

Article

Self-Assembled Single-walled Metal-helical Nanotube (M-HN): Creation of Efficient Supramolecular Catalysts for Asymmetric Reaction

Jian Jiang, Yan Meng, Li Zhang, and Minghua Liu

J. Am. Chem. Soc., Just Accepted Manuscript • DOI: 10.1021/jacs.6b08808 • Publication Date (Web): 10 Nov 2016

Downloaded from http://pubs.acs.org on November 10, 2016

Just Accepted

"Just Accepted" manuscripts have been peer-reviewed and accepted for publication. They are posted online prior to technical editing, formatting for publication and author proofing. The American Chemical Society provides "Just Accepted" as a free service to the research community to expedite the dissemination of scientific material as soon as possible after acceptance. "Just Accepted" manuscripts appear in full in PDF format accompanied by an HTML abstract. "Just Accepted" manuscripts have been fully peer reviewed, but should not be considered the official version of record. They are accessible to all readers and citable by the Digital Object Identifier (DOI®). "Just Accepted" is an optional service offered to authors. Therefore, the "Just Accepted" Web site may not include all articles that will be published in the journal. After a manuscript is technically edited and formatted, it will be removed from the "Just Accepted" Web site and published as an ASAP article. Note that technical editing may introduce minor changes to the manuscript text and/or graphics which could affect content, and all legal disclaimers and ethical guidelines that apply to the journal pertain. ACS cannot be held responsible for errors or consequences arising from the use of information contained in these "Just Accepted" manuscripts.



Journal of the American Chemical Society is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036 Published by American Chemical Society. Copyright © American Chemical Society. However, no copyright claim is made to original U.S. Government works, or works produced by employees of any Commonwealth realm Crown government in the course of their duties.

Self-assembled Single-walled Metal-helical Nanotube (M-HN): Creation of Efficient Supramolecular Catalysts for Asymmetric Reaction

Jian Jiang,[†] Yan Meng,[‡] Li Zhang,[‡] and Minghua Liu^{*,†,‡,§}

[†] Key laboratory of Nanosystem and Hierarchical Fabrication, National Center for Nanoscience and Technology, Beijing, 100190, China

[‡] Key Laboratory of Colloid, Interface and Chemical Thermodynamics, Institute of Chemistry, Chinese Academy of Science, Beijing National Laboratory for Molecular Science (BNLMS), Beijing, 100190, China

⁸Collaborative Innovation Center of Chemical Science and Engineering, Tianjin, 300072 , China

ABSTRACT: Ever since the axial chiral catalysts developed for asymmetric reactions with excellent chiral discrimination and highly efficiencies, the interest in the supramolecular catalyst have also been extensively investigated. Here, hinted from the typical molecular catalyst, we developed a series of metal coordinated nanotube (M-helical nanotube, M-HN) catalysts for asymmetric reactions. The M-HN catalyst was fabricated based on the self-assembly of an L-glutamic acid terminated bolaamphiphile, which formed a single-walled nanotube. On one hand, through the coordination of transition metal ions with the carboxylic acid groups on the nanotube surface, a wide variety of single-walled M-HN catalysts could be fabricated, in which the coordination sites could serve as the catalytic sites. On the other hand, using a slight amount of these catalysts, significant reactivity and enantioselectivity were realized for certain asymmetric reactions under mild conditions. Remarkably, **Bi(III)-HN** could catalyze the asymmetric Diels-Alder reaction with high enantioselectivity (up to 97 % ee) in aqueous system; **Cu(II)-HN** catalyzed the asymmetric Diels-Alder reaction with up to 91% ee within 60 minutes. It was suggested that synergetic effect of the aligned multi-catalytic sites and stereochemical selectivity of the **M-HN** lead to such an excellent catalytic performance. Through this work, we proposed a new concept of single-walled nanotube as catalysts and showed the first example that nanotube catalysts presented high reactivity and enantioselectivity that rivaled to chiral molecular catalyst.

INTRODUCTION

Ever since the axial chiral catalysts have been developed for asymmetric reactions with excellent chiral discrimination and highly efficiencies,^{1,2} the interest in the supramolecular catalyst, which nature and biomimetic supramolecular system often used to perform the asymmetric reactions under mild conditions, has also been extensively investigated.3-6 A series of pioneer works on the DNA7-10 and helical polymers^{11,12} based catalyst revealed that the supramolecular catalyst could, in many cases, work also efficiently. Besides, varieties of chiral supramolecular assemblies such chiral nanocage,13 helical nanorod,14 nanotube¹⁵ and vesicles¹⁶ have been fabricated and successfully applied to the asymmetric reactions. These catalysts showed new trends with growing interest for the asymmetric reactions. For example, Fujita group utilized chiral M_6L_4 cage for asymmetric [2+2] olefin cross photoaddition reaction and gained up to 50% ee value.^{13a} Raymond et al. reported that [Ga₄L₆] chiral assembly can be used as nanoscale molecular flasks for asymmetric cope rearrangement, the chiral product with up to 78% ee was created in the host flask.^{13b} Raynal et al. utilized the chiral benzene-1,3,5-tricaboxamide as building block to construct chiral nanorod-Rh complex and obtained 88% ee for asymmetric hydrogen reaction.¹⁴ We took advantage of the dynamic self-assembly of chiral vesicle structures regulated by compressed CO_2 and catalyzed the direct asymmetric aldol reaction with 93% ee and 99% yield.¹⁵ However, on one hand, in comparison with the large amount efficient molecular catalysts for the asymmetric reactions, there are still fewer examples of the supramolecular catalysts with efficient catalytic performances for the asymmetric reactions. On the other hand, with the development of supramolecular chemistry, it is quite convenient to construct supramolecular chiral architectures,¹⁶ it is still a great challenge to develop better catalysts for asymmetric reactions.

Previously, we have developed a Cu(II) ions coordinated multi-walled nanotube as the catalyst for asymmetric Diels-Alder reaction. However, due to the formation of the multi-walled nanotube, many of the coordination sites were embedded in the layer walls and only a reasonable 52% ee was achieved.¹⁷ Hinted from the efficient molecular catalyst, here, we tried to align the catalytic sites on the surface of nanotube synergistically. Thus, through the regulation on the self-assembly process, we obtained metal-coordinated single-walled helical nanotube (M-HN). Remarkably, these catalysts showed an unprecedented efficiency for the asymmetric reactions, as illus

Scheme 1. The Concept for the Creation of Metal-Coordinated Helical Nanotube (M-HN) Catalyst



The bolaamphiphile terminated with L-glutamic acids was self-assembled through gelation first, which provided a larger amount of single-walled nanotube. Subsequently, such nanotube was dispersed into aqueous solutions containing various metal ions and the **M-HN** can be obtained. **Bi(III)-HN** was efficient for catalyzing asymmetric Mukaiyama Aldol reaction; **Cu(II)-HN** was efficient for catalyzing asymmetric Diels-Alder reaction.

-trated in Scheme 1 and could serve as a new concept of the supramolecular catalyst. The bolaamphiphile terminated with two L-glutamic acids could self-assemble into helical single-walled nanotube via gelation.¹⁸ Upon further reaction of the nanotube with metal ions, a metal coordinated single-walled nanotube (M-helical nanotube or **M-HN**) can be obtained. Since the **M-HN** was obtained by simple reaction of the transition metal ions with the carboxylic acid on the surface of self-assembled single-walled nanotubes, it is easy to fabricate variety kinds of **M-HN**. Among these **M-HN**, we have found that **Bi(III)-HN** can catalyze Mukaiyama-Aldol reaction with up to 97% ee, while **Cu(II)-HN** catalyze Diels-Alder reaction with up to 91% ee within 60 minutes.

RESULTS AND DISCUSSION

Fabrication of the M-HN Nanocatalysts. Experimentally, the bolaamphiphile was firstly added into water and heated to dissolve. Upon cooling to room temperature, a transparent hydrogel with helical single-walled nanotube can be obtained (Fig.1a).¹⁸ These nanotubes were subsequently dispersed into the aqueous solution containing transition metal ions and then we could obtain the metal ion coordinated single-walled nanotube (M-HN) since the carboxylic acid groups on the surface of nanotube can easily react with many transition metal ions. Taking the fabrication of **Bi(III)-HN** as an example, the as prepared hydrogel of the bolaamphiphile was diluted by water and a certain amount of Bi(OTf)₃ was added under stirring.

The resulted dispersion was subjected to atomic force microscopy (AFM) observation and the results are shown in Figure 1b. Compared with nanotube formed by the bolaamphiphile (Figure 1a), the metal coordinated nanotube fully kept as the single-walled nanotube after only loading of 1/50 mol of Bi³⁺ (Figure 1b). TEM image further confirmed the tubular structure (Figure 1c). The elemental mapping observation proved that Bi3+ was well dispersed on the nanotube surface (Figure 1d). In addition, upon coordinating with the metal ions, the nanotube becomes short and more stable. Generally, 0.1-2% metal ion is able to provide discrete M-HN. More metal ions cause a serious aggregation of the nanotubes or even the collapse of the nanotube structures (Figure S1). Since the carboxylic acid can coordinate with various transition metal ions, the above method can serve as a general strategy for the creation of M-HN nanocatalysts.

It should be noted that if the metal ions and the bolaamphiphile were heated together to form a gel, only the multi-walled nanotube could be obtained. In this case, the catalytic effect will be significantly diminished.

These **M-HN** nanocatalysts showed efficient catalytic behaviors for certain asymmetry reactions. Depending on the metal ions, the **M-HN** catalysts could be used for different asymmetry reactions. Two model reactions are performed by these **M-HN**. One is the asymmetric Mukaiyama Aldol reaction catalyzed by **Bi(III)-HN** nanocatalyst, the other is the asymmetry Diels-Alder reaction by **Cu(II)-HN** nanocatalyst.

1



Figure 1. Characterization of the metal helical nanotube (**M**-**HN**). (a) AFM images of the self-assembled helical singlewalled nanotube for the ligand. (b) AFM images of **Bi**(**III**)-**HN** after loading 1/50 mol of Bi^{3^+} . (c) TEM image of **Bi**(**III**)-**HN** after loading 1/50 mol of Bi^{3^+} . (d) Element (C, O and Bi, respectively) mapping images of **Bi**(**III**)-**HN** after loading 1/50 mol of Bi^{3^+} . The size of image a-b was 5×5 µm, the size of enlarge image in a-b is 1×1 µm.

Asymmetric Mukaiyama Aldol Reaction by Bi(III)-HN. Mukaiyama aldol reaction is an efficient method for constructing carbon-carbon bonds, which was developed by Mukaiyama in 1973.¹⁹ In general, Mukaiyama Aldol reaction is performed under anhydrous reaction condition.²⁰ Kobayashi et al first discovered that the reaction could proceed smoothly in aqueous media.²¹ Soon after, the aqueous phase asymmetric Mukaiyama Aldol reaction was extensively investigated and many metal salts such as Cu^{2+} , Zn^{2+} , Fe^{2+} , Yb^{3+} , Sc^{3+} , Eu^{3+} , Gd^{3+} , Bi^{3+} and Pr^{3+} were employed to catalyze the reaction.²² However, all these reactions are limited to the molecular catalyst so far. Here, we testify the possibilities of using M-HN as the catalyst. We first screened the M-HN using various metal ions, as shown in Table 1. The results showed that when Zn(II)-HN, Fe(II)-HN, Eu(III)-HN or Gd(III)-HN were employed, only trace product was gained (entry 2, 3, 7 and 8); while Cu(II)-HN, Pr(III)-HN, Yb(III)-HN and Sc(III)-HN offered a moderate enantioselectivity but low diastereoselectivity (entry 1, 4, 5 and 6). The most exciting result was for Bi(III)-HN, which showed a moderate yield but with excellent diastereoselectivity and enantioselectivity, the syn/anti ratio was about 95:5 and ee value up to 93% for syn (entry 9). To improve the reaction yield, the amount of Bi³⁺ was increased from 0.4 mol% to 1.2 mol% according to aldehyde (the mole ratio of Bi³⁺ to HN was fixed to 1:50), and found that the yield was increased to 91% and diastereoselectivity and enantioselectivity was also increased slightly, 94% ee was obtained for syn product in the optimal reaction condition (entry 10). In addition, we have also investigated the enantioselectivity of the reaction under various mole ratios of Bi³⁺ to HN, and found that 1: 50 of Bi³⁺ to HN gave the best result. High amount

of Bi(III) ion would decrease the enantioselectivity (table S1).

Table 1. Screening and Optimization of the Reaction Condition for Mukaiyama aldol Reaction.^a

OSiMe ₃		M-HN	O OH	
+		0 °C, 40 h		
1	2a		3a	

Entry	Metal Salt	Yield(%)	syn/anti	ee(%,syn/anti)
1	Cu(OTf) ₂	9	72/28	54/4
2	$Zn(OTf)_{2}$	5	52/48	5/o
3	Fe(OTf) ₂	trace	-	-
4	$Pr(OTf)_3$	7	62/38	47/5
5	Yb(OTf) ₃	12	67/33	59/3
6	$Sc(OTf)_3$	9	56/43	25/5
7	Eu(OTf) ₃	trace	-	-
8	Gd(OTf) ₃	trace	-	-
9	Bi(OTf) ₃	45	95/5	93/9
10 ^b	Bi(OTf) ₃	91	96/4	94/10
11 ^c	Bi(OTf) ₃	33	64/36	racemic
12 ^d	Bi(OTf) ₃	28	67/33	racemic
13 ^e	Bi(OTf) ₃	37	-	-

The reaction was carried out with (a) 50 μ M of benzaldehyde, 200 μ M of silyl enol ether, 0.2 μ M of metal salt and 10 μ M of bolaamphiphile; b) 50 μ M of benzaldehyde, 200 μ M of silyl enol ether, 0.6 μ M of Bi³⁺ and 30 μ M of bolaamphiphile; c) 50 μ M of benzaldehyde, 200 μ M of silyl enol ether, 30 μ M of bolaamphiphile, the hydrogel was destroyed by 4 equiv of NaOH before the reaction; d) 50 μ M of Bi³⁺, 30 μ M of bolaamphiphile, the hydrogel was dispersed in EtOH and heated to dissolved before the reaction; e) 50 μ M of benzaldehyde, 200 μ M of silyl enol ether and 0.6 μ M of Bi³⁺.

In order to further evaluate the substrate scope, we applied the optimized condition to the reactions with different substituted aromatic aldehydes and aliphatic aldehydes (Chart 1). To our delight, most of the aromatic aldehydes gave good yield together with moderate to high diastereoselectivity and enantioselectivity (74-94% ee). The highest yield was offered by 4-chlorobenzaldehyde (Chart 1, product 3e), while the high diastereoselectivity and enantioselevtivity were obtained with 2-furaldehyde and 2-thenaldehyde as substrate (Chart 1, product 3f and 3g). The methyl or methoxy substitution on the paraposition of benzaldehyde, gave the product with slightly decreasing of ee and diastereoselectivity (3b and 3c). The aldehyde with electron withdrawing group such as 4fluorobenzaldehyde and 4-chlorobenzaldehyde gave the product 88% and 69% ee respectively, also, the diastereoselectivity decreased apparently (3d and 3e). However, aliphatic aldehydes such as cyclohexanecarbox-aldehyde and butyraldehyde showed only trace products (3h and 3i). Furthermore, to understand the role of the selfassembled nanotubes in the above asymmetric catalysis, several control experiments were performed. First, the nanotube was destroyed by introducing 4 equiv of NaOH, and found that only 33% yield of racemic product was obtained (Table 1, entry 11). Second, the monomeric bolaamphiphile together with the metal ions was dispersed into EtOH solution as the catalyst, 28% yield of racemic product was obtained (Table 1, entry 12). Third, when only 1.2 mol% of Bi³⁺ ions were involved, 37% of yield of racemic products were gained (Table 1, entry 13). These results indicated unambiguously that **Bi(III)-HN** played a key role in the Mukaiyama Aldol reaction and contributed to the enhancement of the enantioselectivity and reactivity.

Chart 1 Substrate Scope for Mukaiyama Aldol Reactions.



Reaction condition: 1 (200 μ M, 4.0 equiv), 2 (50 μ M, 1.0 equiv), HN (30 μ M, 0.6 equiv), Bi(OTf)₃ (0.6 μ M, 1.2% equiv), the reaction was carried out at 0 ^OC for 40 hours.

Asymmetric Diels-Alder Reaction by Cu(II)-HN. In order to know if such M-HN catalyst has some generality, the Cu(II)-HN was used to catalyze the asymmetry Diels-Alder reaction. The substrate azachalcone and cyclopentadiene were used and the reaction was performed under o °C. Experimentally, the azachalcone in CH₂CN was injected into Cu(II)-HN aqueous dispersion first and dispersion became green immediately, suggesting the interaction between the azachalcone and the Cu(II)-HN catalyst. With the adding of another substrate cyclopentadiene, the reaction proceeded rapidly. The results of the reaction were listed in Table 2. Amazingly, the reaction proceeded rapidly and almost completed within two minute when 20 mol% of Cu2+ was loaded (entry 1). Decrease of the amount of Cu²⁺ will lower the reaction speed but all finished within 60 minutes (entry 2-4), even with

o.1 mol% of Cu²⁺, nearly 99% yield can be obtained in 60 minutes (entry 5). The enantioselectivity of the Diels-Alder reaction were also relevant to the amount of Cu²⁺ on the nanotube, when 20 mol% Cu²⁺ was loaded on the nanotubes, the ee value was about 32% (entry 1); the ee increased significantly with the decreasing the amount of Cu²⁺ ions (entry 2-4), and 77% ee was achieved when 0.2 mol% of Cu²⁺ was involved (entry 4). The best result of 91% ee was gained after optimizing the reaction condition carefully (entry 5).

Table 2. Optimization the Reaction Condition for Diels-Alder Reaction



Entry	Cu ²⁺ (mol %)	Time (min.)	Yield (%)	Endo: exo	ee (%, endo)
1	20	2	99	93:7	32
2	5	10	99	92:8	57
3	1	30	99	91:9	72
4	0.2	60	99	91:9	77
5 [°]	0.1	60	99	92:8	91
6 ^b	0.1	60	8	-	-
7 ^c	0.1	60	10	-	racemic
8^{d}	0.1	60	12	-	racemic

Reaction condition: azachalcone **4a** (50 μ M, 1.0 equiv), **5** (500 μ M, 10 equiv), **HN** (50 μ M, 1.0 equiv) and certain amount of Cu(NO₃)₂ was list above, the reaction was carried out under o °C. a) The reaction was performed in 2 % NaCl water solution, 1 equiv NaOH was added to the reaction mixture; b)no bolaamphiphile was involved; c) **HN** was destroyed by adding 4 equiv of NaOH; d) **HN** was destroyed by adding of EtOH and heated to dissolve.

Similar to the case of Bi(III)-HN catalyst, the molar ratio of Cu²⁺ to nanotubes is also important for the catalytic reaction. We have investigated the effect of the amount of Cu(II) ions on the morphology of Cu(II)-HN in supporting information (Fig.S2). It was revealed that when 20 mol% of Cu²⁺ was loaded on HN, the nanotubes were aggregated seriously (Fig S2a). The nanotubes were also aggregated by involving 5 mol% of Cu²⁺ (Fig S2b). However, the nanotubes were well dispersed when 1 mol% of Cu²⁺ was loaded (Fig. S2c), and nearly monodispersed after 0.2 mol% of Cu²⁺ was added to HN dispersion (Fig. S2d). These results indicated that when high amount of copper(II) ions were loaded, nanotubes would be aggregated, in which the excess Cu²⁺ will become the crosslinked ions. These excess ions would not be controlled by the nanotube chirality and will decrease the enantioselectivity of the reaction.

It should be noted that the yield and enantioselectivity were better or comparable to the reported results, even in a short period of time. Actually, in the reported litera1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59 60 tures involving copper(II)-catalyzed Diels-Alder reaction, the amount of Cu²⁺ was 3-20 mol% and the reaction should be underway in 1-3 days.^{7, 23-25} Our Cu(II)-HN has proved to be one of the highest one.

Furthermore, a series of control experiments were also performed as follows: 1) When no **HN** involved, only 8% of yield was obtained (entry 6); 2) The nanotube was destroyed by adding of NaOH, and found that only racemic product was obtained, the reaction rate are also slow, only 10% product was gained even after 60 minutes (entry 7); 3) Adding disassembled monomeric bolaamphiphile instead of the self-assembled nanotube just gave racemic product with low yield (entry 8). These results proved that the self-assembled **Cu(II)-HN** not only increased the enantioselectivity but also enhanced the reaction rates.

The scope of substrate was further investigated, and the results were shown in Chart 2. First, para-substituent of azachalcone analogues were utilized as substrates, and found that the reaction processed smoothly with 0.2 mol% cooper (II), giving nearly full conversion within 60 min (6b and 6c). The electron-withdrawing group substituted azachalcone analogues (6b, 81% ee) obtained higher ee value than the electron-donating group substituted one (6d, 75% ee). Besides, the thiophene and furan substituted azachalcone were also investigated, the reaction could also finish within 180 min using 1 mol% of cooper(II), and 89% ee for 6e, 90% ee for 6f were gained respectively. Thus, our supramolecular strategy provides an alternative method for the synthesis of chiral norbornene compounds. All these results indicate that our self-assembled M-HN catalyst provides a new class of catalyst for the asymmetric reactions.

Chart 2. Substrate Scope for Diels-Alder Reactions.



Reaction condition: azachalcone 4 (50 μ M, 1.0 equiv), 5 (500 μ M, 10 equiv), HN (50 μ M, 1 equiv) and certain amount of Cu(NO₃)₂ were list above, the reaction was carried out under 0 °C. The reaction was performed in 2 % NaCl water solution, 1 equiv NaOH was added to the reaction mixture.

Mechanism Discussion. A possible reaction mechanism for such M-HN catalyzed reaction can be proposed as

following by taking Cu(II)-HN as an example. As shown in Scheme 2, when Cu^{2+} ions were added into the hydrogel dispersion, where the bolaamphiphile formed the nanotube structures, the Cu^{2+} ions coordinated with carboxylic group on the surface of the nanotube (Scheme 2A).

Scheme 2. The Proposed Mechanism for the Cu(II)-HN Catalyzed Diels-Alder Reaction.



A) The proposal structure of **Cu(II)-HN** catalyst, the copper(II) ions were coordinated on the surface of nanotube by the helical chirality manner; B) The substrate of azachalcone was also chiral alignment on the nanotube; C) The catalysis cycle for the Diels-Alder reaction, for the sake of simplicity, only one Cu(II) ion was shown. When azachalcone was introduced, it coordinated with the Cu²⁺ via the C=O and pyridine groups; when cyclopentadiene was added, the reaction substance can only occur on one side due to the stereochemical hindrance produced by the nanotube.

Since the nanotube is chiral, these metal ions are aligned on the nanotube and follow the chirality of the nanotube. When one of the substrates such as azachalcone is added into Cu(II)-HN aqueous dispersion, it will coordinate on the Cu(II)-HN surface. This could be verified from the CD spectral measurements, as shown in Fig.S₃. When azachalcone was added into the HN or Cu(II)-HN dispersion, induced CD signals for azochalcone were observed both in HN and Cu(II)-HN system. In comparison with HN system, a redshift of the absorption band and CD signal corresponding to the coordination of azochalcone with Cu(II) ions were observed in Cu(II)-HN system. These data suggested that the substrate azachalcone was helically aligned on the surface of Cu(II)-HN surface(Scheme 2B). When the second component cyclopentadiene was added, the reaction can be selectively occurred from only one side, as shown in Scheme 2C. The Cu(II)-HN functions multiply. One is alignment of the substrate molecules in a helical way; the other is to provide a stereochemically selective place for the substrate. The curved nanotube is similar to the larger arms in chiral molecular catalyst. Third, since these substrate molecules are accumulated on the nanotube, the reaction can occur synergistically on the nanotube surface, thus significantly improving the reactivity and enantioselectivity.

It should be noted that the amount of the metal ions are important for the efficiency of the M-HN. If there are many metal ions exist in the aqueous solution, they would destroy the nanotube structure or crosslink the nanotube, which will decrease the enantioselectivity due to the loss of stereoechemical control by the nanotube. It is suggested that the mechanism is similar in the case of **Bi(III)-HN** catalyzed Mukaiyama aldol reaction. Interestingly, the reactivity of **Cu(II)-HN** catalyzed D-A reaction is enhanced more significantly than **Bi(III)-HN** does, which might be due stronger interaction of the substrate of azachalcone to **Cu(II)-HN** catalyst than that of aldehyde to **Bi(III)-HN** catalyst.

CONCLUSIONS

In summary, a helical single-wall nanotube was fabricated through the self-assembly of a bolaamphiphile in water. Upon coordination of the nanotube with the metal ions, various **M-HN** catalysts can be created, which were efficient for catalyzing two model asymmetric reactions. The **Bi(III)-HN** showed excellent catalytic effect for the asymmetric Mukaiyama Aldol reaction, achieving both high diastereoselectivity and enantioselectivity. The **Cu(II)-HN** revealed both higher reaction rate and enantioselectivity for asymmetric Diels-Alder reaction. This provides a new concept of the catalyst design by using self-assembled chiral nanostructures as nanocatalysts. Since the self-assembled chiral nanostructures can be easily regulated, more reactions are expected to be applied.

EXPERIMENTAL SECTION

Instruments and materials. ¹H NMR spectras were recorded on a Bruker AV400 spectrometer. ESI-MS was recorded on a Finnigan Surveyor MSQ-plus mass spectrometer. The AFM height images without any image processing except flattening were recorded on a Digital Instrument Nanoscope IIIa Multimode system. TEM images were obtained on a JEM-1011 electron microscope at an accelerating voltage of 100 kV. The TEM samples were prepared by casting a small amount of sample on carboncoated copper grids (300mesh) and dried under strong vacuum. The enantiomeric excess was tested on a Waters 1525 HPLC. Azachalcone²⁶, silyl enol ether²⁷ and bolaamphiphile N, N'-hexadecanedioyl-di-L-glutamic acid³ were synthesized according to previous paper.¹⁸ Milli-Q water (18.2 M Ω ·cm) was used in all cases. All solid and liquid reagents mentioned above were used without further purification.

Mukaiyama-Aldol Reaction. 16.3 mg (30 μ M) of bolaamphiphile was added into 3 mL of water and heated to dissolve, and a transparent hydrogel was obtained after cooling to room temperature, which was dispersed into 15 mL of water solution and cooled to 0 °C, and then Bi(OTf)₃ in water solution (1 mg/mL, 393 uL, 0.6 μ M) was injected into the hydrogel dispersion under vigorous stirring, aldehyde ($50 \ \mu$ M) and 50μ L of silyl enol ether (about $200 \ \mu$ M) was added to the above solution respectively, the reaction was proceed for about 40 h at 0 °C. The result product was extracted with ethyl acetate and purified by silica column chromatography, which was then subjected to chiral HPLC for determination of enantiomer excess.

Diels-Alder Reaction. 27.2 mg (50 μ M) of bolaamphiphile was added into 5 mL of water and heated to dissolve, a transparent hydrogel was obtained after cooling to room temperature, which were dispersed into 20 mL of water solution and cooled to 0 °C, and then a certain amount of Cu(NO₃)₂ in water solution was injected into the hydrogel dispersion under vigorous stirring. After about 0.5 h, azachalcone **4a** (50 μ M) and cyclopentadiene **5** (500 μ M) were added to the above solution respectively, the reaction was carried out at 0 °C under stirring, the reaction progress was monitored by TLC. The result product was extracted with ethyl acetate and purified by silica column chromatography, which was then subjected to chiral HPLC for determination of enantiomer excess.

ASSOCIATED CONTENT

Supporting Information

"This material is available free of charge via the Internet at http://pubs.acs.org."

Experimental details and data.

AUTHOR INFORMATION

Corresponding Author

*liumh@iccas.ac.cn

ACKNOWLEDGMENT

We gratefully acknowledge funding of this research by the Basic Research Development Program (2013CB834504), the National Natural Science Foundation of China (Nos. 91427302, 21473219, 21321063) and "Strategic Priority Research Program" of the Chinese Academy of Sciences (XDB12020200).

REFERENCES

(1) (a) Miyashita, A.; Yasuda, A.; Takaya, H.; Toriumi, K.; Ito, T.; Souchi, T.; Noyori, R. *J. Am. Chem. Soc.* **1980**, *102*, 7932-7934.
(b) Noyori, R.; Takaya, H. *Acc. Chem. Res.* **1990**, *23*, 345-350.
(c) Noyori, R.; Ohkuma, T. *Angew. Chem. Int. Ed.* **2001**, *40*, 40-73.

(2) (a) Xie, J.-H.; Zhou, Q.-L. Acc. Chem. Res. 2008, 41, 581-593. (b) Hu, A-G.; Fu, Y.; Xie, J.-H.; Zhou, H.; Wang, L.-X.; Zhou, Q.-L. Angew. Chem. Int. Ed. 2002, 41, 2348-2350. (c) Han, Z. B.; Wang, Z.; Zhang, X. M.; Ding, K. L. Angew. Chem. Int. Ed. 2009, 48, 5345-5349. (d) Cao, Z. Y.; Wang, X. M.; Tan, C.; Zhao, X. L.; Zhou, J.; Ding, K. L. J. Am. Chem. Soc. 2013, 135, 8197-8200.

(3) (a) Wilson, M. E.; Whitesides, G. M. J. Am. Chem. Soc. 1978, 100, 306-307. (b) Hyster, T. K.; L. Knoerr; Ward, T. R.; Rovis, T. Science 2012, 338, 500-503. (c) Reetz, M. T. Angew. Chem. Int. Ed. 2011, 50, 138-174. (d) Collot, J.; Gradinaru, J.; Humbert, N.; Skander, M.; Zocchi, A.; Ward, T. R. J. Am. Chem. Soc. 2003, 125, 9030-9031. (e) Ward, T. R. Acc. Chem. Res. 2011, 44, 47-57. (f) Letondor, C.; Humbert, N.; Ward, T. R. Proc. Natl. Acad. Sci. U. S.A. 2005, 102, 4683-4687. (g) Letondor, C.; Pordea, A.; Humbert, N.; Ivanova, A.; Mazurek, S.; Novic, M.; Ward, T. R. J. Am. Chem. Soc. 2006, 128, 8320-8328. (h) Zimbron, J. M.; Hei1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59 60 nisch, T.; Schmid, M.; Hamels, D.; Nogueira, E. S.; Schirmer, T.; Ward, T. R. *J. Am. Chem. Soc.* **2013**, *135*, *538*4-*5388*.

(4) (a) Ohashi, M.; Koshiyama, T.; Ueno,T.; Yanase, M.; Fujii, H.; Watanabe, Y. *Angew. Chem. Int. Ed.* 2003, *42*, 1005-1008. (b) Ueno, T.; Koshiyama, T.; Ohashi, M.; Kondo, K.; Kono, M.; Suzuki, A.; Yamane, T.; Watanabe, Y. *J. Am. Chem. Soc.* 2005, *127*, 6556-6562. (c) Reetz, M. T.; Jiao, N. *Angew. Chem. Int. Ed.* 2006, *45*, 2416-2419. (d) Mahammed, A.; Gross, Z. *J. Am. Chem. Soc.* 2005, *127*, 2883-2887. (e) Pordea, A.; Creus, M.; Panek, J.; Duboc, C.; Mathis, D.; Novic, M.; Ward, T. R. *J. Am. Chem. Soc.* 2008, *130*, 8085-8088. (f) Podtetenieff, J.; Taglieber, A.; Bill, E.; Reijerse, E. J.; Reetz, M. T. *Angew. Chem. Int. Ed.* 2010, *49*, 5151-5155. (g) Esmieu, C.; Cherrier, M. V.; Amara, P.; Girgenti, E.; Marchi-Delapierre, C.; Oddon, F.; Iannello, M.; Jorge-Robin, A.; Cavazza, C.; Menage, S. *Angew. Chem. Int. Ed.* 2013, *52*, 3922-3925.

(5) (a) Carey, J. R.; Ma, S. K.; Pfister, T. D.; Garner, D. K.; Kim, H. K.; Abramite, J. A.; Wang, Z. L.; Guo, Z. J.; Lu, Y. *J. Am. Chem. Soc.* 2004, *126*, 10812-10813. (b) Coquiere, D.; Bos, J.; Beld, J.; Roelfes, G. Angew. Chem. Int. Ed 2009, *48*, 5159-5162. (c) Garner, D. K.; Liang, L.; Barrios, D. A.; Zhang, J.-L.; Lu, Y. Acs Catalysis 2011, *1*, 1083-1089. (d) Bos, J.; Fusetti, F.; Driessen, A. J. M.; Roelfes, G. Angew. Chem. Int. Ed. 2012, *51*, 7472-7475. (e) Bos, J.; Garcia-Herraiz, A.; Roelfes, G. Chem. Sci. 2013, *4*, 3578-3582.

(6) (a) Yang, Y.; Liu, J.; Li, Z. Angew. Chem. Int. Ed. 2014, 53, 3120-3124. (b) Dong, Z. Y.; Luo, Q.; Liu, J. Q. Chem. Soc. Rev. 2012, 41, 7890-7908. (c) Raynal, M.; Ballester, P.; Vidal-Ferran, A.; Leeuwen, P. van. Chem. Soc. Rev. 2014, 43, 1734-1787. (d) Ward, T. R. Acc. Chem. Res. 2010, 44, 47-57. (e) Yu, F. T.; Cangelosi, V. M.; Zastrow, M. L.; Tegoni M.; Plegaria, J. S.; Tebo, A. G.; Mocny, C. S.; Ruckthong, L.; Qayyum, H.; Pecoraro, V. L. Chem. Rev. 2014, 114, 3495-3578.

(7) (a) Roelfes, G.; Feringa, B. L. Angew. Chem. Int. Ed. 2005, 44, 3230-3232. (b) Roelfes, G.; A. Boersma, J.; Feringa, B. L. Chem. Comm. 2006, 635-637. (c) Boersma, A. J.; Feringa, B. L.; Roelfes, G. Org. Lett. 2007, 9, 3647-3650. (d) Wang, C.; Jia, G.; Zhou, J.; Li, Y.; Liu, Y.; Lu, S.; Li, C. Angew. Chem. Int. Ed. 2012, 51, 9352-9355. (e) Wang, C.; Jia, G.; Li, Y.; Zhang, S.; Li, C. Chem. Comm. 2013, 1161-1163.

(8) (a) Coquiere, D.; Feringa, B. L.; Roelfes, G. Angew. Chem. Int. Ed. 2007, 46, 9308-9311. (b) Megens, R. P.; Roelfes, G. Chem. Comm. 2012, 6366-6368. (c) Li, Y.; Wang, C.; Jia, G.; Lu, S.; Li, C. Tetrahedron 2013, 69, 6585-6590.

(9) (a) Boersma, A. J.; Feringa, B. L.; Roelfes, G. *Angew. Chem. Int. Ed.* **2009**, *48*, 3346-3348. (b) Park, S.; Ikehata, K.; Watabe, R.; Hidaka, Y.; Rajendran, A.; Sugiyama, H. *Chem. Comm.* **2012**, 10398-10400. (c) Park, S.; Zheng, L.; Kumakiri, S.; Sakashita, S.; Otomo, H.; Ikehata, K.; Sugiyama, H. *Acs Catal.* **2014**, *4*, 4070-4073.

(10) Boersma, A. J.; Coquiere, D.; Geerdink, D.; Rosati, F.; Feringa, B. L.; Roelfes, G. *Nature Chem.* **2010**, *2*, 991-995.

(11) (a) Yamamoto, T.; Suginome, M. Angew. Chem. Int. Ed. **2009**, 48, 539-542. (b) Yamamoto, T.; Yamada, T.; Nagata, Y.; Suginome, M. J. Am. Chem. Soc. **2010**, 132, 7899-7901. (c) Yamamoto, T.; Akai, Y.; Suginome, M. Angew. Chem. Int. Ed. **2014**, 53, 12785-12788. (d) Ke, Y. Z.; Nagata, Y.; Yamada, T.; Suginome, M. Angew. Chem. Int. Ed. **2015**, 54, 9333-9337.

(12) (a) Miyake, G. M.; Iida, H.; Hu, H.-Y.; Tang, Z.; Chen, E. Y. X.; Yashima, E. J. Poly. Sci., Part A: Poly. Chem. 2011, 49, 5192-5198. (b) Miyabe, T.; Hase, Y.; Iida, H.; Maeda, K.; Yashima, E. Chirality 2009, 21, 44-50. (c) Tang, Z.; Iida, H.; Hu, H.-Y.; Yashima, E. Acs Macro Lett. 2012, 1, 261-265. (d) Iida, H.; Iwahana, S.; Mizoguchi, T.; Yashima, E. J. Am. Chem. Soc. 2012, 134, 15103-15113.

(13) (a) Nishioka, Y.; Yamaguchi, T.; Kawano, M.; Fujita, M. J.
 Am. Chem. Soc. 2008, 130, 8160-8161. (b) Brown, C. J.; Bergman,
 R. G.; Raymond, K. N. J. Am. Chem. Soc. 2009, 131, 17530-17531.

(14) (a) Raynal, M.; Portier, F.; Leeuwen, P. W. N. M. van; Bouteiller, L. *J. Am. Chem. Soc.* **2013**, *135*, *17687-17690*. (b) Desmarchelier, A., Caumes, X., Raynal, M.; Vidal-Ferran, A., Leeuwen, P. W. N. M. van; Bouteiller, L. *J. Am. Chem. Soc.* **2016**, *138*, 4908-4916.

(15) Qin, L.; Zhang, L.; Jin, Q. X.; Zhang, J. L.; Han, B. X.; Liu, M. H. Angew. Chem. Int. Ed. **2013**, 52, 7761-7765.

(16) (a) Mateos-Timoneda, M. A.; Crego-Calama, M.; Reinhoudt, D. N. *Chem. Soc. Rev.* **2004**, *33*, 363-372. (b) Perez-Garcia, L.; Amabilino, D. B. *Chem. Soc. Rev.* **2007**, *36*, 941-967. (c) Liu, M. H.; Zhang, L.; Wang, T. Y. *Chem. Rev.* **2015**, *115*, 7304-7397. (d) Zhang, L.; Wang, T. Y.; Shen, Z. C.; Liu, M. H. *Adv. Mater.* **2016**, *28*, 1044-1059.

(17) Jin, Q.; Zhang, L.; Cao, H.; Wang, T.; Zhu, X.; Jiang, J.; Liu, M. *Langmuir* **2011** *27*, 13847-13853.

(18) Jiang, J.; Wang, T.; Liu, M. Chem. Comm. 2010, 7178-7180.
 (19) Mukaiyam, T, K.; Narasaka, K. Chem. Lett. 1973, 1011-1014.

(20) (a) Hosokawa, S.; Tatsuta, K. Mini-Reviews In Organic Chemistry **2008**, 5, 1-18. (b) Matsuo, J.-i.; Murakami, M. *Angew. Chem. Int. Ed.* **2013**, 52, 9109-9118. (c) Beutner, G. L.; Denmark, S. E. *Angew. Chem. Int. Ed.* **2013**, 52, 9086-9096.

(21) Kobayashi, S.; Nagayama, S.; Busujima, T. J. Am. Chem. Soc. **1998**, 120, 8287-8288.

(22) (a) Jankowska, J.; Mlynarski, J. J. Org. Chem. 2006, 71, 1317-1321. (b) Mei, Y.; Dissanayake, P.; Allen, M. J. J. Am. Chem. Soc. 2010, 132, 12871-12873. (c) Ollevier, T.; Plancq, B. Chem. Comm. 2012, 2289-2291. (d) Kitanosono, T.; Ollevier, T.; Kobayashi, S. Chem. Asian. J. 2013, 8, 3051-3062. (e) Kitanosono, T.; Kobayashi, S. Adv. Synth. Catal. 2013, 355, 3095-318.

(23) Otto, S.; Engberts, J. J. Am. Chem. Soc. 1999, 121, 6798-6806.

(24) Zheng, L. F.; Marcozzi, A.; Gerasimov, J. Y.; Herrmann, A. *Angew. Chem. Int. Ed.* **2014**, *53*, 7599-7603.

(25) Zheng, L. F.; Sonzini, S.; Ambarwati, M.; Rosta, E.; Scherman, O. A.; Herrmann, A. *Angew. Chem. Int. Ed.* 2015, *54*, 13007-13011.

(26) Otto, S.; Bertoncin, F.; Engberts, J. B. F. N. J. Am. Chem. Soc. **1996**, *118*, 7702-7707.

(27) Rathore, R.; Kochi, J. K. J. Org. Chem. 1996, 61, 627-639.

