

# Self-Assembled Single-Walled Metal-Helical Nanotube (M-HN): Creation of Efficient Supramolecular Catalysts for Asymmetric Reaction

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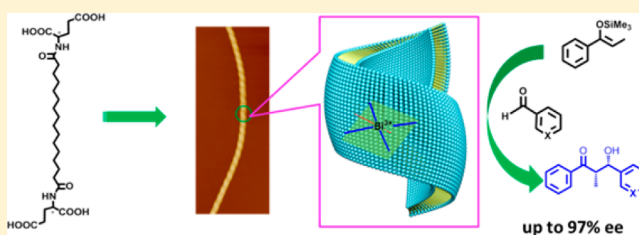
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## S Supporting Information

**ABSTRACT:** Ever since the axial chiral catalysts were developed for asymmetric reactions with excellent chiral discrimination and high efficiencies, the interest in the supramolecular catalyst has also been extensively investigated. Here, with a hint 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 on the basis of 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 Mukaiyama aldol reaction with high enantioselectivity (up to 97% ee) in an aqueous system; Cu(II)-HN catalyzed the asymmetric Diels–Alder reaction with up to 91% ee within 60 min. It was suggested that a synergetic effect of the aligned multicatalytic sites and stereochemical selectivity of the M-HN lead to an excellent catalytic performance. Through this work, we proposed a new concept of a single-walled nanotube as catalyst and showed the first example of nanotube catalysts presenting high reactivity and enantioselectivity that rivaled a chiral molecular catalyst.



## INTRODUCTION

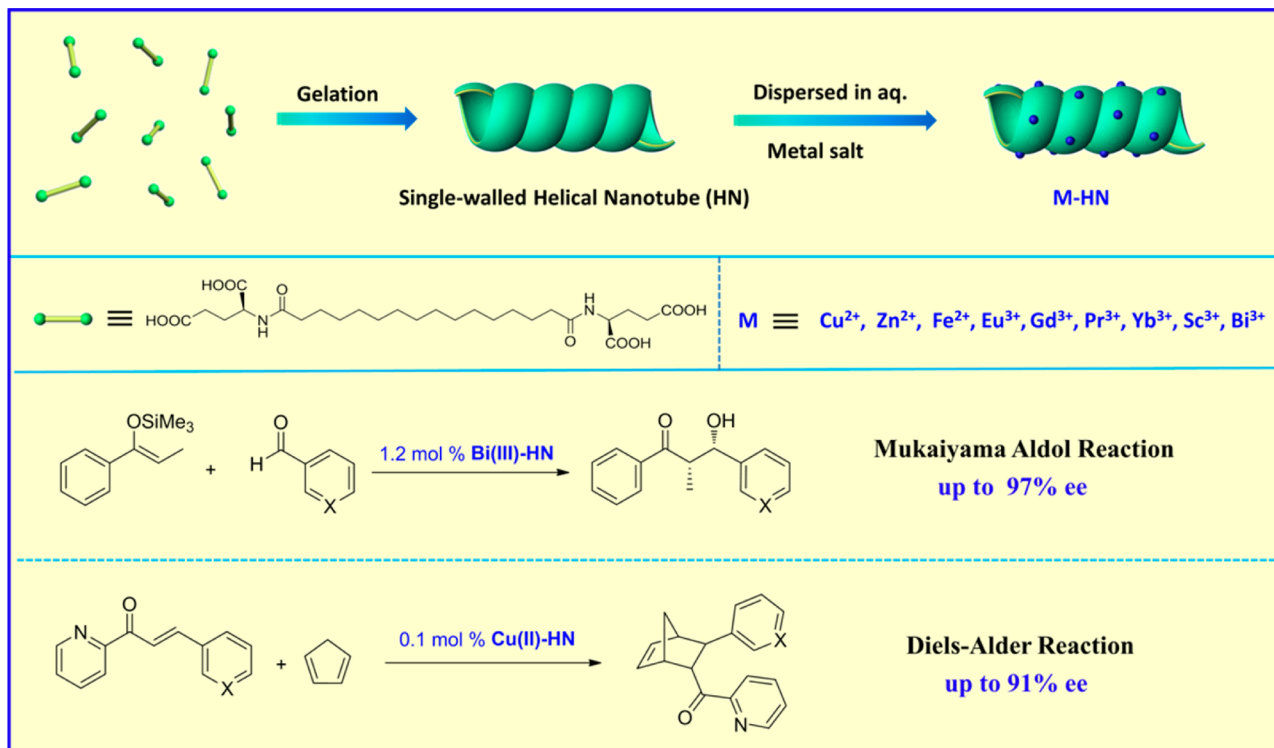
Ever since axial chiral catalysts were developed for asymmetric reactions with excellent chiral discrimination and high efficiencies,<sup>1,2</sup> supramolecular catalysts, which nature and biomimetic supramolecular systems often use to perform asymmetric reactions under mild conditions, have also been extensively investigated.<sup>3–6</sup> A series of pioneer works on DNA<sup>7–10</sup> and helical polymer<sup>11,12</sup> based catalysts revealed that the supramolecular catalyst could, in many cases, also work efficiently. In addition, varieties of chiral supramolecular assemblies such as chiral nanocages,<sup>13</sup> helical nanorods,<sup>14</sup> nanotubes,<sup>15</sup> and vesicles<sup>16</sup> have been fabricated and successfully applied to asymmetric reactions. These catalysts showed new trends with growing interest for asymmetric reactions. For example, Fujita's group utilized a chiral M<sub>6</sub>L<sub>4</sub> cage for an asymmetric [2 + 2] olefin cross photoaddition reaction and gained up to 50% ee value.<sup>13a</sup> Raymond et al. reported that the [Ga<sub>4</sub>L<sub>6</sub>] chiral assembly can be used as nanoscale molecular flask for an asymmetric Cope rearrangement; the chiral product with up to 78% ee was created in the host flask.<sup>13b</sup> Raynal et al. utilized chiral benzene-1,3,5-

tricboxamide as a building block to construct a chiral nanorod–Rh complex and obtained 88% ee for an asymmetric hydrogen reaction.<sup>14</sup> We took advantage of the dynamic self-assembly of chiral vesicle structures regulated by compressed CO<sub>2</sub> and catalyzed the direct asymmetric aldol reaction with 93% ee and 99% yield.<sup>15</sup> However, on one hand, in comparison with the large amount of efficient molecular catalysts for asymmetric reactions, there are still fewer examples of the supramolecular catalysts with efficient catalytic performances for asymmetric reactions. On the other hand, with the development of supramolecular chemistry, it is quite convenient to construct supramolecular chiral architectures,<sup>16</sup> however, it is still a great challenge to develop better catalysts for asymmetric reactions based on supramolecular chiral system.

Previously, we developed a Cu(II)-ion-coordinated multi-walled nanotube as the catalyst for an asymmetric Diels–Alder reaction. However, due to the formation of the multiwalled

Received: August 22, 2016

Published: November 10, 2016

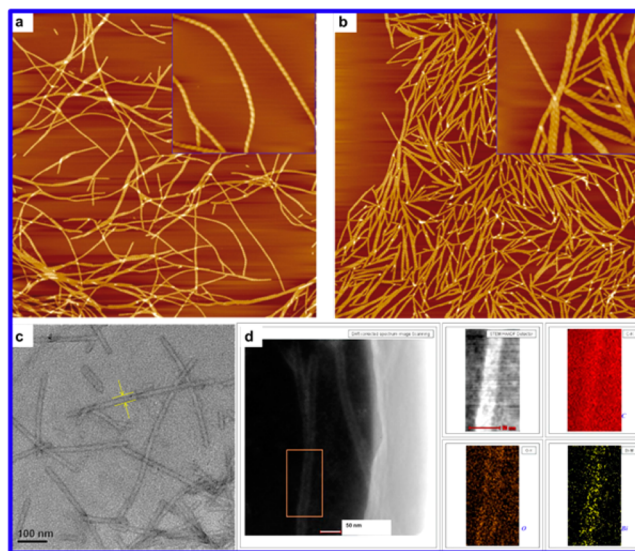
Scheme 1. Concept for the Creation of Metal-Coordinated Helical Nanotube (M-HN) Catalyst<sup>a</sup>

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

nanotube, many of the coordination sites were embedded in the layer walls, and only a reasonable 52% ee was achieved.<sup>17</sup> As hinted from the efficient molecular catalyst, here we tried to align the catalytic sites on the surface of the nanotube synergistically. Thus, through the regulation on the self-assembly process, we obtained metal-coordinated single-walled helical nanotubes (M-HN). Remarkably, these catalysts showed an unprecedented efficiency for the asymmetric reactions, as illustrated in Scheme 1, and could serve as a new concept for supramolecular catalysts. The bolaamphiphile terminated with two *L*-glutamic acids could self-assemble into helical single-walled nanotubes via gelation.<sup>18</sup> 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 a variety of M-HN species. Among these M-HN species, we have found that Bi(III)-HN can catalyze the Mukaiyama aldol reaction with up to 97% ee, while Cu(II)-HN catalyzes the Diels–Alder reaction with up to 91% ee within 60 min.

## RESULTS AND DISCUSSION

**Fabrication of the M-HN Nanocatalysts.** Experimentally, the bolaamphiphile was first added into water, and the mixture was heated to dissolve the material. Upon being cooled to room temperature, a transparent hydrogel with helical single-walled nanotubes can be obtained (Figure 1a).<sup>18</sup> These nanotubes were subsequently dispersed into the aqueous solution containing transition metal ions, and then we could obtain



**Figure 1.** Characterization of the metal-helical nanotube (M-HN). (a) AFM images of the self-assembled helical single-walled nanotube for the ligand. (b) AFM images of Bi(III)-HN after loading 1/50 mol of Bi<sup>3+</sup>. (c) TEM image of Bi(III)-HN after loading 1/50 mol of Bi<sup>3+</sup>. (d) Element (C, O, and Bi, respectively) mapping images of Bi(III)-HN after loading 1/50 mol of Bi<sup>3+</sup>. The size of images a and b was 5 × 5 μm<sup>2</sup>; the size of the enlarged image in parts a and b is 1 × 1 μm<sup>2</sup>.

the metal-ion-coordinated single-walled nanotubes (M-HN) since the carboxylic acid groups on the surface of the nanotube can easily react with many transition metal ions. With 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)<sub>3</sub> was added under stirring. The dispersion that resulted was subjected to atomic force microscopy (AFM) observation, and the results are shown in Figure 1b. In comparison with nanotubes formed by the bolaamphiphile (Figure 1a), the metal-coordinated nanotube fully remained as a single-walled nanotube after only loading 1/50 mol of Bi<sup>3+</sup> (Figure 1b). The TEM image further confirmed the tubular structure (Figure 1c). The elemental mapping observation proved that Bi<sup>3+</sup> was well-dispersed on the nanotube surface (Figure 1d). In addition, upon coordination 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 multiwalled 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 species. One is the asymmetric Mukaiyama aldol reaction catalyzed by Bi(III)-HN nanocatalyst; the other is the asymmetric Diels–Alder reaction by Cu(II)-HN nanocatalyst.

**Asymmetric Mukaiyama Aldol Reaction by Bi(III)-HN.** The Mukaiyama aldol reaction is an efficient method for constructing carbon–carbon bonds, and was developed by Mukaiyama in 1973.<sup>19</sup> In general, the Mukaiyama aldol reaction is performed under anhydrous reaction condition.<sup>20</sup> Kobayashi et al. first discovered that the reaction could proceed smoothly in aqueous media.<sup>21</sup> Soon after, the aqueous phase asymmetric Mukaiyama aldol reaction was extensively investigated, and many metal salts such as Cu<sup>2+</sup>, Zn<sup>2+</sup>, Fe<sup>2+</sup>, Yb<sup>3+</sup>, Sc<sup>3+</sup>, Eu<sup>3+</sup>, Gd<sup>3+</sup>, Bi<sup>3+</sup>, and Pr<sup>3+</sup> were employed to catalyze the reaction.<sup>22</sup> However, all of these reactions are limited to the molecular catalyst so far. Here, we testify to 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 was 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 with an ee value up to 93% for syn (entry 9). To improve the reaction yield, the amount of Bi<sup>3+</sup> was increased from 0.4 to 1.2 mol % according to the amount of aldehyde (the mole ratio of Bi<sup>3+</sup> to HN was fixed to 1:50); we found that the yield was increased to 91%, and diastereoselectivity and enantioselectivity were also increased slightly, as 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 Bi<sup>3+</sup> to HN, and found that 1:50 of Bi<sup>3+</sup> to HN gave the best result. A 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<sup>a</sup>**

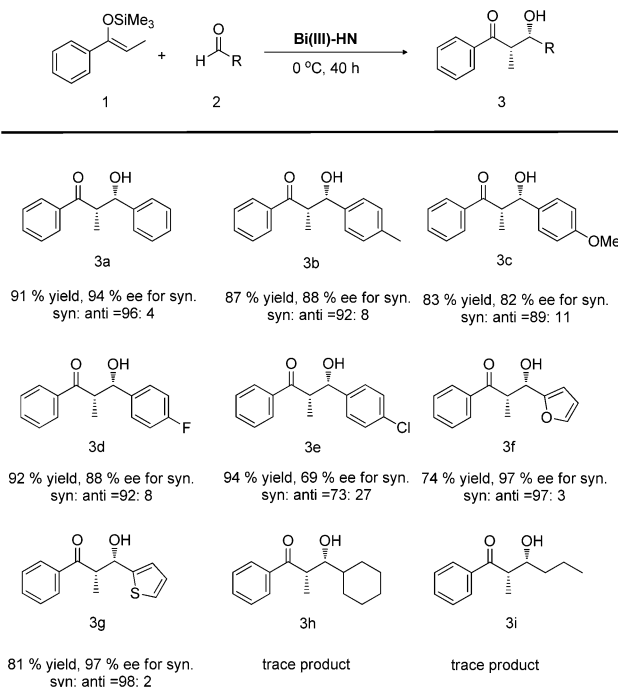
entry	metal salt	yield (%)	syn/anti	ee (% syn/anti)
1	Cu(OTf) <sub>2</sub>	9	72/28	54/4
2	Zn(OTf) <sub>2</sub>	5	52/48	5/0
3	Fe(OTf) <sub>2</sub>	trace		
4	Pr(OTf) <sub>3</sub>	7	62/38	47/5
5	Yb(OTf) <sub>3</sub>	12	67/33	59/3
6	Sc(OTf) <sub>3</sub>	9	56/43	25/5
7	Eu(OTf) <sub>3</sub>	trace		
8	Gd(OTf) <sub>3</sub>	trace		
9	Bi(OTf) <sub>3</sub>	45	95/5	93/9
10 <sup>b</sup>	Bi(OTf) <sub>3</sub>	91	96/4	94/10
11 <sup>c</sup>	Bi(OTf) <sub>3</sub>	33	64/36	racemic
12 <sup>d</sup>	Bi(OTf) <sub>3</sub>	28	67/33	racemic
13 <sup>e</sup>	Bi(OTf) <sub>3</sub>	37		

<sup>a</sup>The reaction was carried out with 50 μM benzaldehyde, 200 μM silyl enol ether, 0.2 μM metal salt, and 10 μM bolaamphiphile. <sup>b</sup>The reaction was carried out with 50 μM benzaldehyde, 200 μM silyl enol ether, 0.6 μM Bi<sup>3+</sup>, and 30 μM bolaamphiphile. <sup>c</sup>The reaction was carried out with 50 μM benzaldehyde, 200 μM of silyl enol ether, and 30 μM of bolaamphiphile, and the hydrogel was destroyed by 4 equiv of NaOH before the reaction. <sup>d</sup>The reaction was carried out with 50 μM benzaldehyde, 200 μM silyl enol ether, 0.2 μM Bi<sup>3+</sup>, and 30 μM of bolaamphiphile; the hydrogel was dispersed in EtOH and heated to dissolution before the reaction. <sup>e</sup>The reaction was carried out with 50 μM benzaldehyde, 200 μM silyl enol ether, and 0.6 μM Bi<sup>3+</sup>.

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 yields 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 enantioselectivity were obtained with 2-furaldehyde and 2-thenaldehyde as substrate (Chart 1, products 3f and 3g). The methyl or methoxy substitution on the para-position of benzaldehyde gave the product with a slight decrease of ee and diastereoselectivity (3b and 3c). The aldehyde with an electron-withdrawing group such as 4-fluorobenzaldehyde and 4-chlorobenzaldehyde gave the product 88% and 69% ee values, respectively; also, the diastereoselectivity apparently decreased (3d and 3e). However, aliphatic aldehydes such as cyclohexanecarboxaldehyde and butyraldehyde showed only trace products (3h and 3i).

Furthermore, to understand the role of the self-assembled 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 Bi<sup>3+</sup> ions were involved, 37% yield of racemic products was obtained (Table 1, entry 13). These results indicated unambiguously that Bi(III)-HN played



Chart 1. Substrate Scope for Mukaiyama Aldol Reactions<sup>a</sup>

<sup>a</sup>Reaction conditions: **1** (200  $\mu\text{M}$ , 4.0 equiv), **2** (50  $\mu\text{M}$ , 1.0 equiv), **HN** (30  $\mu\text{M}$ , 0.6 equiv), and  $\text{Bi}(\text{OTf})_3$  (0.6  $\mu\text{M}$ , 1.2% equiv). The reaction was carried out at 0  $^\circ\text{C}$  for 40 h.

a key role in the Mukaiyama aldol reaction and contributed to the enhancement of the enantioselectivity and reactivity.

**Asymmetric Diels–Alder Reaction by Cu(II)-HN.** In order to know if **M-HN** catalyst has some generality, **Cu(II)-HN** was used to catalyze the asymmetric Diels–Alder reaction. The substrates azachalcone and cyclopentadiene were used, and the reaction was performed under 0  $^\circ\text{C}$ . Experimentally, the azachalcone in  $\text{CH}_3\text{CN}$  was injected into **Cu(II)-HN** aqueous dispersion first, and the dispersion became green immediately, suggesting that there is an interaction between the azachalcone and the **Cu(II)-HN** catalyst. With the addition of another substrate cyclopentadiene, the reaction proceeded rapidly. The results of the reaction were listed in **Table 2**. Amazingly, the reaction proceeded rapidly and was almost completed within 2 min when 20 mol % of  $\text{Cu}^{2+}$  was loaded (entry 1). A decrease in the amount of  $\text{Cu}^{2+}$  will lower the reaction speed, but all finished within 60 min (entry 2–4); even with 0.1 mol % of  $\text{Cu}^{2+}$ , nearly 99% yield can be obtained in 60 min (entry 5). The enantioselectivities of the Diels–Alder reaction were also relevant to the amount of  $\text{Cu}^{2+}$  on the nanotubes; when 20 mol %  $\text{Cu}^{2+}$  was loaded on the nanotubes, the ee value was about 32% (entry 1). The ee increased significantly with the decrease in the amount of  $\text{Cu}^{2+}$  ions (entry 2–4), and 77% ee was achieved when 0.2 mol % of  $\text{Cu}^{2+}$  was involved (entry 4). The best result of 91% ee was gained after optimizing the reaction condition carefully (entry 5).

Similar to the case of the **Bi(III)-HN** catalyst, the molar ratio of  $\text{Cu}^{2+}$  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 the Supporting Information (**Figure S2**). It was revealed that when 20 mol % of  $\text{Cu}^{2+}$  was loaded on **HN**, the nanotubes were aggregated seriously (**Figure S2a**). The nanotubes were also aggregated by involving 5 mol % of  $\text{Cu}^{2+}$  (**Figure S2b**). However, the nanotubes were

Table 2. Optimization the Reaction Condition for Diels–Alder Reaction<sup>a</sup>

entry	$\text{Cu}^{2+}$ (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 <sup>b</sup>	0.1	60	99	92:8	91
6 <sup>c</sup>	0.1	60	8		
7 <sup>d</sup>	0.1	60	10		racemic
8 <sup>e</sup>	0.1	60	12		racemic

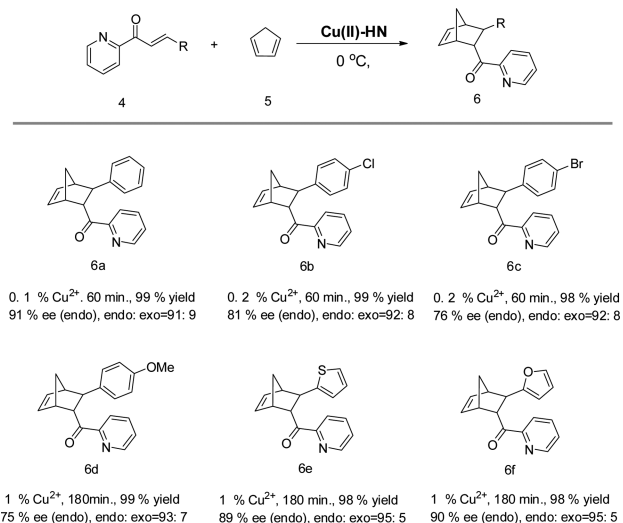
<sup>a</sup>Reaction conditions: azachalcone **4a** (50  $\mu\text{M}$ , 1.0 equiv), **5** (500  $\mu\text{M}$ , 10 equiv), **HN** (50  $\mu\text{M}$ , 1.0 equiv). A certain amount of  $\text{Cu}(\text{NO}_3)_2$  was listed above; the reaction was carried out at 0  $^\circ\text{C}$ . <sup>b</sup>The reaction was performed in 2% NaCl water solution; 1 equiv NaOH was added to the reaction mixture. <sup>c</sup>No bolaamphiphile was involved. <sup>d</sup>**HN** was destroyed by addition of 4 equiv of NaOH. <sup>e</sup>**HN** was destroyed by addition of EtOH and heated to dissolve the material.

well-dispersed when 1 mol % of  $\text{Cu}^{2+}$  was loaded (**Figure S2c**), and nearly monodispersed after 0.2 mol % of  $\text{Cu}^{2+}$  was added to the **HN** dispersion (**Figure S2d**). These results indicated that when a large number of copper(II) ions were loaded, nanotubes would be aggregated, in which the excess  $\text{Cu}^{2+}$  will become the cross-linked 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 literature involving the copper(II)-catalyzed Diels–Alder reaction, the amount of  $\text{Cu}^{2+}$  was 3–20 mol %, and the reaction should be underway in 1–3 days.<sup>7,23–25</sup> Our **Cu(II)-HN** has proven to be one of the highest ones.

Furthermore, a series of control experiments were also performed as follows: (1) When no **HN** was involved, only 8% yield was obtained (entry 6). (2) The nanotube was destroyed by addition of NaOH, and we found that only racemic product was obtained. The reaction rate is also slow, and only 10% of product was gained even after 60 min (entry 7). (3) Addition of 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, the para-substituents of azachalcone analogues were utilized as substrates, and we found that the reaction processed smoothly with 0.2 mol % copper(II), giving nearly full conversion within 60 min (**6b** and **6c**). The electron-withdrawing-group-substituted azachalcone analogues (**6b**, 81% ee) obtained higher ee values than the electron-donating-group-substituted one (**6d**, 75% ee). In addition, the thiophene- and furan-substituted azachalcone species were also investigated; the reaction could also finish within 180 min using 1 mol % of copper(II), and 89% ee for **6e** and 90% ee for **6f** were obtained, respectively. Thus, our supramolecular strategy provides an alternative method for the

Chart 2. Substrate Scope for Diels–Alder Reactions<sup>a</sup>

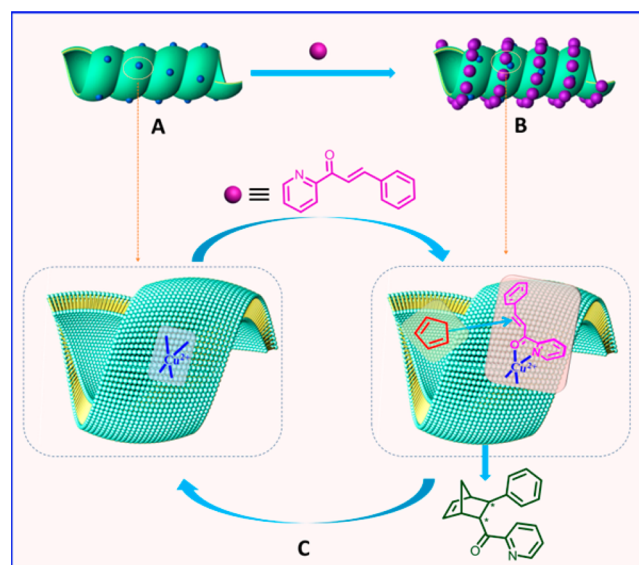
<sup>a</sup>Reaction condition: azachalcone 4 (50  $\mu$ M, 1.0 equiv), 5 (500  $\mu$ M, 10 equiv), HN (50  $\mu$ M, 1 equiv), and a certain amount of Cu(NO<sub>3</sub>)<sub>2</sub> were listed above. The reaction was carried out at 0 °C. The reaction was performed in 2% NaCl water solution, and 1 equiv NaOH was added to the reaction mixture.

synthesis of chiral norbornene compounds. All of these results indicate that our self-assembled M-HN catalyst provides a new class of catalyst for the asymmetric reactions.

**Mechanism Discussion.** A possible reaction mechanism for the M-HN-catalyzed reaction can be proposed as follows, by taking Cu(II)-HN as an example. As shown in Scheme 2, when Cu<sup>2+</sup> ions were added into the hydrogel dispersion, and where the bolaamphiphile formed the nanotube structures, the Cu<sup>2+</sup> ions coordinated with the carboxylic group on the surface of the nanotube (Scheme 2A).

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 the 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 Figure S3. When azachalcone was added into the HN or Cu(II)-HN dispersion, induced CD signals for azochalcone were observed in both HN and Cu(II)-HN systems. In comparison with the HN system, a redshift of the absorption band and a CD signal corresponding to the coordination of azochalcone with Cu(II) ions were observed in the Cu(II)-HN system. These data suggested that the substrate azachalcone was helically aligned on the surface of Cu(II)-HN (Scheme 2B). When the second component, cyclopentadiene, was added, the reaction can selectively occur 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 the 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 amounts 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 cross-link the nanotube, which will

Scheme 2. Proposed Mechanism for the Cu(II)-HN-Catalyzed Diels–Alder Reaction<sup>a</sup>

<sup>a</sup>(A) The proposed structure of Cu(II)-HN catalyst is shown, with the copper(II) ions coordinated on the surface of nanotube in the helically chiral manner. (B) The substrate of azachalcone was also in chiral alignment on the nanotube. (C) The catalysis cycle for the Diels–Alder reaction is shown; for the sake of simplicity, only one Cu(II) ion was shown. When azachalcone was introduced, it coordinated with the Cu<sup>2+</sup> 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.

decrease the enantioselectivity due to the loss of stereochemical control by the nanotube. It is suggested that the mechanism is similar in the case of the Bi(III)-HN-catalyzed Mukaiyama aldol reaction. Interestingly, the reactivity of the Cu(II)-HN-catalyzed D–A reaction is enhanced more significantly than Bi(III)-HN is, which might be due to 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-walled 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. 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 for 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.** <sup>1</sup>H NMR spectra 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 carbon-coated copper grids (300 mesh) and dried under strong vacuum. The enantiomeric excess was tested on a Waters 1525 HPLC. Azachalcone,<sup>26</sup> silyl enol ether,<sup>27</sup> and bolaamphiphile *N,N'*-hexadecanedioyl-di-L-glutamic acid<sup>3</sup> were synthesized according to a previous paper.<sup>18</sup> Milli-Q water (18.2 MΩ cm) was used in all cases. All solid and liquid reagents mentioned above were used without further purification.

**Mukaiyama Aldol Reaction.** A 16.3 mg (30 μM) portion of bolaamphiphile was added into 3 mL of water and heated to dissolve the material, and a transparent hydrogel was obtained after the reaction mixture was cooled to room temperature. The hydrogel was dispersed into 15 mL of water solution and cooled to 0 °C, and then Bi(OTf)<sub>3</sub> in water solution (1 mg/mL, 393 μL, 0.6 μM) was injected into the hydrogel dispersion under vigorous stirring. Aldehyde (50 μM) and 50 μL of silyl enol ether (about 200 μM) were added to the above solution, respectively; the reaction proceeded for about 40 h at 0 °C. The resulting 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.** A 27.2 mg (50 μM) portion of bolaamphiphile was added into 5 mL of water and heated to dissolve the material. A transparent hydrogel was obtained after the reaction mixture was cooled to room temperature. The hydrogel was dispersed into 20 mL of water solution and cooled to 0 °C, and then a certain amount of Cu(NO<sub>3</sub>)<sub>2</sub> in water solution was injected into the hydrogel dispersion under vigorous stirring. After about 0.5 h, azachalcone **4a** (50 μM) and cyclopentadiene **5** (500 μM) were added to the above solution, respectively; the reaction was carried out at 0 °C under stirring, and the reaction progress was monitored by TLC. The resulting 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

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b08808.

Experimental details and data (PDF)

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### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

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).

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