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Synthetic Methods

Highly Enantioselective and Efficient Asymmetric Epoxidation Catalysts: Inorganic Nanosheets Modified with α-Amino Acids as Ligands**

*Jiuzhao Wang, Liwei Zhao, Huimin Shi, and Jing He**

Persistent efforts have been dedicated to the development of effective chiral catalysts for asymmetric synthesis. Exploration of chiral ligands has been reported to provide the most successful choices for metal-catalyzed homogeneous asymmetric reactions.[1] Almost all the effective ligands reported for homogeneous catalytic reactions share one prominent feature: a rigid and bulky structure that is vital to creating effective asymmetric microenvironments around metal active sites.[2] Recently, solid surfaces have been used with success to promote heterogeneous asymmetric catalysis, thus preserving the high enantioselectivity of or even attaining higher product *ee* values than their homogeneous analogues[3] by virtue of so-called confinement effects.[4] In addition, the heterogeneous catalysts, produced by immobilizing homogeneous catalysts on solid surfaces, retain the active sites of homogeneous analogues and are easily separated and recycled.[5] However, there are still great challenges in heterogeneous asymmetric catalysis: 1) Confinement has been reported to be successful in some cases to enhance metal-catalyzed asymmetric synthesis, but it is not always valid owing to the complicated geometrical and chemical microenvironment in pores or on surfaces.[6] More assured and efficient strategies are still desired. 2) Constraining catalytic centers to solids usually reduces the reaction rate because of the emergence of liquid/solid interfaces and the diffusion limitation, which is a general issue for heterogeneous catalysis. So it is very hard for heterogeneous asymmetric catalysis to achieve excellent conversion and enantioselectivity at the same time.[7] Only few successful solutions have been reported so far.[3a,b,8] 3) Carrying out heterogeneous catalysis in a pseudo-homogeneous mode has been reported to be a feasible alternative[9] to remedy the loss of catalytic activity. But a great difficulty arises in the implementation of facile liquid/solid separation.[10] Soluble polymers have been applied as supports to facilitate homogeneous catalytic reactions and liquid/liquid separation.[11] Nevertheless, the flexible chains of polymers, which adopt random conformation in solvent, are scarcely helpful to asymmetric induction.

To all above challenges, elaborately designing a catalyst which combines the best aspects of both solid-phase chemistry and solution-phase chemistry, thereby affording excellent activity and meanwhile high enantioselectivity is no doubt highly desirable. Hence, we report herein a novel, efficient chiral catalyst by using inorganic nanosheets to modify with pristine α-amino acids that serve as ligands. α-Amino acids are well-known, naturally occurring chiral units for the design of powerful chiral ligands for metal-catalyzed asymmetric synthesis.[12] The inorganic nanosheets employed here are positively charged brucite-like layers of layered double hydroxides (LDHs). The metal center used here is vanadium, which has been reported to demonstrate efficacy in the asymmetric epoxidation of allylic alcohols.[2e,13] The asymmetric epoxidation reactions of allylic alcohols holds a prominent place in synthetic organic chemistry as optically pure epoxides are important building blocks and pharmaceutical targets.[14]

LDHs have the general stoichiometry $[M^{2+}_{1-x}M^{3+}_{x}(OH)_2]^{x+}\ [A^{n-}]_{x/n}\cdot y\,H_2O$ and the structure is composed of positively charged brucite-like metal hydroxide layers intercalated with anions $[A^{n-}]$ and water molecules. Both metal cations and intercalated anions can be varied over a wide range,[15] thus giving rise to a variety of chemical compositions.[16] This study employs the brucite-like layer composed of, but not limited to, zinc and aluminium hydroxides. Figure 1 schematically illustrates the ligands proposed in this work. The α-amino acids (**a**; Figure 1) were first intercalated into the interlayer regions of LDHs as anions to produce the ligands **b**. The positively charged brucite-like layer interacts with the α-amino acid anions through electrostatic attraction with the carboxylate groups. The basal spacing (d_{003}), determined from the powder XRD patterns, is 1.23, 0.90, and 0.90 nm for L-glutamate-, L-alanine-, and L-serine-intercalated LDHs (see Figure S1 in the Supporting Information), corresponding to the tilt arrangement of interlayer anions at 48°, 45°, and 36°, respectively. The LDHs intercalated with α-amino acid anions were then delaminated in formamide[16b] or water to produce transparent or translucent colloidal ligands (**c**; Figure 1, and see Figure S2 in the Supporting Information) displaying a Tyndall effect. The L-glutamate-intercalated LDHs were much more difficult to fully delaminate because the interlayer L-glutamate anions are attached to the brucite-like layers through double carboxylate groups. So the attempt to delaminate L-

[*] J. Wang, L. Zhao, H. Shi, Prof. J. He
State Key Laboratory of Chemical Resource Engineering
Beijing University of Chemical Technology
Box 98, Beijing, 100029 (China)
E-mail: jinghe@263.net.cn

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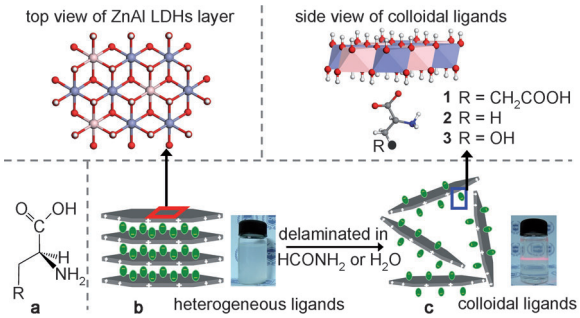

Figure 1. The α-amino acids used as ligands attached to the brucite-like layers. (●: Zn, ●: Al, ●: N, ●: C, ●: O, ●: H; blue: Zn-O octahedron, pink: Al-O octahedron). L-glutamic acid (**1**), L-alanine (**2**), and L-serine (**3**) in pristine (homogeneous) state are labeled **a**; their anions (green) in intercalated (heterogeneous) or delaminated (colloidal) states are labeled as **b** and **c**, respectively.

glutamate-intercalated Zn/Al LDHs led to large swelling or expansion of the interlayer gallery.

The vanadium-catalyzed asymmetric epoxidation was first performed using each of the three L-glutamate ligands **1a**–**1c** [**1a**: L-glutamic acid (homogeneous), **1b**: intercalated L-glutamate (heterogeneous), **1c**: delaminated **1b** (pseudo-homogeneous)] with 2-methyl cinnamyl alcohol as the substrate, a disubstituted allylic alcohol (Table 1). The reaction was carried out preliminarily at 0 °C (entries 1 and 2) in a dichloromethane/formamide (1:21) medium. The catalyst resulting from attaching L-glutamate to the brucite-like layer (**1c**), led to an increase in the *ee* value of the product from 42 % to 97 % for *trans* isomers and from 16 % to 54 % for *cis* isomers. That is, noticeable improvement of the enantioselectivity was achieved by using inorganic nanosheets. By increasing the reaction temperature from 0 (entry 2) to 20 °C (entry 3), the enhancement of enantioselectivity was preserved. Similarly, enhancement of enantioselectivity resulting from using **1b** was observed for both *cis* and *trans* isomers in dichloromethane (entries 4 and 5). By increasing the loading of $VO(OiPr)_3$ from 1.5 mol % (entry 3) to 3.0 mol % (entries 8 and 9), the product yield after the same (entry 9) or even shorter (entry 8) reaction time was enhanced to more than twice without any loss of enantioselectivity. In comparison to the result using **1a** as the ligand (entry 6), the *ee* values for *trans* isomers increased from 53 % to 92 % when using **1b** as the ligand (entry 7) and to 93 % when using **1c** as the ligand (entry 9). The swelling of the interlayer gallery of L-glutamate-intercalated LDHs caused no visible adverse effect on the *ee* values, but the catalytic efficiency was increased significantly (entry 8 versus 7); the product yield increased from 83 % after 1050 minutes to 93 % after 520 minutes. The ligand **1b** was simply dispersed throughout the reaction medium and used as a solid suspension together with $VO(OiPr)_3$. The catalytic efficiency of the solid/liquid catalytic system (entry 7) is inferior to the homogeneous catalysis (entry 6) because of the diffusion limitation in a heterogeneous reaction. The solid/liquid interfacial diffusion limitation was greatly avoided by swelling L-glutamate-intercalated LDHs (**1c**), as can be observed by comparing entry 8 and 6 in Table 1. The interlayer expansion

Table 1: Asymmetric epoxidation of 2-methyl cinnamyl alcohol in organic medium.[a]

Entry	Ligand[b]	$VO(OiPr)_3$ [mol %]	*t* [min]	Yield [%][c]	*cis*/*trans*	*ee* [%][d] *cis*[e]	*trans*[f]
1	**1a**[g]	1.5	1440	47	26:74	16	42
2	**1c**[g]	1.5	1440	30	27:73	54	97
3	**1c**	1.5	1440	35	30:70	46	95
4[h]	**1a**	1.5	1440	71	20:80	14	38
5[h]	**1b**	1.5	1440	28	23:77	48	92
6	**1a**	3.0	520	99	49:51	16	53
7	**1b**	3.0	1050	83	34:66	68	92
8	**1c**	3.0	520	93	25:75	63	96
9	**1c**	3.0	1440	99	38:62	56	93
10[i]	**1c**	0	1440	–	–	–	–
11[j]	Zn/Al layers	3.0	1440	61	9:91	–	–
12	**2a**	3.0	520	93	39:61	7	50
13	**2b**	3.0	1050	71	22:78	69	95
14	**2c**	3.0	520	89	24:76	15	94
15	**2c**	3.0	1440	95	39:61	51	97
16	**2c**	1.5	1440	43	23:77	16	96
17	**3a**	3.0	520	91	40:60	17	62
18	**3b**	3.0	1050	81	28:72	64	95
19	**3c**	3.0	520	84	22:78	27	92
20	**3c**	3.0	1440	94	36:64	51	96
21	**3c**	1.5	1440	51	25:75	15	96

[a] All data were reproduced at least twice and reported as an average. 3.0 mol % α-amino acid was used. The reaction was performed at 20 °C and in CH_2Cl_2/$HCONH_2$ (1:21) solvent mixture if not otherwise indicated. [b] Delamination was performed in formamide. [c] Yield of the epoxy alcohol isolated after chromatographic purification. [d] Determined on a Varian Prostar 210 HPLC using a Daicel Chiral AD-H column. [e] The excess enantiomer is (2*R*, 3*S*). [f] The excess enantiomer is (2*R*, 3*R*). [g] The reaction was carried out at 0 °C. [h] Only dichloromethane was used as the solvent. [i] No $VO(OiPr)_3$ was introduced. [j] No α-amino acids or their anions were present.

of **1c** facilitated the decrease or even elimination of solid/liquid interfaces, thus allowing the catalytic reaction to be carried out under pseudo-homogeneous conditions. The pseudo-homogeneous catalysis increased the yield from 83 % (entry 7) to 93 % (entry 8) in only half the time, almost reaching the level of the homogeneous catalytic system within the same time period (99 %; entry 6). Given the results in the absence of either vanadium as the catalytic center (entry 10) or the α-amino acid as the chiral ligand (entry 11), it is clear that the enhancement of chiral induction originates from the α-amino acid anions attached to brucite-like layers. Although $VO(OiPr)_3$ and the LDHs together (entry 11) were also active in the epoxidation, the activity was found to be inferior to that of its complex with **1b** (entry 11 versus 7), and **1c** (entry 11 versus entry 8 or 9). The pseudo-homogeneous nature of the catalytic system using **1c** as the ligand can be seen more clearly from the yield-time profiles (Figure 2a). In using **1c** as ligand, it is clearly observed that the profile of yield versus time approaches that of the one using **1a** as the ligand, thus supporting the implementation of pseudo-homogeneous catalysis when the brucite-like layers bearing α-amino acid anions were swollen or delaminated into a colloidal dispersion. Furthermore, ligands **1b** and **1c** not only provide an *ee* value that is much higher than that

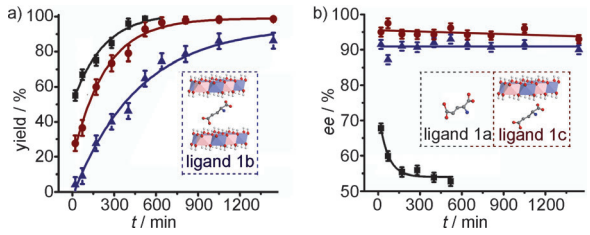

Figure 2. Profiles of the yield of epoxy alcohol (a) and *ee* value of *trans*-epoxy alcohol (b) versus reaction time in the epoxidation of 2-methyl cinnamyl alcohol using **1a** (■), **1b** (▲), and **1c** (●) as ligands.

obtained with **1a**, but also maintains an *ee* value of around 90% (**1b**) and 95% (**1c**), respectively, throughout the reaction (Figure 2b).

To confirm the utility of the LDH nanosheets, L-alanine (**2a**) and L-serine (**3a**) were employed (Table 1; the designations **a**, **b**, and **c** follow as for **1**). Similar to the observation for L-glutamate, the attachment of either L-alanine or L-serine to brucite-like layers resulted in noticeable improvement of the enantioselectivity for the *trans* and *cis* isomers. The *ee* value for the *trans* isomers increased to 95% (entry 13) and 94% (entry 14) when using **2b** and **2c**, respectively, as the ligand; the *ee* value obtained with **2a** as the ligand was 50% (entry 12). There was also an increase to 95% (entry 18) and 92% (entry 19) with **3b** and **3c**, respectively, when compared to the 62% obtained with **3a** (entry 17). The delamination of L-alanine- or L-serine-intercalated LDHs (**2c** and **3c**, respectively) enhanced the reaction rate significantly, thus achieving a pseudo-homogeneous system as observed for L-glutamate. Through delamination (entry 14 and 19), the product yields were observed to be higher than those obtained from the heterogeneous reaction (entries 13 and 18) after half the time period, and approach those from the homogeneous reaction (entries 12 and 17) after the same time period, but increase in the *ee* values was well preserved. By reducing the amount of $VO(OiPr)_3$ by half to alter the ratio of vanadium to the ligand from 1:1 to 1:2 (entries 16 and 21), the yield was found to decrease by half with **2c** and by less than one half with **3c**. The reaction rate when using either **2c** or **3c** as the ligand seems less sensitive to the vanadium/ligand ratio than **1c**, which probably originates from the fact that **1c** was swollen whereas **2c** and **3c** were delaminated. Interestingly, the *ee* value was hardly influenced in either case.

As demonstrated by the asymmetric epoxidation of 2-methyl cinnamyl alcohol, it is feasible to implement an epoxidation reaction using a pseudo-homogeneous catalyst, derived from attaching α-amino acids to brucite-like layers, and to significantly improve the enantioselectivity of the reaction. The strategy was then demonstrated in the asymmetric catalytic epoxidations of cinnamyl alcohol and isoprenol (Table 2). In the epoxidation of cinnamyl alcohol, a monosubstituted allylic alcohol, significant improvement in the *ee* value was achieved by using the catalysts derived from the nanosheet attachment. The *ee* values for the epoxidation products of the cinnamyl alcohol obtained with the LDHs nanosheet modified catalysts increased to greater than 80%

Table 2: Asymmetric epoxidation of monosubstituted allylic alcohol and homoallylic alcohol in $CH_2Cl_2/HCONH_2$ medium.[a]

Entry	Ligand[b]					
		Yield[c] [%]	*ee* [%][d]	*t* [min]	Yield [%][c]	*ee* [%][e]
1	**1a**	75	21	400	62	18
2	**1b**	51	84	640	47	>99
3	**1c**	68	81	640	58	>99
4	**2a**	76	11	400	80	8
5	**2b**	40	89	640	48	99
6	**2c**	71	84	640	66	>99
7	**3a**	79	32	400	67	20
8	**3b**	48	94	640	46	>99
9	**3c**	75	85	640	61	>99

[a] All data were reproduced at least twice and reported as an average. 3.0 mol% $VO(OiPr)_3$ and 3.0 mol% α-amino acid were used. The reaction was performed at 20°C. [b] Delamination was performed in formamide. [c] Yield of the epoxy alcohol isolated after chromatographic purification. The reaction time was 24 h for the epoxidation of cinnamyl alcohol. [d] Determined on a Varian Prostar 210 HPLC using a Daicel Chiral AD-H column. [e] Determined on a Shimadzu GC-2010 with an Astec G-TA chiral capillary column.

from the 21% obtained with ligand **1a**, the 11% obtained with ligand **2a**, and the 32% obtained with ligand **3a**. The product yield was improved when using the pseudo-homogeneous catalyst compared to the heterogeneous catalyst (entry 2 versus 3, entry 5 versus 6, and entry 8 versus 9), thus approaching the levels of homogeneous system (comparing the entry for ligand **c** to **a**) within the same time period. In the epoxidation of isoprenol, a small monosubstituted homoallylic alcohol, which is a long-standing problem in asymmetric epoxidation, the improvement in the *ee* value is striking. The *ee* values of the products obtained from using the LDHs nanosheets modified catalysts were increased to greater than 99% compared to the 18% obtained with ligand **1a**, the 8% obtained with ligand **2a**, and the 20% obtained with ligand **3a**. Owing to the ready diffusion of the smaller isoprenol, faster epoxidation was achieved than for the cinnamyl alcohol when using the either of the heterogeneous catalysts (**1b**, **2b**, and **3b**). The yields can also be improved by using the pseudo-homogeneous catalysts (**1c**, **2c**, and **3c**) relative to the heterogeneous catalysts (**1b**, **2b**, and **3b**), without any noticeable change to the *ee* values.

As the **1b**/$VO(OiPr)_3$, **2b**/$VO(OiPr)_3$, and **3b**/$VO(OiPr)_3$ catalysts are heterogeneous, they were easily separated from the reaction medium by simple filtration. After the first run, 4.3%, 6.1%, and 6.2% vanadium were dected in the filtrate for **1b**, **2b**, and **3b**, respectively. For the fresh catalyst, 2.1%, 3.4%, and 4.6% vanadium were detected in the solvent for **1b**, **2b**, and **3b** respectively, before running the epoxidation. That is, the vanadium in the filtrate primarily came from using it in excess relative to the ligand content, and this could be avoided by additionally modifying the optimized vanadium loading. Accordingly, for **1b**, for example, the yield only slightly decreased for the third recycle and the *ee* value for the *trans* isomer (major product) was fully retained (Figure 3a). The vanadium was recovered in 92% yield after three catalytic runs. In the recycle runs, the chiral α-amino acids

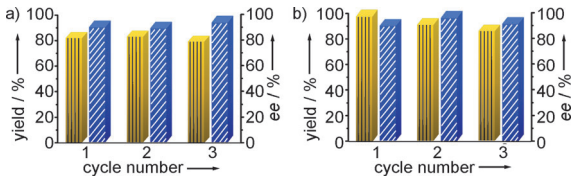

Figure 3. The recycling of the catalyst using **1b** (a) or **1c** (b) as the ligand in the epoxidation of 2-methyl cinnamyl alcohol (yellow: yield, blue: ee_{trans} value).

remain connected to the brucite layers through electrostatic interactions, and this is not only supported by the FT-IR spectra (see Figure S3 in the Supporting Information) but also by the good recovery of α-amino acids in solid catalysts. For the pseudo-homogeneous catalyst using **1c** as the ligand, the fraction of colloidized particles is hard to recover, with 2.7% and 3.2% vanadium detected in the filtrate after first and third catalytic run, respectively, thus giving rise to a slight reduction of the yield. The vanadium was recovered in 90% after three catalytic runs. Regardless, the *ee* value for the *trans* isomer was maintained at the same level in the recycle runs (Figure 3b). It was more difficult to recover ligands **2c** and **3c** because of their thorough delamination. The difficulty in recovery of the colloidal particles is not a new finding, therefore we obtained **2c** and **3c** by performing the delamination in water to facilitate a liquid/liquid separation. Aqueous medium has been recognized as a green solvent to offer numerous advantages over traditional organic solvents.[13i,17] The asymmetric epoxidation of 2-methyl cinnamyl alcohol was thus performed in aqueous medium using cheaper, water-soluble $VOSO_4$ as the source of the catalytic center. As can be seen in Table 3, excellent catalytic activity was achieved in both the homogeneous (**2a** and **3a**) and liquid/liquid catalytic systems (**2c** and **3c**). These results are similar to those obtained by using formamide as the solvent, that is, attachment of the α-amino acids to the brucite-like layers led to catalysts that resulted in enhancement of the enantioselectivity. Prolonging the reaction time for the liquid/liquid system hardly had any adverse effects on the enantioselectivity, but did increase the yield of the epoxy alcohol to above 95%, thus matching the yield observed in the homogeneous system. No noticeable loss of the catalytic efficiency and *ee* value for the *trans* isomer has been observed after the three runs. After the catalytic reaction, the catalytic center and colloidal ligand were present in the aqueous phase (upper) while the product remained in the organic phase (see Figure S4 in the Supporting Information). Therefore, the colloidal catalysts were recycled simply and easily by direct liquid/liquid separation after the reaction terminated.

Table 3: Asymmetric epoxidation of 2-methyl cinnamyl alcohol in aqueous medium.[a]

Ligand[b]	*t* [min]	Yield[c] [%]	*cis*/*trans*	*ee* [%][d]	
				cis[e]	*trans*[f]
2a	720	93	16:84	23	14
2c (fresh)	720	81	7:93	60	99
2c (fresh)	1440	96	6:94	56	99
2c (2nd run)	1440	97	3:97	47	97
2c (3rd run)	1440	98	2:98	33	98
3a	720	91	30:70	6	38
3c (fresh)	720	86	8:92	49	99
3c (fresh)	1440	95	7:93	48	99
3c (2nd run)	1440	98	13:87	19	98
3c (3rd run)	1440	96	9:91	22	97

[a] All data were reproduced at least twice and reported as an average. 3.0 mol% $VOSO_4$ and 3.0 mol% α-amino acid were used. The reaction was performed at 20°C. [b] Delamination was performed in water. [c] Yield of the epoxy alcohol isolated after chromatographic purification. [d] Determined on a Varian Prostar 210 HPLC using a Daicel Chiral AD-H column. [e] The excess enantiomer is (2*R*, 3*S*). [f] The excess enantiomer is (2*R*, 3*R*).

To explain the enhancement of enantioselectivity seen with the attachment of nanosheets, we propose that the nanosheet serves as a "huge", "rigid" substituent that imposes steric effects upon the formation of the transition states. As can be seen from the FT-IR spectra (see Figure S5 in the Supporting Information), the introduction of $VO(OiPr)_3$ to the glutamate-intercalated LDHs results in the emergence of the band at 567 cm^{-1} that is attributed to the vanadium–nitrogen vibration, and a red-shift of the signals for the C–N stretching vibration and N–H out-of-plane vibration. The bands at 1593 and 1405 cm^{-1} are assigned to the asymmetric and symmetric vibrations, respectively, of the L-glutamate carbonyl group and are preserved after introduction of the vanadium, thus indicating the vanadium coordination did not interrupt the electrostatic interactions between the interlayer L-glutamate and the brucite-like layer. The introduction of vanadium results in a shift of the ^{13}C NMR signal corresponding to the L-glutamate carboxylate carbon atom from $\delta = 180$ to 185 ppm (see Figure S6 in the Supporting Information). In the ^{51}V NMR spectra (see Figure S7 in the Supporting Information), the central ^{51}V signal assigned to the characteristic vanadium/L-glutamate complex[18] is clearly observed in each case. The replacement of the proton with the brucite-like layer causes the central signal of ^{51}V to shift downfield from $\delta = -553$ to -520 or -525 ppm. According to the epoxidation mechanism previously proposed,[19] the huge and rigid brucite-like layer, bearing α-amino acid anions as chelating moieties for vanadium as the catalytic site, is supposed to provide the necessary rigidity and more effective steric effects to direct the approach of and restrict the coordination of allylic alcohol molecules to the activated vanadium centers. The DFT[20] calculations reveal that there is hydrogen bonding between V=O and the brucite-like layer (O_3···H) in addition to those between the brucite-like layer and COO^- of L-glutamate (O_1···H and O_2···H). The O_3···H, having a length and angle of 1.80 Å and 161°, respectively, as calculated, enhances the rigidity of the linkage of brucite-like layers to L-glutamate. In the epoxidation, the convex access of the catalyzed substrate (isoprenol for example) to form the transition-state **B** (TSB) leading to the *S*-configured product alters the parameters of O_3···H to 2.01 Å and 138° (Figure 4), thus nearly breaking O_3···H. The concave access of isoprenol resulting in the transition-state **A** (TSA) leading to the *R*-configured product increases the O_3···H distance to 2.10 Å but makes no noticeable alteration of the O_3···H angle (164° versus 161°), and thereby facilitates the formation of more

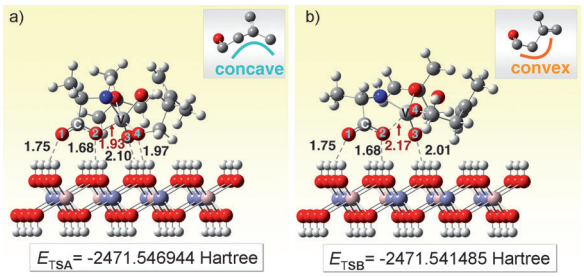

Figure 4. The calculated energies and primary bonding distances for transition-states **A** (a) and **B** (b) in the vanadium-catalyzed epoxidation of isoprenol using **1c** as ligand.

hydrogen bonds between isoprenol and the brucite-like layer (O_4···H: in 1.97 Å and 176°). As a result, the energy gap between transition states **A** and **B** increases from 7.95 kJ mol^{-1} for the homogeneous system to 14.33 kJ mol^{-1} for the heterogeneous system, thus accounting for the improvement in the *ee* value.

In conclusion, we have demonstrated in this work that an impressive enhancement of enantioselectivity of the vanadium-catalyzed epoxidation of allylic alcohols can be achieved by attaching α-amino acid anions as ligands to nanosheets. This approach is successful because: 1) By virtue of the steric synergies of rigid inorganic layers, remarkable enhancement of chiral induction has been achieved in this study. The huge inorganic layers can make a stable and rigid environment around the chiral center, and thus have significant impact upon the enantiomeric selectivity by restricting or directing the access trajectory of reactant molecules. 2) The delamination of nanosheets allows the catalytic reactions to be carried out under pseudo-homogeneous reaction conditions, thereby significantly increasing the reaction rate while preserving the enhancement of the enantioselectivity. 3) In using environmentally friendly water as the solvent, the colloidal catalyst can be directly separated from the products by simple liquid/liquid separation. The catalysts were therefore easily recycled without loss of catalytic activity and enantioselectivity. Although success is reported here for α-amino acids and nanosheets of LDHs, the method promises to be suitable for a variety of other chiral ligands and inorganic layers. The strategy proves versatile and viable for ligand modification and enantioselectivity enhancement. Its application to a variety of asymmetric reactions and detailed investigation into the mechanism both deserve additional attention.

Experimental Section

The attachment of L-glutamate (**1a**) to the brucite-like layer was carried out by ion exchange using Zn/Al-NO_3 LDHs as precursor. The attachment of L-alanine (**2a**) and L-serine (**3a**) to the Zn/Al brucite-like layer was implemented by co-precipitation. The Zn/Al molar ratio was manipulated around 2:1 in each case. The resulting chemical composition was calculated as $[Zn_{0.60}Al_{0.41}(OH)_2](L\text{-glutamate}^-)_{0.17}(CO_3)_{0.03}\cdot 0.78H_2O$, $[Zn_{0.61}Al_{0.39}(OH)_2](alanine^-)_{0.13}(NO_3^-)_{0.26}\cdot 0.42H_2O$, or $[Zn_{0.63}Al_{0.37}(OH)_2]$ $(serine^-)_{0.13}(NO_3^-)_{0.24}\cdot 0.24H_2O$ according to ICP and C, H, N elemental analysis results.

Representative experimental procedure for catalytic epoxidations: 5.0 μL of $VO(OiPr)_3$ (0.02 mmol) and 15 mL (equivalent to 0.02 mmol of L-glutamate) of ligand **1c** (1 mg mL^{-1} in formamide) was dispersed in CH_2Cl_2 (1 mL) and $HCONH_2$ (6 mL). After the mixture was stirred for 1 h at 20 °C, 0.6 mL of TBHP (1.59 mmol) in CH_2Cl_2 and 110 μL of 2-methyl cinnamyl alcohol (0.71 mmol) were added. Otherwise, 3.6 mg of $VOSO_4\cdot H_2O$ (0.02 mmol) and 21 mL (equivalent to 0.02 mmol of L-serine) of ligand 3c (1 mg mL^{-1} in water) was stirred for 2 h at 20 °C, and then 0.6 mL of TBHP (1.59 mmol) in CH_2Cl_2 and 110 μL of 2-methyl cinnamyl alcohol (0.71 mmol) were added.

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