Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 63 (2007) 4422–4428

# 1,1′-Binaphthyl ligands with bulky 3,3′-tertiaryalkyl substituents for the asymmetric alkyne addition to aromatic aldehydes

Qin Wang,[a] Shan-Yong Chen,[a] Xiao-Qi Yu[a,b,*] and Lin Pu[c,*]

[a]*Department of Chemistry, Key Laboratory of Green Chemistry and Technology (Ministry of Education), Sichuan University, Chengdu, Sichuan 610064, PR China*
[b]*State Key Laboratory of Biotherapy, West China Hospital, West China Medical School, Sichuan University, Chengdu, Sichuan 610041, PR China*
[c]*Department of Chemistry, University of Virginia, Charlottesville, VA 22904-4319, USA*

Received 25 January 2007; revised 12 March 2007; accepted 14 March 2007
Available online 16 March 2007

**Abstract**—The BINOL ligand (*R*)-**2** that contains bulky 3,3′-tertiaryalkyl groups shows improved catalytic properties over the previously reported 3,3′-substituted BINOL ligands in the asymmetric alkyne addition to aromatic aldehydes. It catalyzes the phenylacetylene addition to aromatic aldehydes with high enantioselectivity (86–94% ee) and good yields without using $Ti(O^iPr)_4$ and a Lewis base additive. The catalytic properties of several analogs of (*R*)-**2** in the asymmetric alkyne addition to aldehydes have also been studied.
© 2007 Elsevier Ltd. All rights reserved.

## 1. Introduction

Chiral propargylic alcohols are versatile precursors to many organic compounds.[1,2] One efficient way to synthesize this class of compound is by the catalytic asymmetric alkyne addition to aldehydes. Recent research activity in this area has led to the development of a number of highly enantioselective catalysts.[3–12] Among these, using 1,1′-bi-2-napthol (BINOL) and its derivatives has attracted our particular attention.[5–7] We found that BINOL in combination with $Et_2Zn$ and $Ti(O^iPr)_4$ can catalyze the highly enantioselective reaction of alkynes with aromatics, aliphatic and α,β-unsaturated aldehydes.[5] We also synthesized the BINOL derivative (*S*)-**1** that contained two bulky 3,3′-anisyl substituents.[6] This compound was found to catalyze the asymmetric alkynylzinc addition to aromatic aldehydes without $Ti(O^iPr)_4$. Although using (*S*)-**1** simplified the catalytic process, its enantioselectivity and productivity were still limited. For example, the reaction of phenylacetylene with 1-naphthylaldehyde catalyzed by (*S*)-**1** in combination with $Et_2Zn$ showed 45% yield and 80% ee. Therefore, we propose to further improve the catalytic properties of (*S*)-**1** by studying the BINOL derivative (*R*)-**2** that contains the bulky 3,3′-tertiaryalkyl substituents very close to the BINOL center. Herein, our use of (*R*)-**2** and its analogs in the asymmetric alkyne addition to aromatic aldehydes is reported. This chiral ligand has shown improved catalytic properties over (*S*)-**1**.

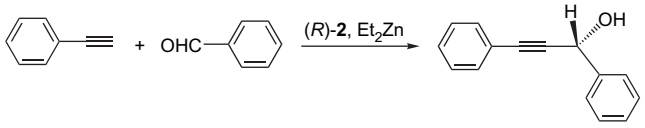
* Corresponding authors. Tel.: +1 434 924 6953; fax: +1 434 924 3710; e-mail: lp6n@virginia.edu

0040–4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.03.080

## 2. Results and discussion

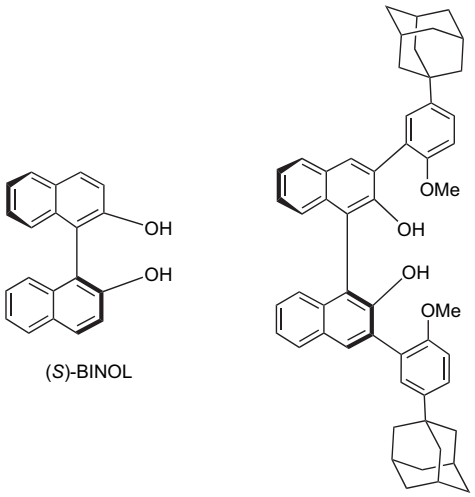
### 2.1. Asymmetric alkyne addition to aromatic aldehydes using (*R*)-2

Compound (*R*)-**2** was prepared from (*R*)-BINOL following the procedure recently reported.[13] We first tested the use of (*R*)-**2** in combination with $Et_2Zn$ to catalyze the reaction of phenylacetylene with benzaldehyde to make 1,3-diphenyl-2-propyn-1-ol without using $Ti(O^iPr)_4$ (Scheme 1). The results are summarized in Table 1. Similar to (*S*)-**1**, (*R*)-**2** showed much greater enantioselectivity in THF than in other solvents. The optimized conditions were identified by using (*R*)-**2** (30 mol %) to catalyze the reaction of phenylacetylene with benzaldehyde in THF at 0 °C, which gave the propargylic alcohol product with 91% ee (entry 11). The configuration of the product was *R* as determined by comparing the HPLC (ChiralDiacel OD column) data with the literature.[5e]

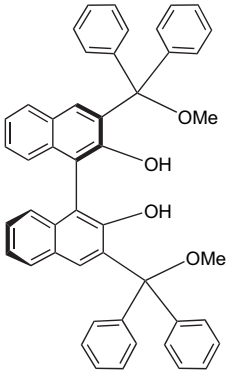



**Scheme 1**. Reaction of phenylacetylene with benzaldehyde in the presence of (*R*)-**2** and $Et_2Zn$.

We used (*R*)-**2** to catalyze the reaction of phenylacetylene with various aromatic aldehydes by applying the conditions of entry 11 in Table 1. As shown in Table 2, high enantioselectivity was observed for the reactions of phenylacetylene




(*S*)-BINOL (*S*)-**1**




(*R*)-**2**

**Table 1**. Results for the reaction of phenylacetylene with benzaldehyde catalyzed by (*R*)-**2**[a]

| Entry | (*R*)-2 (mol %) | Solvent | *T* (°C) | ee (%) |
|---|---|---|---|---|
| 1[b] | 20 | $CH_2Cl_2$ | 0 | 3 |
| 2[b] | 20 | Toluene | 0 | 10 |
| 3[b] | 20 | Ether | 0 | 47 |
| 4[b] | 20 | THF | 0 | 74 |
| 5[c] | 20 | THF | 0 | 53 |
| 6 | 20 | THF | 0 | 85 |
| 7 | 20 | THF | 30 | 55 |
| 8 | 20 | THF | −21 | 89 |
| 9 | 15 | THF | 0 | 80 |
| 10 | 25 | THF | 0 | 89 |
| *11* | *30* | *THF* | *0* | *91* |
| 12 | 35 | THF | 0 | 91 |

[a] Unless indicated otherwise the following procedure was used. (*R*)-**2** and $Et_2Zn$ (2 equiv) in THF (3 mL) were stirred at rt for 1 h, and then phenylacetylene (1.5 equiv) was added. After an additional hour, benzaldehyde was added at 0 °C.

[b] (*R*)-**2**, Phenylacetylene, and $Et_2Zn$ in solvent were stirred at rt for 2 h. Then benzaldehyde was added at 0 °C.

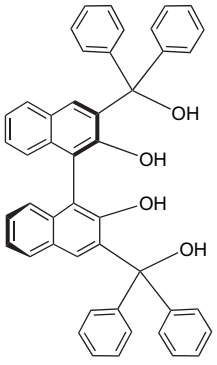
[c] Phenylacetylene and $Et_2Zn$ in THF (1 mL) were stirred at rt for 1 h, and then (*R*)-**2** in THF (2 mL) was added. After an additional hour, benzaldehyde was added at 0 °C.

with benzaldehydes containing *ortho*-, *meta*-, *para*-, electron-withdrawing, and electron-donating substituents. For the reaction of 1-naphthylaldehyde, good enantioselectivity (90% ee) and yield (70%) were also obtained, which is significantly improved over the use of (*S*)-**1**. In general, using (*R*)-**2** gave more consistently good yields and significantly reduced the $ZnEt_2$ addition side products often observed when using (*S*)-**1**.

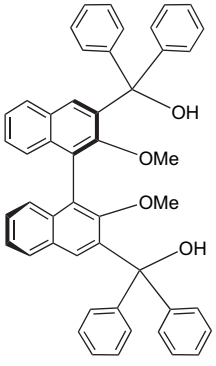
## 2.2. Asymmetric alkyne addition to aromatic aldehydes using the analogs of (*R*)-2

In order to better assess the various factors that influence the enantioselectivity of (*R*)-**2**, we prepared several analogs of (*R*)-**2**, including (*R*)-**3**,[13,14] (*R*)-**4**,[13] and (*R*)-**5**,[15] and studied their use for the reaction of phenylacetylene with benzaldehyde in the presence of $Et_2Zn$ by applying the conditions of entry 11 in Table 1. In Table 3, the results using (*R*)-**3**, (*R*)-**4**, and (*R*)-**5** as the catalysts are summarized and are compared with that of (*R*)-**2**.

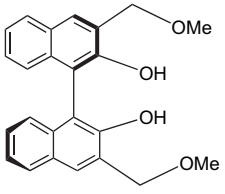
Compound (*R*)-**3** not only showed greatly reduced enantioselectivity over (*R*)-**2** but also gave the product with the opposite configuration. This indicates that the structures of the catalytic sites are very different for these two compounds. When (*R*)-**2** is treated with $Et_2Zn$, deprotonation of the two hydroxyl groups of (*R*)-**2** may require 2 equiv of $Et_2Zn$ to generate the zinc complex **6**. When (*R*)-**3** is treated with $Et_2Zn$, its four hydroxyl groups will require 4 equiv of $Et_2Zn$ for deprotonation and the resulting zinc complex could have at least three isomeric structures **7**–**9** without including the isomers containing a zinc atom bridging the two




(*R*)-**3**

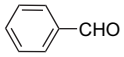
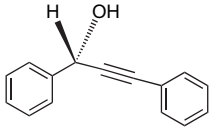
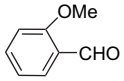
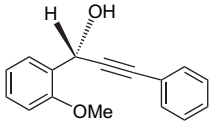
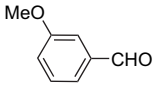
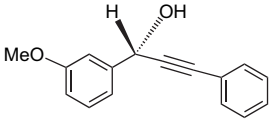
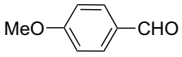
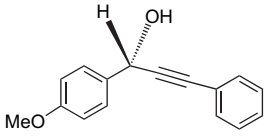
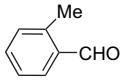
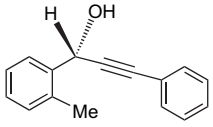
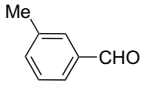
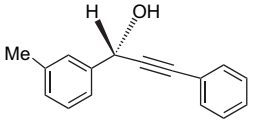
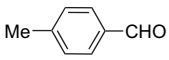
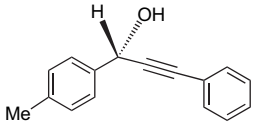
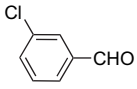
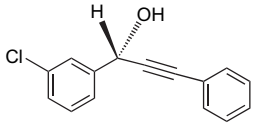
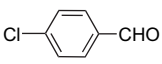
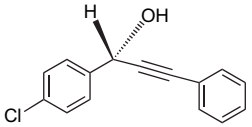
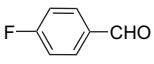
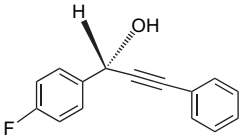
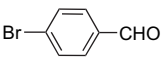
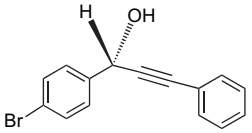
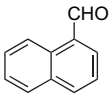
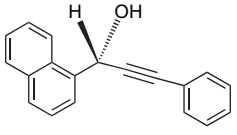


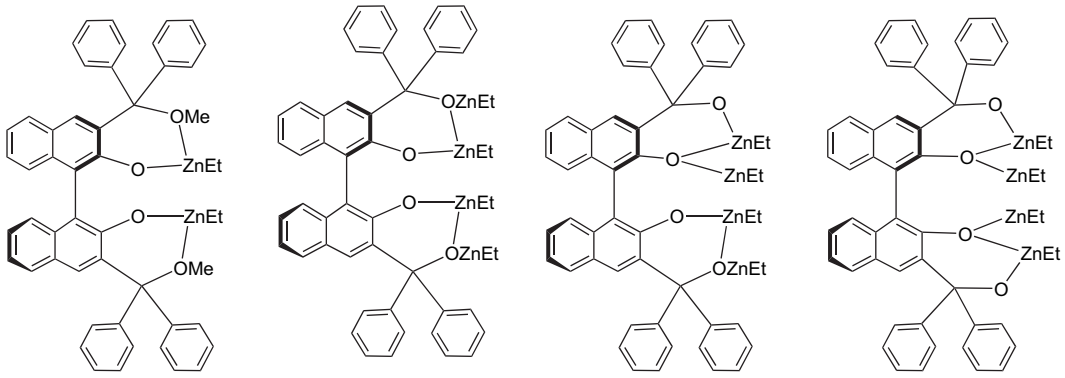

(*R*)-**4**




(*R*)-**5**

**Table 2**. Results for phenylacetylene addition to aldehydes catalyzed by (*R*)-**2**

| Entry | Aldehyde | Product | Isolated yield (%) | ee (%) |
|---|---|---|---|---|
| 1 |  |  | 81 | 91 |
| 2 |  |  | 76 | 87 |
| 3 |  |  | 75 | 94 |
| 4 |  |  | 70 | 86 |
| 5 |  |  | 67 | 90 |
| 6 |  |  | 71 | 90 |
| 7 |  |  | 77 | 88 |
| 8 |  |  | 80 | 86 |
| 9 |  |  | 75 | 92 |
| 10 |  |  | 80 | 90 |
| 11 |  |  | 75 | 92 |
| 12 |  |  | 70 | 90 |

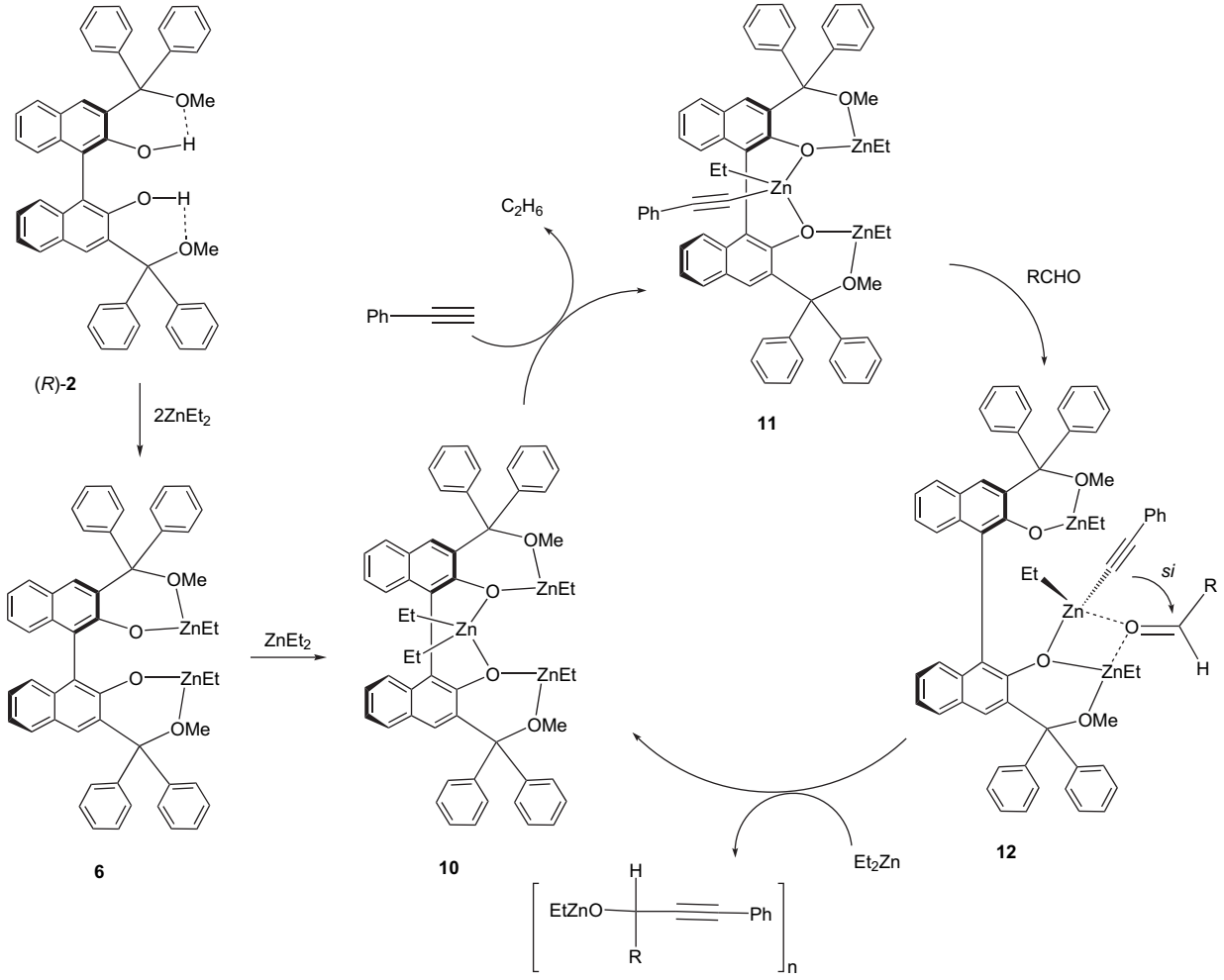



central oxygens. An aldehyde molecule could be activated by coordinating to one or two of the Lewis acidic zinc centers in **6–9** for the subsequent alkyne addition reaction. Because many of the zinc centers in **7–9** have very different steric and electronic environments from those in **6**, it could explain the very different catalytic properties between (*R*)-**2** and (*R*)-**3**.

**Table 3**. Results for the reaction of phenylacetylene with benzaldehyde in the presence of the chiral ligands and $Et_2Zn$

| Entry | Catalyst | ee (%) | Configuration |
|---|---|---|---|
| 1 | (*R*)-**2** | 91 | *R* |
| 2 | (*R*)-**3** | 28 | *S* |
| 3 | (*R*)-**4** | No reaction | |
| 4 | (*R*)-**5** | 32 | *R* |

Compound (*R*)-**5** showed greatly reduced enantioselectivity in comparison with (*R*)-**2** (entry 4, Table 3). This demonstrates that the bulky diphenyl substitutents on each of the 3,3′-bis(methoxymethyl) groups are important for the high stereo selectivity. The same product configuration for (*R*)-**2** and (*R*)-**5** suggests a similar catalyst structure. The loss

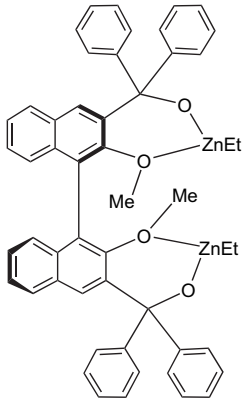



**Scheme 2**. A proposed mechanism for the catalytic asymmetric reaction of phenylacetylene with aldehydes in the presence of (*R*)-**2** and $Et_2Zn$.

of catalytic activity found for (*R*)-**4** indicates that this ligand cannot form a catalytically active site.

On the basis of the study of ligands (*R*)-**2**, (*R*)-**3**, (*R*)-**4**, and (*R*)-**5**, a reaction mechanism for the catalytic asymmetric alkyne addition to aldehydes in the presence of (*R*)-**2** could be proposed (Scheme 2). Reaction of (*R*)-**2** with excess $Et_2Zn$ will generate **10** via **6**. The Lewis base activated $Et_2Zn$ unit in **10** can react with phenylacetylene to generate the zinc acetylide in **11**. Coordination of an aldehyde with the two tricoordinated zinc centers in **11** will give **12**. Migration of the phenylacetylide to the activated aldehyde carbonyl followed by displacement by $Et_2Zn$ will regenerate **10** and form the zinc propargyloxide product.

When (*R*)-**4** is treated with 2 equiv of $ZnEt_2$, complex **13** could be generated. Because of the two central methyl groups in **13**, the two central oxygen atoms are both sterically and electronically unfavorable to coordinate to $ZnEt_2$ for the formation of an intermediate like **10**. In **10**, the two central basic oxygen atoms coordinate with $Et_2Zn$ and activate the subsequent deprotonation of phenylacetylene. Without such activation, (*R*)-**4** cannot produce the nucleophilic alkynylzinc reagent. This could explain the inactivity of (*R*)-**4** for the catalytic asymmetric alkyne addition.




**13**

## 2.3. Asymmetric alkyne addition to aromatic aldehydes using (*R*)-3 in the presence of Lewis base additives

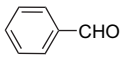
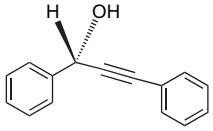
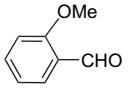
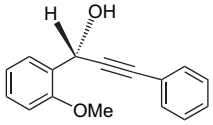
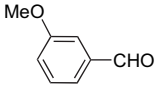
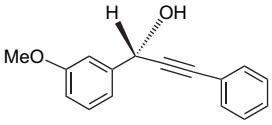
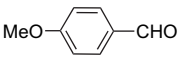
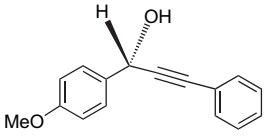
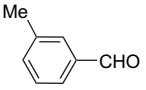
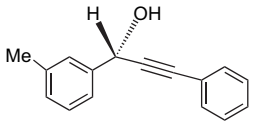
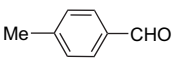
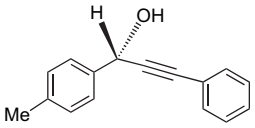
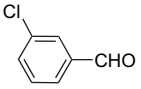
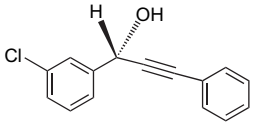
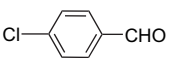
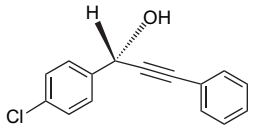
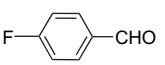
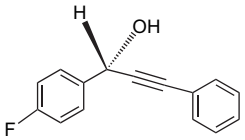
As described in the previous section, the tetrahydroxyl ligand (*R*)-**3** shows very poor enantioselectivity for the phenylacetylene addition to benzaldehyde. Since the tetrahydroxyl functions of (*R*)-**3** are similar to those of TADDOLs that have shown high enantioselectivity in many asymmetric reactions including the asymmetric organozinc additions,[16] we attempted to improve the reaction catalyzed by (*R*)-**3** with the addition of various Lewis bases. Table 4 summarizes the results for the reaction of phenylacetylene with benzaldehyde catalyzed by (*R*)-**3** in combination with $ZnEt_2$ (2.0 equiv) and a Lewis base at room temperature. The Lewis bases were added while (*R*)-**3** and $Et_2Zn$ were mixed. We found that addition of 2 equiv $Et_3N$ boosted the ee up to 80% (entry 9). With or without the Lewis bases, the configuration of the propargylic alcohol product remained as *S* as determined by comparing the HPLC data with those reported.[10e]

**Table 4**. Reaction of phenylacetylene with benzaldehyde catalyzed by using (*R*)-**3**, $ZnEt_2$, and a Lewis Base

| Entry | (*R*)-**3** (equiv) | Additive[a] (equiv) | ee (%) |
|---|---|---|---|
| 1 | 0.2 | HMPA (2) | 15(*S*) |
| 2 | 0.2 | DMSO (2) | 7(*S*) |
| 3 | 0.2 | Pyridine (2) | 9(*S*) |
| 4 | 0.2 | $Ph_3PO$ (2) | 7(*S*) |
| 5 | 0.2 | IM (2) | 22(*S*) |
| 6 | 0.2 | DMBA (2) | 66(*S*) |
| 7 | 0.2 | DMA (2) | 76(*S*) |
| 8 | 0.2 | NMM (2) | 77(*S*) |
| *9* | *0.2* | *$Et_3N$ (2)* | *80(S)* |
| 10 | 0.2 | $Et_3N$ (1) | 77(*S*) |
| 11 | 0.2 | $Et_3N$ (4) | 77(*S*) |

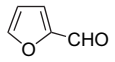
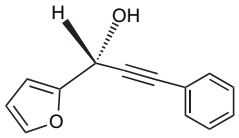
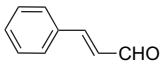
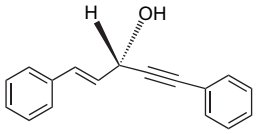
[a] IM: Imidazole. DMBA: *N*,*N*-dimethylbenzylamine. DMA: *N*,*N*-dimethylaniline. NMM: *N*-methylmorpholine.

**Table 5**. Results for phenylacetylene addition to aldehydes catalyzed by using (*R*)-**3**, $ZnEt_2$, and $Et_3N$

| Entry | Aldehyde | Product | Yield (%) | ee (%) |
|---|---|---|---|---|
| 1 |  |  | 83 | 80 (*S*) |
| 2 |  |  | 76 | 86 |
| 3 |  |  | 74 | 76 |
| 4 |  |  | 65 | 66 |
| 5 |  |  | 76 | 70 |
| 6 |  |  | 84 | 69 |
| 7 |  |  | 83 | 50 |
| 8 |  |  | 75 | 57 |
| 9 |  |  | 78 | 51 |

(*continued*)

**Table 5**. (*continued*)

| Entry | Aldehyde | Product | Yield (%) | ee (%) |
|---|---|---|---|---|
| 10 |  |  | 83 | 54 |
| 11 |  |  | 75 | 65 |

The conditions in entry 9 of Table 4 were used for the reaction of phenylacetylene with other aromatic aldehydes. As the results summarized in Table 5 show, up to 86% ee was observed for the reaction with the *ortho*-substituted benzaldehyde (entry 2, Table 5). Generally, the ee's were above 50% for the reaction of a variety of aromatic aldehydes and cinnamaldehyde.

The Lewis base $Et_3N$ probably coordinates to the zinc centers in the zinc complexes of (*R*)-**3**, such as **7**–**9**. This could modify the structure of the catalyst and lead to the higher enantioselectivity than without the additive. However, the enantioselectivity of (*R*)-**3** even with the additive is still significantly lower than that of (*R*)-**2** in almost all the cases.

## 3. Summary

We have synthesized the BINOL ligand (*R*)-**2** that contains bulky 3,3′-tertiaryalkyl groups. This compound shows improved catalytic properties over the previously reported 3,3′-substituted BINOL ligands in the asymmetric alkyne addition to aromatic aldehydes. It can catalyze the phenylacetylene addition to aromatic aldehydes with high enantioselectivity without using $Ti(O^iPr)_4$ and a Lewis base additive. Several analogs of (*R*)-**2** have also been synthesized and their catalytic properties in the asymmetric alkyne addition to aldehydes have been studied.

## 4. Experimental section

### 4.1. General data

All the solvents were dried according to the standard methods prior to use. Aldehydes were purchased from Lancaster and used directly. Diethylzinc (1.1 M in toluene) and deuterated chloroform was purchased from Aldrich Chemical Co. $^n$BuLi (2.5 M in hexane) was purchased from ACROS Chemical Co.

**4.1.1. A typical experimental procedure for the asymmetric alkyne addition to aromatic aldehydes by using (*R*)-2.** Under argon, diethylzinc (2.0 equiv) was added to a solution of (*R*)-**2** (0.3 equiv) in THF (3 mL, distilled over sodium) in a 10-mL flask. After the mixture was stirred at room temperature for 1 h, phenylacetylene (1.5 equiv) was added and the stirring continued for an additional hour. Then, an aldehyde (0.25 mmol) was added at 0 °C, and the reaction mixture was stirred for 36–40 h. The reaction was quenched with saturated $NH_4Cl$. The resulting mixture was extracted with $CH_2Cl_2$ and the extract was dried over $MgSO_4$. After removal of the volatile solvent under reduced pressure, the residue was passed through a short silica gel column eluted with 2–10% ethyl acetate in petrol ether to afford the propargylic alcohol product. The enantiomeric purity of the product was determined by using HPLC Chiralcel OD column.

**4.1.2. A typical experimental procedure for the asymmetric alkyne addition to aromatic aldehydes by using (*R*)-3 and $Et_3N$.** Under an argon atmosphere, diethylzinc (2.0 equiv) was added to a solution of (*R*)-**3** (0.2 equiv) in THF (3 mL, distilled over sodium) in a 10-mL flask, and then $Et_3N$ (2 equiv) was added. After the mixture was stirred at room temperature for 1 h, phenylacetylene (1.5 equiv) was added and the stirring continued for an additional hour. Then, an aldehyde (0.25 mmol) was added at 0 °C, and the reaction mixture was stirred for 36–40 h. The reaction was quenched with saturated $NH_4Cl$. The resulting mixture was extracted with $CH_2Cl_2$ and the extract was dried over $MgSO_4$. After removal of the volatile solvent under reduced pressure, the residue was passed through a short silica gel column eluted with 2–10% ethyl acetate in petrol ether to afford the propargylic alcohol product. The enantiomeric purity of the product was determined by using HPLC Chiralcel OD column.

**4.1.3. General procedure for the preparation of racemic propargylic alcohol.** All the racemic propargylic alcohols were prepared for the HPLC analysis according to the following procedure. Under argon, $^n$BuLi (0.12 mL, 2.5 M in hexane) was added into a solution of phenylacetylene (0.35 mmol) in 3 mL tetrahydrofuran in a 10-mL round bottom flask. After stirring for 3 h, an aldehyde (0.25 mmol) was added and the reaction was continuously stirred for 8 h. The reaction mixture was quenched with ice, extracted with methylene chloride, and the extract was dried over $MgSO_4$. After the volatile solvent was removed under reduced pressure, the residue was passed through a short silica gel eluted with 2–10% ethyl acetate in petrol ether to afford the desired racemic product.

**4.1.4. Determination of the ee's of the chiral propargylic alcohol products formed by using (*R*)-2 as the catalyst.** All the ee's were determined by Chiral HPLC: Chiralcel OD column and 254 nm UV detector. The solvents used were hexane/2-propanol=9/1 at 1.0 mL/min unless indicated otherwise.

*1,3-Diphenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$= 9.5 min (*R*), and $t_{minor}$=16.9 min (*S*).
*1-(2-Methoxyphenyl)-3-phenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$=10.9 min, and $t_{minor}$=13.5 min.
*1-(3-Methoxyphenyl)-3-phenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$=12.7 min, and $t_{minor}$=21.6 min.
*1-(4-Methoxyphenyl)-3-phenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$=10.8 min, and $t_{minor}$=22.7 min.
*1-(2-Methylphenyl)-3-phenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$=7.2 min, and $t_{minor}$=14.3 min.
*1-(3-Methylphenyl)-3-phenyl-prop-2-yn-1-ol*. Retention time: $t_{major}$=8.0 min, and $t_{minor}$=17.5 min.

*1-(4-Methylphenyl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=7.3 min, and $t_{minor}$=14.0 min.
*1-(3-Chlorophenyl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=7.6 min, and $t_{minor}$=22.9 min.
*1-(4-Chlorophenyl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=7.5 min, and $t_{minor}$=21.1 min.
*1-(4-Bromophenyl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=7.9 min, and $t_{minor}$=23.0 min.
*1-(4-Fluorophenyl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=7.1 min, and $t_{minor}$=18.3 min.
*1-(Naphthalen-1-yl)-3-phenyl-prop-2-yn-1-ol.* Retention time: $t_{major}$=9.8 min, and $t_{minor}$=19.1 min (10% *i*-PrOH in hexane at 1.2 mL/min).

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 20328203, 20272039), Program for New Century Excellent Talents in University and Scientific Fund of Sichuan Province for Outstanding Young scientist. L.P. thanks the partial support of this work from the US National Institute of Health (R01GM58454/R01EB002037-05) and Changjiang Scholarship of the Educational Ministry of China.

## References and notes

1. (a) Marshall, J. A.; Wang, X. J. *J. Org. Chem.* **1992**, *57*, 1242–1252; (b) Henderson, M. A.; Heathcock, C. H. *J. Org. Chem.* **1988**, *53*, 4736–4745; (c) Fox, M. E.; Li, C.; Marino, J. P., Jr.; Overman, L. E. *J. Am. Chem. Soc.* **1999**, *121*, 5467–5480; (d) Myers, A. G.; Zheng, B. *J. Am. Chem. Soc.* **1996**, *118*, 4492–4493.
2. (a) Vourloumis, D.; Kim, K. D.; Petersen, J. L.; Magriotis, P. A. *J. Org. Chem.* **1996**, *61*, 4848–4852; (b) Trost, B. M.; Krische, M. J. *J. Am. Chem. Soc.* **1999**, *121*, 6131–6141; (c) Roush, W. R.; Sciotti, R. J. *J. Am. Chem. Soc.* **1994**, *116*, 6457–6458; (d) Burgess, K.; Jennings, L. D. *J. Am. Chem. Soc.* **1991**, *113*, 6129–6139.
3. For reviews, see: (a) Pu, L. *Tetrahedron* **2003**, *59*, 9873–9886; (b) Pu, L.; Yu, H. B. *Chem. Rev.* **2001**, *101*, 757–824; (c) Frantz, D. E.; Fassler, R.; Tomooka, C. S.; Carreira, E. M. *Acc. Chem. Res.* **2000**, *33*, 373–381; (d) Lu, G.; Li, Y. M.; Li, X. S.; Chan, A. S. C. *Coord. Chem. Rev.* **2005**, *249*, 1736–1744.
4. (a) Anand, N. E.; Carreira, E. M. *J. Am. Chem. Soc.* **2001**, *123*, 9687–9688; (b) Frantz, D. E.; Fassler, R.; Carreira, E. M. *J. Am. Chem. Soc.* **2000**, *122*, 1806–1807; (c) Sasaki, H.; Boyall, D.; Carreira, E. M. *Helv. Chim. Acta* **2001**, *81*, 964–971; (d) Boyall, D.; Lopez, F.; Sasaki, H.; Frantz, D.; Carreira, E. M. *Org. Lett.* **2000**, *2*, 4233–4236; (e) Boyall, D.; Frantz, D. E.; Carreira, E. M. *Org. Lett.* **2002**, *4*, 2605–2606.
5. (a) Moore, D.; Pu, L. *Org. Lett.* **2002**, *4*, 1855–1857; (b) Gao, G.; Moore, D.; Xie, R.-G.; Pu, L. *Org. Lett.* **2002**, *4*, 4143–4146; (c) Moore, D.; Huang, W.-S.; Xu, M.-H.; Pu, L. *Tetrahedron Lett.* **2002**, *43*, 8831–8834; (d) Lan, L.; Pu, L. *Tetrahedron* **2004**, *60*, 7427–7430; (e) Gao, G.; Xie, R.-G.; Pu, L. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5417–5420; (f) Gao, G.; Wang, Q.; Yu, X.-Q.; Xie, R.-G.; Pu, L. *Angew. Chem., Int. Ed.* **2006**, *45*, 122–125.
6. Xu, M.-H.; Pu, L. *Org. Lett.* **2002**, *4*, 4555–4557.
7. (a) Lu, G.; Li, X.-S.; Chan, W.-L.; Chan, A. S. C. *Chem. Commun.* **2002**, 172–173; (b) Li, X.-S.; Lu, G.; Kwok, W. H.; Chan, A. S. C. *J. Am. Chem. Soc.* **2002**, *124*, 12636–12637; (c) Lu, G.; Li, X.-S.; Chen, G.; Chan, W. L.; Chan, A. S. C. *Tetrahedron: Asymmetry* **2003**, *14*, 449–452; (d) Liu, Q.-Z.; Xie, N.-S.; Luo, Z.-B.; Cui, X.; Cun, L.-F.; Gong, L. Z.; Mi, A.-Q.; Jiang, Y. Z. *J. Org. Chem.* **2003**, *68*, 7921–7924; (e) Takita, R.; Yakura, K.; Ohshima, T.; Shibasaki, M. *J. Am. Chem. Soc.* **2005**, *127*, 13760–13761.
8. (a) Dahmen, S. *Org. Lett.* **2004**, *6*, 2113–2116; (b) Fang, T.; Du, D.-M.; Lu, S.-F.; Xu, J.-X. *Org. Lett.* **2005**, *7*, 2081–2084; (c) Wolf, C.; Liu, S. *J. Am. Chem. Soc.* **2006**, *128*, 10996–10997.
9. (a) Xu, Z.-Q.; Wang, R.; Xu, J.-K.; Da, C.-S.; Yan, W.-J.; Chen, C. *Angew. Chem., Int. Ed.* **2003**, *42*, 5747–5749; (b) Xu, Z.-Q.; Chen, C.; Xu, J.-K.; Miao, M.-B.; Yan, W.-J.; Wang, R. *Org. Lett.* **2004**, *6*, 1193–1195; (c) Jiang, B.; Chen, Z.-L.; Xiong, W.-N. *Chem. Commun.* **2002**, 1524–1525; (d) Jiang, B.; Si, Y.-G. *Adv. Synth. Catal.* **2004**, *346*, 669–674; (e) Zhou, Y.-F.; Wang, R.; Xu, Z.-Q.; Yan, W.-J.; Liu, L.; Gao, Y.-F.; Da, C.-S. *Tetrahedron: Asymmetry* **2004**, *15*, 589–591.
10. (a) Niwa, S.; Soai, K. *J. Chem. Soc., Perkin Trans. 1* **1990**, 937–943; (b) Ishizaki, M.; Hoshino, O. *Tetrahedron: Asymmetry* **1994**, *5*, 1901–1904; (c) Kamble, R. M.; Singh, V. K. *Tetrahedron Lett.* **2003**, *44*, 5347–5349; (d) Li, M.; Zhu, X.-Z.; Yuan, K.; Cao, B.-X.; Hou, X.-L. *Tetrahedron: Asymmetry* **2004**, *15*, 219–222; (e) Pizzuti, M. G.; Superchi, S. *Tetrahedron: Asymmetry* **2005**, *16*, 2263–2269.
11. Corey, E. J.; Cimprich, K. A. *J. Am. Chem. Soc.* **1994**, *116*, 3151–3152.
12. Trost, B. M.; Weiss, A. H.; Wangelin, A. J. von. *J. Am. Chem. Soc.* **2006**, *128*, 8–9.
13. Wang, Q.; Chen, X.; Tao, L.; Wang, L.; Xiao, D.; Yu, X.-Q.; Pu, L. *J. Org. Chem.* **2007**, *72*, 97–101.
14. Dixon, D. I.; Tillman, A. L. *Synlett* **2005**, 2635–2638.
15. Orito, Y.; Hashimoto, S.; Ishizuka, T.; Nakajima, M. *Tetrahedron* **2006**, *62*, 390–400.
16. Seebach, D.; Beck, A. K.; Heckel, A. *Angew. Chem., Int. Ed.* **2001**, *40*, 92–138.