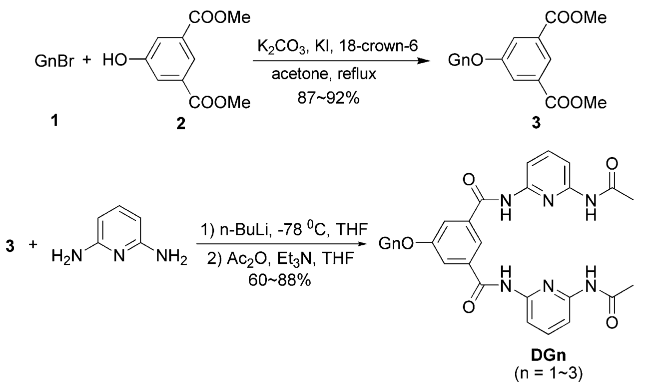
Metallodendrimers have been emerging as a promising class of catalysts as demonstrated in the pioneering work by van Koten in 1994 due to their well-defined and tunable molecular architectures as well as nano-order size.[1] To date, a number of organometallic dendrimers with catalytic sites at the core or at the periphery have been reported.[2] Most of these reported catalysts were prepared by covalent attachment of the chiral centers onto the dendritic supports. Such a covalent approach, however, often suffered from time-consuming synthesis as well as difficult recycling of the often expensive dendritic support in the case of catalyst deactivation. An interesting alternative approach has recently been developed, which relies on the noncovalent anchoring of catalyst to the soluble support using well-defined binding sites.[3] This reversible noncovalent method not only facilitates the immobilization of catalyst, but also enables the easy reuse of the dendritic support. Although many supramolecular dendrimers based on noncovalent interactions have been intensively studied, however, few of them have been employed in catalysis.[4,5] To the best of our knowledge, there is no report on the synthesis of supramolecular chiral dendritic catalysts and their applications in asymmetric catalysis.

Monodentate chiral phosphorus ligands have recently attracted considerable attention because of their excellent performance, relatively simple synthesis from readily available building materials and good stability.[6] Recently, we reported two kinds of chiral dendritic monodentate phosphoramide ligands, in which the chiral monodentate phosphoramide units were attached onto the focal point of the dendritic wedges *via* chemical bond approach.[7] It was found that the dendritic wedges played important role on the enantioselectivity and reactivity in the Rh-catalyzed asymmetric hydrogenation of functionalized olefins, such as α-dehydroamino acid derivatives and enamides. Higher enantioselectivity was achieved as the dendritic wedges on the N-atom of the phosphoramidite ligand became bigger.[7b] As an extension of our research,[7,8] here we report the synthesis and application of a new kind of supramolecular chiral dendritic monophosphites assembled by hydrogen bonding.

Results and discussion

To achieve the formation of stable hydrogen-bonding assembly, a suitable combination of multiple hydrogen bonds is necessary. In this regard, we employ the well-established Hamilton receptor for our study, which can form six hydrogen bonds with barbituric acid derivatives in apolar solvent.[9] Both supramolecular building blocks are readily available and can be easily modified by attaching functional groups. To exemplify our new immobilization strategy, series of dendritic Hamilton receptors and barbiturates bearing a chiral monophosphite were designed and synthesized. Thus, the chiral monophosphite could be easily anchored onto the focal point of the dendritic support by way of complementary hydrogen-bonding interactions (Fig. 1).

For the synthesis of the dendritic Hamilton receptors, Fréchet-type dendrimer was chosen as the support due to its inertness to reaction. The O-alkylation of dimethyl 5-hydroxyisophthalate with dendrons **1** afforded the dendritic diesters **3** (**3a**–**3c**). Subsequent treatment of compound **3** with excess 2,6-diaminopyridine in the presence of n-BuLi, followed by the acylation with acetic anhydride, led to the dendritic receptors **DG*ₙ*** (**DG**$_1$–**DG**$_3$) in 60–88% yields (Scheme 1).



Scheme 1

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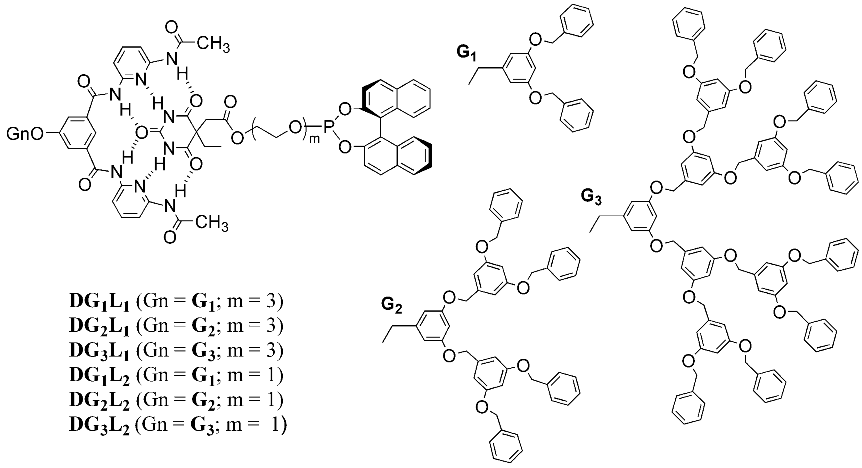
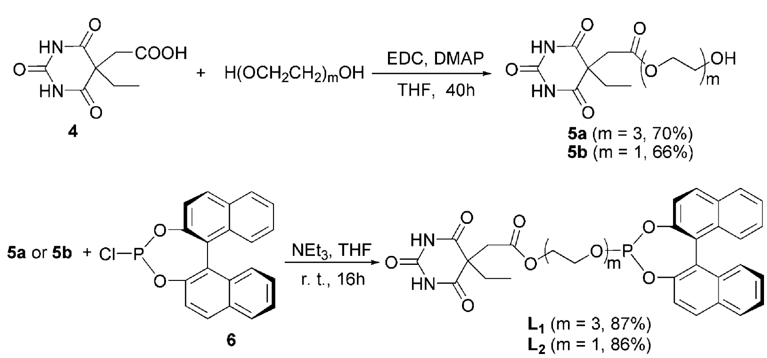


Fig. 1 Supramolecular chiral dendritic monophosphite ligands assembled by hydrogen bonding.

To investigate the potential effect of the dendritic support on the catalytic performance, two barbiturate-based chiral phosphite ligands L_1 and L_2 containing an oligoglycol linker of different length between the barbiturate group and the phosphite moiety were designed. As shown in Scheme 2, an EDC coupling of the barbiturate-functionalized carboxyl acid **4**[10] with ethylene glycol or triethylene glycol gave the barbiturate-containing alcohols **5** in moderate yields. Then, **5** reacted with chlorophosphite **6**[11] to furnish the barbiturate-based ligands L_1 and L_2 in good yields, respectively. All these dendritic Hamilton receptors and monophosphite ligands were well characterized by ^{1}H, ^{13}C and ^{31}P NMR spectroscopy as well as MALDI-TOF or HRMS mass spectrometry. The obtained results are consistent with the compounds synthesized.

With these complementary components in hand, supramolecular dendritic monophosphite ligands assembled by hydrogen bonding were prepared by mixing one equivalent of the corresponding dendritic receptor DG_n with one equivalent of the barbiturate-based ligands (L_1 or L_2) in dry $CDCl_3$. The thus-formed supramolecular dendrimers were studied by ^{1}H and ^{31}P NMR spectra. Generally, the first-generation receptor DG_1 only partially participated in the formation of the supramolecular dendritic assembly because of its poor solubility in $CDCl_3$. To our delight, the second- and third-generation receptor DG_2 and DG_3 could complex the barbiturate-based ligands effectively in $CDCl_3$ irrespective of the linkage length between the barbiturate group and the phosphite moiety. For example, the proton NMR spectrum of a 1 : 1 (molar ratio) mixture of DG_3 and L_1 showed large downfield shift for the NH protons relative to the free components (Fig. 2). After complexation, the amide protons of dendritic receptor shifted downfield from 7.89 and 8.33 ppm to 9.13 and 9.61 ppm, respectively, and the imide protons of the barbiturate-based ligand also shifted greatly downfield from 8.20 ppm to 12.73 ppm. The phosphorus NMR study further confirmed the formation of the supramolecular dendritic ligands. Due to the partial self-association of the barbiturate moiety, ^{31}P NMR spectrum of the free ligand L_1 in $CDCl_3$ showed two peaks at 139.3 and 140.9 ppm. In contrast, for the mixture of DG_3 and L_1, only one peak at 140.7 ppm was observed without appearing the signals of the free ligand L_1, indicative of the formation of the third-generation supramolecular monophosphite ligand DG_3L_1. Similarly, complexation of L_2 with DG_3 was also demonstrated by ^{1}H and ^{31}P NMR spectra (Fig. 2).

In order to investigate the asymmetric induction of these supramolecular chiral monophosphites, the Rh-catalyzed asymmetric hydrogenation of α-phenylenamide (**7a**) in CH_2Cl_2 was chosen as a standard reaction. The catalysts were prepared *in situ* by reacting 2 equiv. of the preformed supramolecular ligands with $[Rh(COD)_2]BF_4$ in CH_2Cl_2 at room temperature. As shown in Table 1, hydrogenation proceeded smoothly in the presence of 2.0 mol% Rh/DG_3L_1 catalyst under atmosphere hydrogen pressure, providing the reduced product with complete



Scheme 2

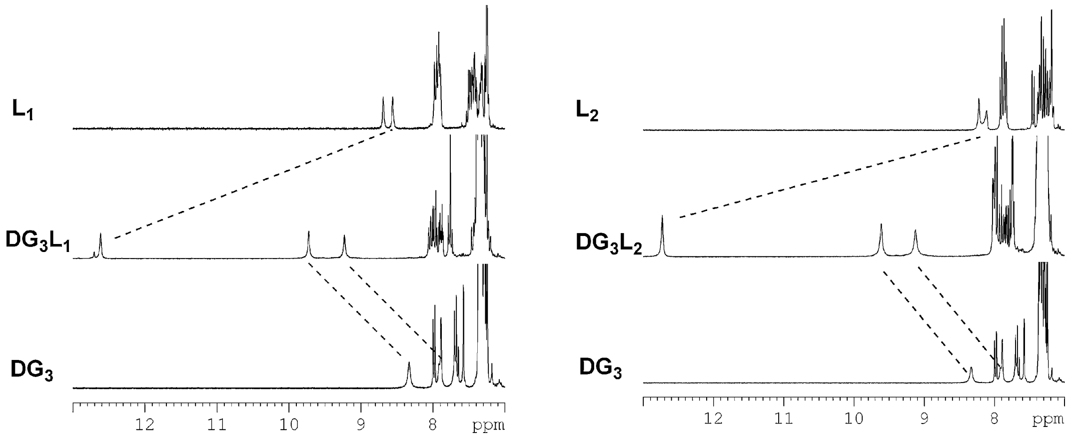
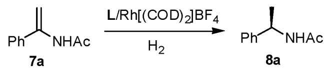


Fig. 2 Partial ^{1}H NMR spectra ($CDCl_3$, 300 MHz, 295 K, 8.0 mM) of **L**, **DG_3L** and **DG_3**.

Table 1 Condition optimization for the Rh-catalyzed asymmetric hydrogenation of α-phenylenamide (**7a**)[a]



Entry	Ligand	H_2/atm	Conv. (%)[b]	Ee (%)[b]
1	**DG_3L_1**	1	100	82
2	**DG_3L_1**	20	100	86 (85)[c]
3	**DG_3L_1**	60	100	87
4[d]	**DG_3L_1**	60	100	89
5	**DG_1L_1**	20	100	80
6	**DG_2L_1**	20	100	82
7	**DG_1L_2**	60	100	30
8	**DG_2L_2**	60	37	37
9	**DG_3L_2**	60	88	64 (93)[e]

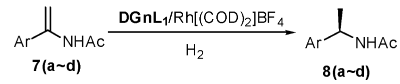
[a] Reaction conditions: 0.1 mmol substrate, 2 mol% $[Rh(COD)_2]BF_4$, Rh/ligand = 1 : 2.2 (mol/mol), 1.5 mL DCM, 20 °C, 20 h; [b] Based on chiral GC analysis; [c] Data in parentheses was obtained with catalyst Rh/**L_1**; [d] Hydrogenation was carried out at −5 °C; [e] Data in parentheses was obtained with catalyst Rh/**L_2**.

conversion and good enantioselectivity (entry 1). It was found that higher hydrogen pressure provided better enantioselectivity (entries 1–3). Slightly higher enantioselectivity was observed when the reaction was carried out under lower temperature (entry 4). Interestingly, the enantioselectivity increased obviously with increasing dendrimer generation (entries 2, 5 and 6). It was also noted that the third-generation catalyst afforded comparable enantioselectivity to that obtained from the catalyst bearing the free ligand **L_1** (entry 2, 86% *vs.* 85% ee).

Then, we investigated the effect of the linkage length between the barbiturate group and the phosphite moiety on the catalyst performance (Table 1). In sharp contrast to Rh/**DG_nL_1**, catalysts Rh/**DG_nL_2** with a short linkage showed much lower enantioselectivity and reactivity (entries 7–9). Higher generation dendrimer catalyst gave much better enantioselectivity which, however, was significantly lower than that obtained from the catalyst bearing the free ligand **L_2** (entry 9, 64% *vs.* 93% ee). The negative dendrimer effect was probably due to the steric effect of the bulk dendritic wedges.

To further demonstrate the efficiency of these supramolecular dendritic catalysts, other enamides (Table 2) and α-dehydroamino acid esters (Table 3) were hydrogenated by using the second- and

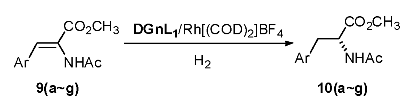
Table 2 Asymmetric hydrogenation of enamides catalyzed by supramolecular dendritic Rh/**DG_nL_1** catalysts[a]



Entry	Ligands	Ar	Ee (%)[b]
1	**DG_3L_1**	C_6H_5 (**7a**)	87
2	**DG_2L_1**	4-Cl-C_6H_5 (**7b**)	83
3	**DG_3L_1**	4-Cl-C_6H_5 (**7b**)	87(87)[c]
4	**DG_2L_1**	4-Br-C_6H_5 (**7c**)	85
5	**DG_3L_1**	4-Br-C_6H_5 (**7c**)	88(86)[c]
6	**DG_2L_1**	4-Me-C_6H_5 (**7d**)	89
7	**DG_3L_1**	4-Me-C_6H_5 (**7d**)	90(89)[c]

[a] Reaction conditions: 0.1 mmol substrate, 2 mol% $[Rh(COD)_2]BF_4$, Rh/**DG_nL_1** = 1 : 2.2 (mol/mol), 60 atm H_2, 1.5 mL DCM, 20 °C, 20 h; [b] Based on chiral GC analysis; [c] Data in parentheses were obtained with catalyst Rh/**L_1**.

Table 3 Asymmetric hydrogenation of α-dehydroamino acid esters catalyzed by supramolecular dendritic Rh/**DG_nL_1** catalysts[a]



Entry	Ligands	Ar	Ee (%)[b]
1	**DG_2L_1**	C_6H_5 (**9a**)	83
2	**DG_3L_1**	C_6H_5 (**9a**)	87(88)[c]
3	**DG_2L_1**	4-Cl-C_6H_5 (**9b**)	83
4	**DG_3L_1**	4-Cl-C_6H_5 (**9b**)	85(88)[c]
5	**DG_2L_1**	4-Br-C_6H_5 (**9c**)	86
6	**DG_3L_1**	4-Br-C_6H_5 (**9c**)	86(88)[c]
7	**DG_2L_1**	4-F-C_6H_5 (**9d**)	83
8	**DG_3L_1**	4-F-C_6H_5 (**9d**)	86(87)[c]
9	**DG_2L_1**	4-MeO-C_6H_5 (**9e**)	87
10	**DG_3L_1**	4-MeO-C_6H_5 (**9e**)	87(91)[c]
11	**DG_2L_1**	3-Cl-C_6H_5 (**9f**)	81
12	**DG_3L_1**	3-Cl-C_6H_5 (**9f**)	83(87)[c]
13	**DG_2L_1**	H (**9g**)	90
14	**DG_3L_1**	H (**9g**)	90(91)[c]

[a] Reaction conditions: 0.1 mmol substrate, 2 mol% $[Rh(COD)_2]BF_4$, Rh/**DG_nL_1** = 1 : 2.2 (mol/mol), 1.5 mL DCM, 20 °C, 20 h; [b] Based on chiral GC analysis; [c] Data in parentheses were obtained with catalyst Rh/**L_1**.

Table 4 Catalyst recycling in the asymmetric hydrogenation of **7a** catalyzed by dendritic Rh/$\mathbf{DG_3L_1}$ catalyst[a]

Cycle	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Conv (%)	100	100	100	100	100	88
Ee (%)	85	86	85	85	85	84

[a] Reaction conditions: 0.1 mmol substrate, 2 mol% $[Rh(COD)_2]BF_4$, Rh/$\mathbf{DG_3L_1}$ = 1 : 2.2 (mol/mol), 60 atm H_2,1.5 mL DCM, 20 °C, 20 h.

third-generation dendritic ligands $\mathbf{DG_2L_1}$ and $\mathbf{DG_3L_1}$. Generally, complete conversions and good enantioselectivities (83–90% ee) were obtained in all cases. Notably, in comparison with $\mathbf{DG_2L_1}$, the third-generation supramolecular dendritic ligand $\mathbf{DG_3L_1}$ gave better enantioselectivities, which were comparable to those obtained from the free ligand $\mathbf{L_1}$.

Another important feature of dendrimer catalysts is the easy and reliable separation of the chiral catalysts.[2c] To explore the recyclability of the supramolecular dendritic catalyst, the Rh/$\mathbf{DG_3L_1}$-catalyzed asymmetric hydrogenation of methyl 2-acetamido cinnamate was chosen as the standard reaction. Upon the completion of the reaction, the catalyst was quantitatively precipitated by the addition of hexane and reused at least five times with similar reactivities and enantioselectivities (Table 4).

Conclusions

In summary, we have developed a new type of supramolecular chiral dendritic monophosphite ligands through the hydrogen-bonding assembly for the first time. These supramolecular ligands were successfully applied in the Rh-catalyzed asymmetric hydrogenation of enamides and α-dehydroamino acid derivatives with good enantioselectivities, which are comparable to those obtained from the free chiral monophosphite ligands. The supramolecular catalyst could be recycled and reused readily at least 5 times without obvious loss of enantioselectivity and reactivity. These supramolecular ligands are modular, and further applications to other asymmetric reactions are underway in our laboratory.

Experimental

General

Unless otherwise noted, all experiments were carried out under an inert atmosphere of dry nitrogen by using standard Schlenk-type techniques, or performed in a nitrogen-filled glovebox. ^{1}H NMR, ^{13}C NMR and ^{31}P NMR spectra were recorded on a Bruker Model Advance DMX 300 or 400 Spectrometer (^{1}H 300 MHz, ^{13}C 75 MHz and ^{31}P 162 MHz, respectively). Chemical shifts (δ) are given in ppm and are referenced to residual solvent peaks (^{1}H and ^{13}C NMR) or to an external standard (85% H_3PO_4, ^{31}P NMR). MALDI-TOF mass spectra were obtained on a BIFLEX III instrument with α-cyano-4-hydroxycinnamic acid (CCA) as the matrix. All enantiomeric excess values were obtained from GC analysis with a Chrompack CHIR-L-VAL column. All solvents were dried using standard, published methods and were distilled under a nitrogen atmosphere before use. All other chemicals were used as received from Aldrich or Acros without further purification.

General procedure for the preparation of Fréchet-type dendritic diester 3a ~ 3c

3a (G_n = G_1)[12a]**.** To a solution of dendritic benzyl bromide **1** (1.5 g, 3.9 mmol) in acetone (50 mL) was added dimethyl 5-hydroxyisophthalate (0.87 g, 4.1 mmol), K_2CO_3 (0.7 g, 4.7 mmol), KI, and a catalytic amount of 18-crown-6. The resulting mixture was refluxed overnight. After removing the solvent, the residue was extracted with CH_2Cl_2 (50 mL × 2). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4, purified by flash column chromatography to give **3a** (1.8 g, 90% yield) as a white solid. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 3.93 (s, 6H), 5.04 (s, 4H), 5.06 (s, 2H), 6.59 (d, J = 2.1 Hz, 1H), 6.68 (d, J = 1.97 Hz, 2H), 7.30–7.43 (m, 10H), 7.81 (s, 2H), 8.29 (d, J = 0.92 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ: 52.4, 70.2, 70.3, 101.9, 106.4, 120.2, 123.3, 127.5, 128.0, 128.6, 131.9, 136.8, 138.5, 158.7, 160.3, 166.1.

3b (G_n = G_2)[12b]**.** Following the procedure for **3a**. 87% yield; ^{1}H NMR (300 MHz, $CDCl_3$) δ: 3.92 (s, 6H), 5.00 (s, 4H), 5.03 (s, 8H), 5.07 (s, 2H), 6.56–7.68 (m, 9H), 7.25–7.42 (m, 20H), 7.82 (s, 2H), 8.29 (d, J = 0.66 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ: 51.4, 69.0, 69.1, 69.3, 100.6, 100.8, 105.3, 105.4, 119.1, 122.3, 126.5, 127.0, 127.2, 127.6, 130.8, 135.8, 137.4, 138.1, 157.7, 159.1, 159.2, 165.0.

3c (G_n = G_3)[12]**.** Following the procedure for **3a**. Yield 90%; ^{1}H NMR (300 MHz, CDCl3) δ: 3.89 (s, 6H), 4.95 (s, 12H), 5.00 (s, 16H), 5.03 (s, 2H), 6.53–6.56 (m, 7H), 6.65–6.67 (m, 14H), 7.29–7.41 (m, 40H), 7.80 (d, J = 1.4 Hz, 2H), 8.28 (d, J = 1.4 Hz, 1H). ^{13}C NMR (75 MHz, CDCl3) δ: 52.5, 70.1, 70.2, 70.3, 101.7, 101.9, 106.5, 120.2, 123.4, 127.3, 127.6, 127.7, 128.1, 128.4, 128.5, 128.7, 132.0, 136.9, 138.7, 139.3, 139.4, 158.8, 160.2, 160.3, 166.1. MS (MALDI-TOF): m/z for $C_{115}H_{100}O_{19}$ Calcd 1785.7. found 1808.3 $[M + Na]^+$, 1824.3 $[M + K]^+$.

General procedure for the preparation of the dendritic Hamilton receptor DG_1–DG_3

$\mathbf{DG_1}$. To a solution of 2,6-diaminopyridine (recrystallized from hot ethyl acetate) (0.24 g, 1.56 mmol) in THF at −78 °C was added dropwise a solution of n-BuLi in hexane (2.5 M, 1.6 mL), and stirred at −78 °C for a further 30 min. A solution of compound **3a** (0.2 g, 0.39 mmol) in 10 mL THF was then added. The reaction mixture was stirred at −78 °C for 4 h, then gradually warmed to room temperature and stirred overnight. The reaction was then quenched with a saturated aqueous solution of NH_4Cl, and extracted with CH_2Cl_2. The organic layer was washed with water and brine, dried over Na_2SO_4 and concentrated *in vacuo.* After the residue was resolved in THF, Ac_2O and Et_3N were added. The reaction mixture was allowed to stir overnight. After the solvent was removed, the residue was purified by flash column chromatography to provide the compound $\mathbf{DG_1}$ (0.18 g, 60% yield for two steps) as a white powder. ^{1}H NMR (300 MHz, DMSO-d$_6$) δ: 2.11 (s, 6H), 5.10 (s, 4H), 5.23 (s, 2H), 6.66–6.76 (m, 3H), 7.32–7.46 (m, 10H), 7.79–7.84 (m, 8H), 8.14 (s, 1H), 10.15 (s, 2H), 10.48 (s, 2H). ^{13}C NMR (75 MHz, DMSO-d$_6$) δ: 23.9, 69.4, 69.5, 101.2, 106.4, 109.4, 110.5, 117.6, 120.0, 127.7, 127.8, 128.4, 135.6, 136.9, 139.0, 140.0, 150.0, 150.6, 158.3, 159.6, 164.9, 169.3. MS (MALDI-TOF): m/z for $C_{43}H_{38}N_6O_7$: calcd. 750.3, found 751.0 $[M + H]^+$, 773.0 $[M + Na]^+$, 789.0 $[M + K]^+$.

DG_2. Following the procedure for **DG_1**. 70% yield; ^{1}H NMR (300 MHz, $CDCl_3$) δ: 2.14 (s, 6H), 4.95 (s, 4H), 4.99 (s, 8H), 5.02 (s, 2H), 6.55–6.66 (m, 9H), 7.28–7.40 (m, 20H), 7.62–7.71 (m, 4H), 7.91–7.99 (m, 7H), 8.41 (br. 2H). ^{13}C NMR (300 MHz, $CDCl_3$) δ: 24.5, 70.0, 70.1, 70.2, 101.6, 101.8, 106.3, 106.4, 109.8, 110.2, 117.5, 117.9, 127.5, 128.0, 128.6, 135.9, 136.7, 138.2, 139.1, 140.7, 149.3, 149.8, 159.2, 160.1, 160.2, 164.4, 169.0. MS (MALDI-TOF): *m/z* for $C_{71}H_{62}N_6O_{11}$: calcd. 1174.4, found 1175.0 [M + H]$^+$, 1197.0 [M + Na]$^+$, 1213.0 [M + K]$^+$.

DG_3. Following the procedure for **DG_1**. 88% yield; ^{1}H NMR (300 MHz, $CDCl_3$) δ: 2.08 (s, 6H), 4.91 (s, 8H), 4.94 (s, 4H), 4.97 (s, 16H), 5.01 (s, 2H), 6.52–6.64 (m, 21H), 7.25–7.38 (m, 40H), 7.58–7.70 (m, 6H), 7.89–8.00 (m, 5H), 8.33 (br., 2H). ^{13}C NMR (300 MHz, $CDCl_3$) δ: 24.5, 70.0, 70.1, 70.2, 101.6, 102.0, 106.4, 109.7, 110.0, 117.4, 117.9, 127.1, 127.5, 127.8, 128.0, 128.3, 128.3, 128.6, 129.9, 136.0, 136.7, 138.2, 139.2, 140.8, 149.3, 149.7, 159.2, 160.1, 160.1, 164.2, 168.8. MS (MALDI-TOF): *m/z* for $C_{127}H_{110}N_6O_{19}$: calcd. 2022.8, found 2023.3 [M + H]$^+$, 2045.4 [M + Na]$^+$, 2061.4 [M + K]$^+$.

General procedure for the preparation of barbiturate-containing alcohols 5a and 5b

5a. To a solution of barbituric acid derivative **4** (0.50 g, 2.34 mmol) and 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDCI, 0.49 g, 2.55 mmol) in THF (50 mL) at 0 °C was added triethylene glycol (1.40 g, 9.33 mmol). The resulting mixture was allowed to stand overnight at room temperature. After the solvent was removed under reduced pressure, the residue was purified by flash column chromatography to give **5a** (0.56 g, 70% yield) as a colorless oil. ^{1}H NMR (300 MHz, DMSO-d_6) δ: 0.82 (t, J = 7.53 Hz, 3H), 1.78 (q, J = 7.55 Hz, 2H), 3.02 (s, 2H), 3.42–3.57 (m, 10H), 4.09(t, J = 4.35 Hz, 2H), 4.56 (t, J = 5.4 Hz, 1H), 11.47 (s, 2H). ^{13}C NMR (75 MHz, DMSO-d_6) δ: 8.3, 31.7, 52.2, 60.2, 64.2, 68.0, 69.6, 69.8, 72.3, 79.1, 150.0, 170.9, 172.6. HRMS (ESI) for $C_{14}H_{22}N_2O_8$, [M + H]$^+$: calcd. 347.1449, found 347.1453.

5b. Following the procedure for **5a**, **4** (1.30 g, 6.07 mmol), EDCI (1.40 g, 7.29 mmol) and ethylene glycol (2.90 g, 46.78 mmol) yielded **5b** (1.0 g, 66% yield) as a white solid. ^{1}H NMR (300 MHz, acetone-d_6) δ: 0.96 (t, J = 7.53 Hz, 3H), 1.89 (q, J = 7.50 Hz, 2H), 3.10 (s, 2H), 3.66–3.72 (m, 2H), 3.88 (t, J = 5.73 Hz, 1H), 4.10 (t, J = 4.80 Hz, 2H), 10.22 (s, 2H). ^{13}C NMR (75 MHz, acetone-d_6) δ: 8.9, 33.0, 60.4, 67.6, 150.2, 172.1, 173.3. HRMS (ESI) for $C_{10}H_{14}N_2O_6$, [M + H]$^+$: calcd. 259.0925, found 259.0924.

General procedure for the preparation of barbiturate-based chiral monophosphite ligands L_1 and L_2

L_1. To a solution of the corresponding barbituric acid ester **5a** (500 mg, 1.45 mmol) and Et_3N (0.31 mL, 2.17 mmol) in THF (10 mL) at 0 °C was added dropwise a solution of (*S*)-[1,1′-binaphthyl-2,2′-diyl]chlorophosphite **6** (510 mg, 1.45 mmol) in THF (10 mL). The resulting mixture was stirred at room temperature for 16 h. The precipitate of Et_3NHCl was filtered over a pad of Celite. After the solvent was removed under reduced pressure, the residue was purified by flash column chromatography to give **L_1** (830 mg, 87% yield) as a white foam. ^{1}H NMR (300 MHz, DMSO-d_6) δ: 0.80 (t, J = 7.41 Hz, 3H), 1.74 (q, J = 8.46 Hz, 2H), 3.00 (s, 2H), 3.56–3.60 (m, 8H), 3.97–4.08 (m, 4H), 7.19–7.64 (m, 8H), 8.06–8.19 (m, 4H), 11.50 (s, 2H). ^{13}C NMR (75 MHz, DMSO-d_6) δ: 8.3, 25.1, 31.7, 52.1, 64.1, 64.4, 68.0, 69.7, 69.7, 69.8, 121.7, 121.9, 123.3, 125.1, 125.3, 125.8, 126.0, 126.6, 126.7, 128.6, 128.7, 130.3, 130.7, 130.8, 131.1, 131.7, 132.0, 146.9, 147.9, 147.9, 150.1, 170.9, 172.7. ^{31}P NMR (162 MHz, DMSO-d_6) δ: 146.4; HRMS (SIMS) for $C_{34}H_{33}N_2O_{10}P$, [M + H]$^+$: calcd. 661.1946, found 661.1943; [M + Na]$^+$: 683.1759.

L_2. Following the procedure for **L_1**, **5b** (300 mg, 1.16 mmol), Et_3N (0.23 mL, 1.74 mmol) and (*S*)-[1,1′-binaphthyl-2,2′-diyl]chlorophosphite **6** (407 mg, 1.16 mmol) yielded **L_2** (570 mg, 86% yield) as a white foam. ^{1}H NMR (300 MHz, DMSO-d_6) δ: 0.85 (t, J = 7.41 Hz, 3H), 1.74 (q, J = 8.46 Hz, 2H), 3.10 (s, 2H), 3.96–4.16 (m, 4H), 7.19–7.69 (m, 8H), 8.06–8.20 (m, 4H), 11.54 (s, 2H); ^{13}C NMR (75 MHz, DMSO-d_6) δ: 8.4, 31.7, 52.2, 62.8, 64.5, 121.6, 121.7, 123.3, 125.2, 125.4, 125.9, 126.0, 26.7, 126.8, 128.6, 128.7, 130.5, 130.7, 130.9, 131.2, 131.7, 132.0, 146.8, 147.9, 150.1, 171.1, 172.7; ^{31}P NMR (162 MHz, DMSO-d_6) δ: 146.3; HRMS (SIMS) for $C_{30}H_{25}N_2O_8P$, [M + H]$^+$: calcd. 571.1246, found 571.1293.

General procedure for the asymmetric hydrogenation of enamides

The dendritic supramolecular monophosphite (9×10^{-3} mmol), generated by mixing one equivalent of the corresponding dendritic receptor and one equivalent of the barbitaric-based monophosphite in dichloromethane (1 mL), and $Rh(COD)_2BF_4$ (4×10^{-3} mmol) in CH_2Cl_2 (1 mL) were stirred at room temperature for 10 min under nitrogen atmosphere. Then, in a 50 mL glass-lined stainless steel reactor with a magnetic stirring bar was charged with phenylenamide (16.1 mg, 0.1 mmol), the above *in situ* prepared catalyst (1 mL, 2×10^{-3} mmol). The autoclave was closed and pressurized with hydrogen to 60 atm. The mixture was stirred at ambient temperature for 20 h. After carefully venting of hydrogen, conversion and enantioselectivity of the reduced product were determined by chiral GC with a 25 m Chir-l-val capillary column.

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