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Enantioselective addition of alkynylzinc to arylaldehydes catalyzed by azetidino amino alcohols bearing an additional stereogenic center

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ABSTRACT

Chiral azetidino amino alcohol ligands bearing an additional stereogenic center were readily prepared and used as catalysts for the asymmetric addition of alkynylzinc to aromatic aldehydes with enantioselectivities of up to 87% ee. The relationship between the reaction enantioselectivity and the structure of the chiral ligands was also evaluated in this reaction. The experimental results showed that the enantioselectivity level of the reaction was greatly influenced by the second stereogenic center attached to azetidine ring, but the stereochemical sense was only determined by the configuration of the azetidine ring. A possible transition structure for the catalytic asymmetric addition was also proposed.

1. Introduction

Chiral propargylic alcohols are useful and versatile building blocks for the synthesis of a wide range of natural products and pharmaceuticals.[1] Asymmetric additions of organometallic reagents to aldehydes have a strategic synthetic advantage because a new C–C bond is formed. The asymmetric addition of alkynylzinc reagents to aldehydes has received special attention in the presence of either stoichiometric or catalytic quantities of chiral ligands in recent years because of their good tolerance of various functionalities.[2] A variety of chiral catalysts based on *N*-methylephedrine,[3] BINOL and its derivatives,[4] β-hydroxy amides,[5] bisoxazolidines,[6] imino alcohols,[7] and other amino alcohol compounds[8] have been used successfully for the asymmetric addition of alkynylzinc to aldehydes. Chiral β-amino alcohols, which can be easily prepared from chiral α-amino acids or other sources, are one of the most widely employed types of ligands in asymmetric synthesis, especially in the asymmetric addition of alkylzinc to aldehydes,[9] where amino alcohol ligands have been shown to exhibit excellent enantioselectivity. By contrast, to date chiral β-amino alcohols have not been extensively applied to similar asymmetric addition of alkynylzinc to aldehydes.[3,8] The main reason for the lack of broad application of β-amino alcohols in the alkynylation of aldehydes may be the lower enantioselectivity of alkynylation than of the corresponding alkylation in the presence of *a catalytic amount* of ligands. Therefore, it seems highly desirable to explore the application of new and effective chiral β-amino alcohol ligands in the asymmetric addition of alkynylzinc to aldehydes.

In previous reports on the asymmetric addition of alkynylzinc reagents to aldehydes,[10] an interesting phenomenon was that the introduction of an additional chiral element into the nitrogen atom on the same framework greatly influenced the enantioselectivity of the alkynylation reaction. That is, a remarkable improvement in the enantioselectivity resulted if an additional chiral element matched the stereogenic center on skeleton. For example, Chan et al. described the relationship between ligand structure based on 1,2-diphenyl amino alcohols and enantioselectivity by the means of an additional axial chirality element, and their results suggested that the effective match of the (*R*)-binaphthyl moiety with the (1*R*,2*S*)-amino alcohol unit gave good enantioselectivity in the asymmetric addition of alkynylzinc to aldehydes (Fig. 1, **2** vs **1** or **3**).[10a] Recently, Wan et al. reported similar results based on *N*-methylephedrine structure via the introduction of an additional stereogenic center into nitrogen atom (Fig. 1, **5** vs **4** or **6**).[10b]

In recent years,[11] we have been exploring the use of chiral azaheterocycle-based ligands in catalytic asymmetric synthesis. Recently,[12] we found that the four-membered heterocycle-based backbone was a good potential unit for the enantioselective addition of various organozincs to aldehydes, and the highly enantioselective ethylation, methylation, and arylation of aldehydes were realized in the presence of catalytic amounts of chiral *N*-ferrocenylmethyl azetidin-2-yl(diphenyl)methanol. However, asymmetric addition of alkynylzinc to aldehydes gave relatively lower enantioselectivities (71–85% ee). In addition, the synthesis of the chiral ligands from L-(+)-methionine was very inconvenient, and involved a multistep synthesis. Therefore, the search for the easily available and new chiral ligand for the asymmetric addition of alkynylzinc to aldehydes will continue. Herein, we report the synthesis of some chiral ligands with an additional stereogenic center on nitrogen atom, and their application in the asymmetric addition of alkynylzinc to aldehydes.

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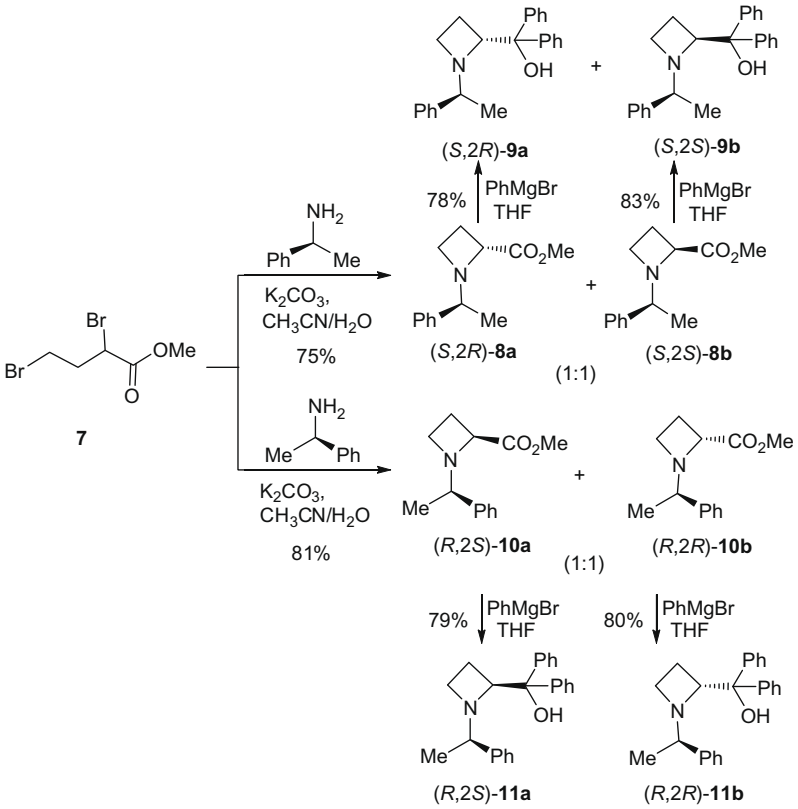
2. Results and discussion

The chiral ligands **9** and **11** were easily synthesized from commercially available (*S*)- or (*R*)-α-methylbenzylamine and methyl 2,4-dibromobutanoate **7** according to the previously reported procedure (Scheme 1).[13] First methyl 2,4-dibromobutanoate **7** was reacted with enantiomerically pure (*S*)- or (*R*)-α-methylbenzyl amine to produce the corresponding mixture of diastereomeric *N*-alkylazetidine esters **8** (75%) and **10** (81%), respectively. Then the chromatographic separation of the diastereomeric esters **8** and **10** by the preparative silica gel TLC gave the desired esters (*S*,2*R*)-**8a**, (*S*,2*S*)-**8b**, (*R*,2*S*)-**10a,** and (*R*,2*R*)-**10b**, respectively, in enantiomerically pure form. The treatment of the four esters with phenylmagnesiumbromide afforded the chiral ligands (*S*,2*R*)-**9a**, (*S*,2*S*)-**9b**, (*R*,2*S*)-**11a,** and (*R*,2*R*)-**11b**, respectively. The chiral ligands (*R*,2*S*)-**11a** and (*R*,2*R*)-**11b** were new compounds. In addition, the absolute configuration of the chiral ligand (*R*,2*S*)-**11a** was further determined by X-ray diffraction (Fig. 1).[14]

In order to examine the catalytic behavior of the ligands and seek the influence of a second stereogenic center, the addition of alkynylzinc to benzaldehyde was first investigated under our previous reaction conditions (10 mol % of ligands, 200 mol % of diethylzinc, 10 mol % of DiMPEG 2000 and toluene as solvent).[12] The alkynylzinc reagent was formed in situ by deprotonation of phen-



Scheme 1. Synthesis of the chiral ligands **9** and **11**.

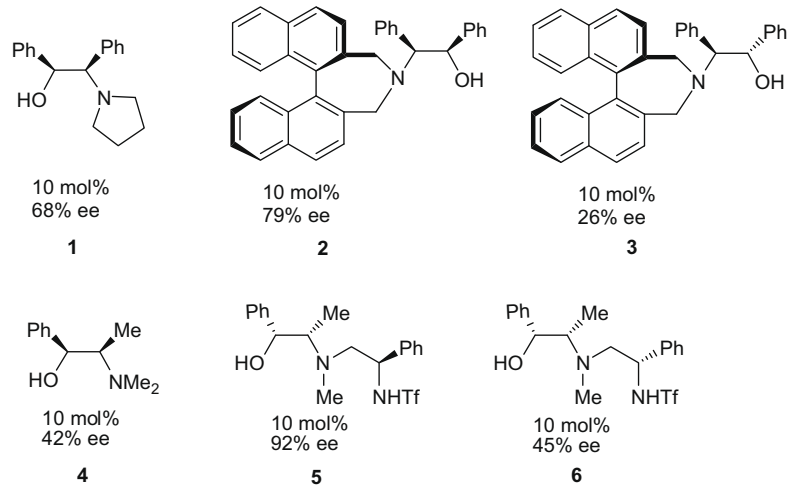
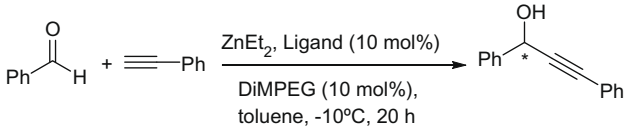


Figure 1. The structure of some β-amino alcohols.

ylacetylene with diethylzinc at room temperature. Two pairs of enantiomers (*S*,2*R*)-**9a**, (*R*,2*S*)-**11a**, and (*S*,2*S*)-**9b** (*R*,2*R*)-**11b** were tested, and the results are summarized in Table 1 (entries 1–4).

Table 1
Asymmetric addition of alkynylzinc to benzaldehyde catalyzed by ligands **9** and **11**[a]



Entry	Ligand	Yield[b] (%)	ee[c] (%)	Config.[d]
1	(*S*,2*R*)-**9a**	66	65	*S*
2	(*S*,2*S*)-**9b**	76	82	*R*
3	(*R*,2*S*)-**11a**	70	64	*R*
4	(*R*,2*R*)-**11b**	82	82	*S*

[a] The mol ratio of phenylacetylene/Et_2Zn/benzaldehyde was 2:2:1.
[b] Isolated yields.
[c] Determined by HPLC using a chiralcel OD column. The product chromatograms were compared against a known racemic mixture.
[d] Absolute configuration assigned by known elution order from a chiralcel OD column according to the literature.

As can be seen from Table 1, the asymmetric addition of phenylacetylene to benzaldehyde led to the desired products in 66–84% yields with 62–82% ee (entries 1–4). It was shown that both the enantioselectivity and the reactivity were very sensitive to the structure of the chiral ligands. When the ligand (*S*,2*S*)-**9b** and its enantiomer (*R*,2*R*)-**11b** were employed, the alkynylation of benzaldehyde afforded high ee values (82% ee) and good chemical yields (76%, 81%, Table 1, entries 2 and 4). The ligand (*S*,2*R*)-**9a** and its antipode (*R*,2*S*)-**11a** not only showed relatively low catalytic activity (66–70%), but also gave the product with relatively low ee values (64-65% ee, Table 1**,** entries 1 and 3). It was interesting to compare the results obtained from the chiral compounds (*S*,2*S*)-**9b** and (*R*,2*R*)-**11b** with those from their diastereomers (*S*,2*R*)-**9a** and (*R*,2*S*)-**11a**, respectively. For example, the ligand (*S*,2*S*)-**9b** gave the product with an (*R*)-configuration with 82% ee while its diastereomers (*S*,2*R*)-**9a** and (*R*,2*S*)-**11a** afforded the product with an (*S*)-configuration with 65% ee, (*R*)-configuration with 64% ee, respectively. These results suggested that the absolute configuration of the addition products was only determined by the configuration of the azetidine ring. At the same time, these results also indicated that the match of the configuration of the azetidine ring with the configuration of the additional stereogenic center was crucial to obtain high enantioselectivity.

Recently, we described the synthesis of the ferrocenyl azetidino alcohol **12** (Fig. 3) and its application as a catalyst.[12] We observed that the hindrance of the bulky ferrocenyl group relative to the phenyl group was essential for obtaining higher enantioselectivity. A similar phenomenon was observed by Zhang et al. in the asymmetric addition of alkynylzinc to aldehydes.[15] In their experience, replacement of the phenyl group on the nitrogen atom of the five-membered heterocycle-based skeleton with a bulky 2,4,6-trimethylphenyl substituent led to an increase in the enantioselectivity from 65% ee (the ligand **14** (Fig. 3)) to 77% ee (the ligand **13** (Fig. 3)). A comparison of the results (82% ee) obtained by the ligand (*S*,2*S*)-**9b** with those (84.6% ee) by **12** demonstrates that the same effect, which was resulted by the large ferrocenyl group, was achieved by the means of the match of the second stereogenic center on nitrogen atom with the stereogenic center of the azetidine ring. In addition, the chiral ligand (*S*,2*S*)-**9b** was easily prepared in two steps in contrast to the compound **12**.

Based on a great number of previous theoretical studies on the mechanism of the asymmetric addition of alkylzinc to aldehydes[16] and our experimental results, a plausible mechanism for the asymmetric addition of alkynylzinc to benzaldehyde catalyzed by ligand **11a** can be proposed (Scheme 2).

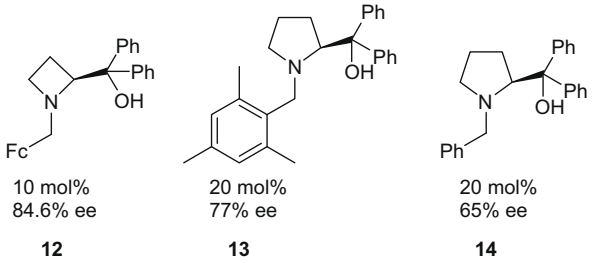
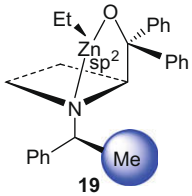
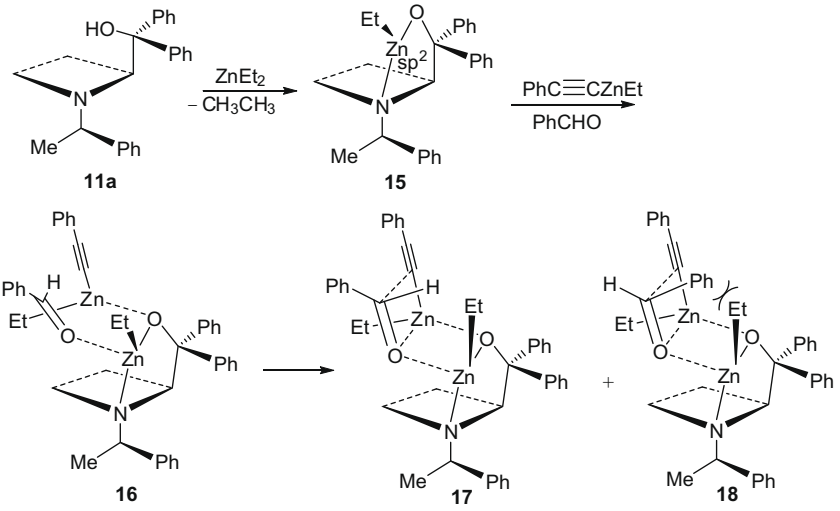


Figure 3. The structure of some β-amino alcohols.

The reaction of diethylzinc with the ligand **11a** first yielded the corresponding zinc aminoalkoxide **15**, which acted as a bifunctional catalyst. The lone pair electrons of oxygen atom of benzaldehyde coordinated with the Lewis acidic Zn atom at the less hindered face of the five-membered ring chelate **15**, and then the adjacent basic oxygen accepted alkynylzinc at Zn to form the product-forming, mixed-ligand complex **16**. The phenylacetylene group transfer from the alkynylzinc to the aldehyde from both the *Si*-face and the *Re*-face resulted in the *anti*-5/4/4-fused tricyclic transition states **17** and **18**, respectively. In the transition state **17**, a nonbonded repulsion between Et and Ph is absent, but steric repulsive interaction between the Et and Ph groups disfavors the transition state **18**. As a result, the transition state **17** is the favored structure, and the addition product with (*R*)-configuration was afforded. Therefore, if the absolute configuration of azetidine ring was *S*, the configuration of the addition product was *R*. Conversely, if the absolute configuration of azetidine ring was *R*, the result would be opposite to the above statement. These were in good agreement with the experimentally observed results.



The X-ray structures of the non-complexed ligands did not provide direct information about the structure of the catalytically active metal complex, but they did help in understanding the reaction mechanism and the effect of free ligands on reaction enantioselectivity. The X-ray structure analysis of **11a** revealed that the *N*-methylbenzyl group on the nitrogen atom of the heterocycle is positioned *anti* to the diphenylhydroxymethyl group on the heterocycle (Fig. 2). The four-membered N1, C9, C10, C11 ring moiety is almost a planar structure with the sum of the four bond angles being 353.2°. The N(1)–C(9)–C(10), C(9)–C(10)–C(11), N(1)–C(11)–C(10), and C(9)–N(1)–C(11) bond angles are 88.8°, 86.6°, 88.3°, and 89.5°, respectively. The values of the torsion angles C(10)–C(11)–C(12)–C(19) and C(9)–N(1)–C(7)–C(6) were −167.1(4)° and −174.5(4)°, respectively, indicating that two phenyl substituents point in the same direction. The replacement of the hydrogen atom on the hydroxyl group in **11a** by an ethylzinc moiety gave the catalyst **15**. Compared with free ligand **11a**, the catalyst **15** should not lead to any significant structural distortion because ground-state conformation in free ligand **11a** resembles that in the complex **15**. Thus, two phenyl groups pointing in the same direction with respect to the five-membered ring can inhibit cooperatively one face of the catalyst **15**. If the configuration of the second stereogenic center on the nitrogen atom is *S*, the methyl group on the additional chiral carbon atom and one phenyl



Scheme 2. Transition structures derived from β-amino alcohol (*R*,2*S*)-**11a**.

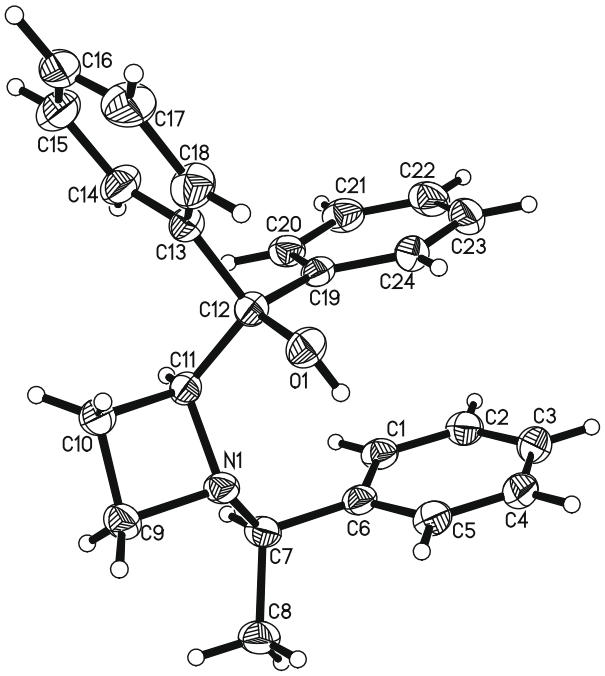
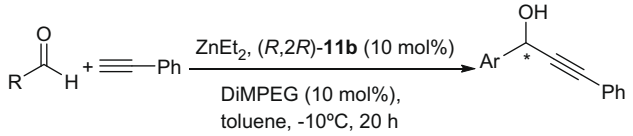


Figure 2. ORTEP drawing of the X-ray crystallographic structure of ligand (*R*,2*S*)-**11a**. Selected bond lengths (Å) and angles (°): N(1)–C(9) 1.499(6); N(1)–C(11) 1.500(6); C(9)–C(10) 1.532(8); C(10)–C(11) 1.546(7); C(9)–N(1)–C(11) 89.5(3); N(1)–C(9)–C(10) 88.8(4); C(9)–C(10)–C(11) 86.6(4); N(1)–C(11)–C(10) 88.3(3). N(1)–C(11)–C(12)–C(19) 91.2(5); N(1)–C(11)–C(12)–C(13) −147.5(4); N(1)–C(11)–C(12)–O(1) −31.5(5); C(10)–C(11)–C(12)–C(19) −167.1(4); C(9)–N(1)–C(7)–C(6) −174.5(4); C(12)–C(19)–C(24)–C(23) −176.0(5); C(4)–C(5)–C(6)–C(7) 178.2(5).

substituent in diphenylhydroxymethyl group will be located on the *cis* side of the coordination five-membered ring, as in **19**, blocking more effectively one face of the catalyst **19** and resulting in enantioselectivity higher than that of **11a**. This result indicated that the steric hindrance effect of the methyl group was more effective than that of the phenyl substituent. This point may be explained from the X-ray structures of **11a** (Fig. 2). The values of the torsion angles C(12)–C(19)–C(24)–C(23) and C(4)–C(5)–C(6)–C(7) were −176.0(5)° and 178.2(5)°, respectively, indicating that a π–π interaction exists between two phenyl groups pointing toward the same direction, which may inhibit free rotation of phenyl substituents. As a result, two relatively parallel phenyl groups provided much room for the approach of benzaldehyde and alkynylzinc from this face compared with methyl and phenyl substituents. Therefore, the catalyst **15** is less effective in stereodifferentiation than **19**, giving lower enantioselectivity.

To examine substrate generality under the above-mentioned reaction conditions, the most successful enantiomer (*R*,2*R*)-**11b** was tested for the asymmetric addition of phenylactylene to various aromatic aldehydes, and the results are presented in Table 2. As can be seen from Table 2, the chiral ligand (*R*,2*R*)-**11b** was effective in various substituted aromatic aldehydes, including *ortho*-, *para*-, and *meta*-substituted benzaldehydes (Table 2, entries 1–14). The presence of electron-donating or electron-withdrawing substituents on the aromatic ring is also compatible with these

Table 2
Asymmetric addition of alkynylzinc to aldehydes catalyzed by ligand (*R*,2*R*)-**11b**[a]



Entry	R	Yield[b] (%)	ee[c] (%)	Config.[d]
1	*o*-$MeOC_6H_4$	56	76	(*S*)
2	*m*-$MeOC_6H_4$	68	75	(*S*)
3	*p*-$MeOC_6H_4$	56	76	(*S*)
4	*m*-$PhOC_6H_4$	77	80	(*S*)
5	*o*-MeC_6H_4	80	87	(*S*)
6	*m*-MeC_6H_4	66	79	(*S*)
7	*p*-MeC_6H_4	75	78	(*S*)
8	*o*-ClC_6H_4	59	84	(*S*)
9	*m*-ClC_6H_4	70	69	(*S*)
10	*p*-ClC_6H_4	80	68	(*S*)
11	*o*-BrC_6H_4	76	80	(*S*)
12	*m*-BrC_6H_4	78	80	(*S*)
13	*p*-BrC_6H_4	77	72	(*S*)
14	3,4-$OCH_2OC_6H_3$	72	75	(*S*)
15	2-Naph	49	84	(*S*)
16	$PhCH_2CH_2$	51	18	(*S*)

[a] The mol ratio of phenylacetylene/Et_2Zn/aldehydes was 2:2:1.
[b] Isolated yields.
[c] Determined by HPLC using a chiralcel OD column. In all cases, the product chromatograms were compared against a known racemic mixture.
[d] Absolute configuration assigned by known elution order from a chiralcel OD column according to the literature.

reaction conditions. High enantioselectivity was also observed for the addition to 2-naphthaldehyde (Table 2, entry 15). The best asymmetric induction (as high as 87% ee) was found by using an aldehyde bearing a 2-MeC_6H_4 group as the substrate (Table 2, entry 5). The chiral ligand (*R*,2*R*)-**11b** is comparable to the existing β-amino alcohol ligands for alkynyl addition using a terminal alkyne and diethylzinc in the presence of catalytic amounts of chiral ligands[8] although the maximum asymmetric induction obtained was 87% ee.

The chiral ligand **11b** was also tested with aliphatic aldehyde 3-phenylpropionaldehyde, but very low enantioselectivity (only 18% ee) was obtained under the same reaction conditions as arylaldehydes (Table 2, entry 15). Therefore, further extension of the substrate scope for aliphatic aldehydes was not performed.

3. Conclusion

In conclusion, we described the preparation of a series of chiral azetidino amino alcohol ligands with an additional stereogenic center, and their catalytic capabilities in the asymmetric addition of alkynylzinc to aldehydes. The chiral ligand (*R*,2*R*)-**11b** was found to be highly effective in the enantioselective alkynylation of aldehydes. Studies on the structure-relationship showed that the absolute configuration of the addition products was only determined by the configuration of the azetidine ring, and the match of the configuration of the azetidine ring with the configuration of the additional chiral center was crucial to obtain high enantioselectivity. Efforts to extend the application of these ligands to other enantioselective metal-catalyzed reactions are also in progress.

4. Experimental

4.1. General

Unless otherwise noted, all reactions were carried out under argon or nitrogen using standard Schlenk and vacuum line techniques. Toluene was freshly distilled over calcium hydride prior to use. Other reagents were obtained from commercial sources and used as received without further purification. Melting points were determined using YRT-3 melting point apparatus and are uncorrected. Optical rotations were measured with Perkin Elmer, model 341 Polarimeter at 20 °C in $CHCl_3$. The enantiomeric purity was determined by HPLC using a chiral column with hexane/propan-2-ol (ratio as indicated) as the eluent. The chromatographic system consisted of a JASCO model PU-1580 intelligent HPLC pump and a JASCO model UV-1575 intelligent UV–vis detector (254 nm). The injection loop had a 20 μL capacity. The column used was a Chiralcel OD (250 × 4.6 mm) from Daicel Chemical Ind., Ltd (Japan). The column was operated at ambient temperature. NMR spectra (^1H and ^{13}C) were performed on a Bruker DPX 400 (400 MHz) spectrometer using solutions in $CDCl_3$ (referenced internally to Me_4Si); *J* values are given in hertz. TLC was performed on dry silica gel plates developed with hexane/ethyl acetate. Mass spectra were obtained using a Bruker esquire-3000 instrument with an electrospray ionization source (ESIMS). All the ESIMS spectra were performed using MeOH as the solvent. Methanol was dried with $Mg(OCH_3)_2$.

Complexes **8**–**10** were synthesized according to the literature procedure.[12,13]

4.2. Synthesis of the azetidine-carbinol

To the Grignard reagent solution prepared from 817 mg (5.2 mmol) bromobenzene in 3 mL THF and 124 mg (5.2 mmol) magnesium in 5 mL THF was gradually added 278 mg (1.27 mmol) compound **10** dissolved in 1 mL THF at −20 °C over a period of 30 min. The mixture was then allowed to reach room temperature. After stirring for 24 h, the reaction was quenched with saturated aqueous NH_4Cl (10 mL) at 0 °C. The product was separated and the aqueous phase extracted with Et_2O (3 × 10 mL). The combined organic phases were washed with brine (15 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The resulting residue was purified by the preparative TLC with hexane/EtOAc (8:1, v/v) as the developing solvent to give the ligand up to 80% yield.

4.2.1. Diphenyl-(l-((1*R*)-phenylethyl)azetidin-(2*S*)-yl)-methanol (*R*,2*S*)-11a

White solid, yield 79%, mp 95–97 °C. $[\alpha]_D^{20} = +63.6$ (*c* 1.00, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ 7.57–7.05 (m, 15H), 5.32 (br s, 1H), 4.65 (t, 1H, *J* = 7.7 Hz), 3.32–3.26 (m, 1H), 3.08–3.03 (m, 1H), 2.94–2.90 (m, 1H), 2.04–1.87 (m, 2H), 1.17 (d, 3H, *J* = 6.8 Hz). ^{13}C NMR (100 MHz, CD_3Cl): δ 147.5, 144.7, 142.9, 128.1, 128.0, 127.0, 126.7, 126.5, 126.4, 125.5, 75.5, 68.4, 57.8, 42.7, 19.1, 12.8. IR (KBr pellet): 3028, 2970, 2844, 1490, 1448, 1397, 1167, 998, 747, 702. MS: *m/z* (ESI) 344 (M^++1). HRMS-ESI *m/z* calcd for $C_{24}H_{25}NO+H^+$ 344.2014, found 344.2022.

4.2.2. Diphenyl-(l-((1*R*)-phenylethyl)azetidin-(2*R*)-yl)-methanol(*R*,2*R*)-11b

White solid, yield 80%, mp 98–100 °C. $[\alpha]_D^{20} = +22.4$ (*c* 1.00, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ 7.64–6.85 (m, 15H), 5.31 (br s, 1H), 4.28 (t, 1H, *J* = 7.8 Hz), 3.22–3.17 (m, 1H), 3.10–3.06 (m, 1H), 3.00–2.94 (m, 1H), 1.92–1.80 (m, 2H), 0.86 (d, 3H, *J* = 6.9 Hz). ^{13}C NMR (100 MHz, CD_3Cl): δ 148.0, 145.1, 140.5, 128.1, 128.0, 127.1, 126.5, 126.4, 125.9, 125.6, 75.7, 69.8, 61.1, 44.9, 19.7, 19.4. IR (KBr pellet): 3025, 2970, 2843, 1491, 1448, 1395, 1180, 973, 747, 702. MS: *m/z* (ESI) 344 (M^++1). HRMS-ESI *m/z* calcd for $C_{24}H_{25}NO+H^+$ 344.2014, found 344.2021.

4.3. General procedure for the asymmetric alkynylation of aryl aldehydes

Under a nitrogen atmosphere, diethylzinc (1.0 mL, 200 mol %, 1.0 mol/L in hexane) and phenylacetylene (110 μL, 200 mol %) were added to a dried Schlenk tube containing toluene (2 mL), the chiral ligand (*R*,2*R*)-**11b** (22 mg, 10 mol %), and DiMPEG (100 mg, 10 mol %, mw = 2000). The resulting mixture was stirred for 2 h at room temperature. After the mixture was cooled to −10 °C, aldehyde (0.5 mmol) was added under nitrogen atmosphere. The reaction mixture was stirred for 20 h at −10 °C. The reaction was quenched by the addition of saturated aqueous NH_4Cl (8 mL). The mixture was extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were washed with brine, dried over anhydrous Na_2SO_4, and evaporated under reduced pressure. Purification of the residue by the preparative silica gel TLC plate (hexane/EtOAc) afforded the pure propargylic alcohol. The ee was determined by HPLC analyses using a chiralcel OD column. In all cases, the product chromatograms were compared against a known racemic mixture.

4.4. X-ray crystallographic study[14]

A prismatic crystal of (*R*,2*S*)-**11a** (0.20 × 0.18 × 0.16 mm) was selected and mounted on a glass fiber. Crystallographic data was measured on a Rigaku RAXIS-IV imaging plate area detector. The data were collected at 291(2) K using graphite-monochromated Mo Kα (λ = 0.71073 Å), 2.13° < θ < 25.48°. The structures were solved by a direct method, and expanded by using Fourier techniques. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. All calculations

were performed using the teXsan crystallographic software package. Crystal data for (*R*,2*S*)-**11a**: triclinic P_1, $a = 6.0146(12)$ Å, $\alpha = 94.11(3)^\circ$, $b = 8.6987(17)$ Å, $\beta = 98.46(3)^\circ$, $c = 9.7283(19)$ Å, $\gamma = 102.49(3)^\circ$, $V = 488.70(17)$ Å^3; formula unit $C_{24}H_{25}NO$ with $Z = 1$, $D_{calcd} = 1.167$ g cm^{-3}, F (0 0 0) = 184, μ(Mo Kα) = 0.070 mm^{-1}. Full-matrix least-squares refinement on F^2 based on 1650 independent reflections ($R_{int} = 0.0000$) converged with 1650 parameters. Final R indices [$I > 2\sigma(I)$]: $R_1 = 0.0731$, $wR_2 = 0.2004$; R indices (all data): $R_1 = 0.0797$, $wR_2 = 0.2140$; GoF = 1.033.

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