JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

pubs.acs.org/JACS

Asymmetric Hydrogenation via Capture of Active Intermediates Generated from Aza-Pinacol Rearrangement

Chang-Bin Yu,[†] Wen-Xue Huang,[†] Lei Shi,[†] Mu-Wang Chen,[†] Bo Wu,[†] and Yong-Gui Zhou*[,†,‡]

[†]State Key Laboratory of Catalysis, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China

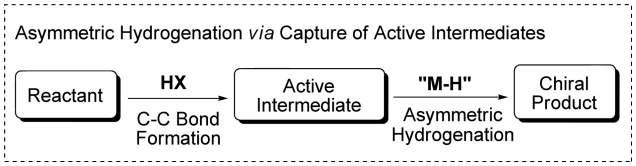
[‡]State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, Shanghai 200032, China

Supporting Information

ABSTRACT: An efficient palladium-catalyzed asymmetric hydrogenation via capture of an active intermediate generated in situ from acid-catalyzed aza-Pinacol rearrangement has been successfully developed, providing efficient access to chiral exocyclic amines with up to 98% ee. Three-, four-, and five-membered cyclic *N*-sulfonyl amino alcohols are viable substrates. This study opens a new window to the application of asymmetric hydrogenation.

Asymmetric hydrogenation is undoubtedly one of the most important synthetic methods in organic chemistry, as it provides general access to versatile building blocks for chemical synthesis, medicines, and functionalized materials.[1] Generally, the substrate scope includes stable and isolable olefins, ketones, imines, and aromatics. Extension of the substrate scope is still highly desirable in asymmetric hydrogenation.[2] A novel type is asymmetric hydrogenation via capture of inseparable and instable active intermediates (Scheme 1), especially for active

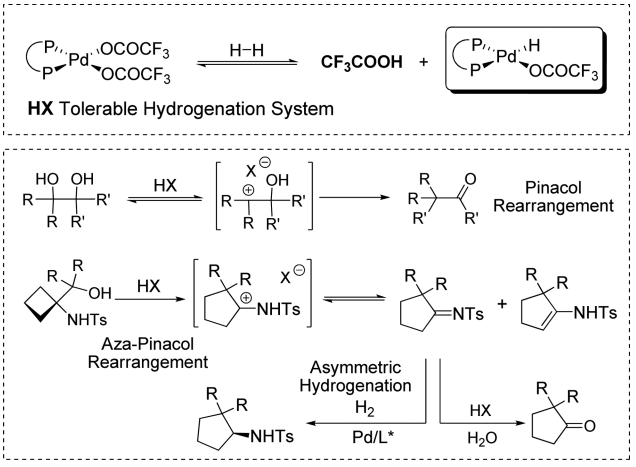
Scheme 1. Combination of Hydrogenation and C−C Bond Formations



intermediates involving C−C bond formation. One obvious advantage is the systematic utilization of inseparable, unstable, and reversible active intermediates due to the irreversibility of hydrogenation; the other is rapid construction of chiral compounds that are difficult to synthesize in traditional ways. However, few reports on asymmetric hydrogenation of active intermediates involving C−C bond formation have appeared.[3]

As powerful strategies for forming α-quaternary carbonyl structures, the pinacol[4] and semipinacol[5] rearrangements play an important role in organic chemistry. However, their analogue, the aza-pinacol rearrangement, is relatively limited, mainly because of the instability of the rearrangement product imine, iminium, or enamine (the pinacol rearrangement product ketone is relatively stable) and the weak driving force, which leads to poor regio- and diastereoselectivity and unpredictable side reactions.[6] Over the past decade, chiral Pd complexes have been successfully applied by us and other groups in asymmetric hydrogenation of aromatic compounds,[7] ketones,[8] ketimines,[9] and enesulfonamides[10] and asymmetric hydrogenolysis of *N*-sulfonyl amino alcohols[11] with Brønsted acids as additives. In a mechanistic study of Pd-catalyzed asymmetric hydrogenation,[7f] we found that 1 equiv of trifluoroacetic acid is generated in the formation of active palladium hydride species (Scheme 2) and

Scheme 2. Asymmetric Hydrogenation via Capture of Active Intermediates Generated in Situ from Brønsted Acid-Catalyzed Aza-Pinacol Rearrangement



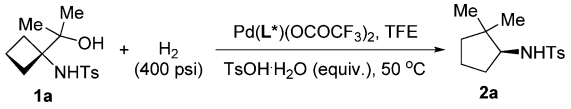
that the Pd catalytic system is relatively tolerant to acid, oxygen, and water. On the basis of these findings, we envisioned that the combination of a Pd catalyst and a Brønsted acid could be suitable for asymmetric hydrogenation via the capture of the carbonium ion active intermediate generated in situ from the Brønsted acid-catalyzed aza-pinacol rearrangement of cyclic *N*-sulfonyl amino alcohols (Scheme 2). Notably, convergent asymmetric hydrogenation of several active intermediates gives a single product in the presence of acid; the side reactions can be inhibited. Herein we report an enantioselective Pd-catalyzed hydrogenation of cyclic *N*-sulfonyl amino alcohols. The present strategy opens a new window to the application of asymmetric hydrogenation.

Received: July 31, 2014

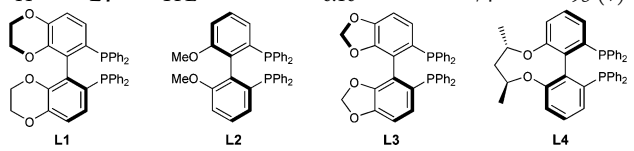
   dx.doi.org/10.1021/ja5075745 | J. Am. Chem. Soc. XXXX, XXX, XXX−XXX

First, four-membered *N*-sulfonyl amino alcohol **1a**[12] was used as a model substrate to assay the best reaction conditions. Pd[(*S*)-SynPhos](OCOCF$_3$)$_2$ and *p*-toluenesulfonic acid (TsOH·H$_2$O) (200 mol %) were selected as the hydrogenation catalyst and acid to begin the investigation, and the reaction was run in trifluoroethanol (TFE) at 50 °C. **1a** was fully consumed, but in addition to the decomposition product *p*-toluenesulfonamide generated by TsOH, no desired product was obtained (Table 1, entry 1). Since *p*-toulenesulfonamide could be a leaving group under acidic conditions, we thought that a catalytic amount of Brønsted acid might inhibit the side reaction. To our delight, when 20 mol % acid was added, the desired product **2a** was obtained in 51% isolated yield with 91% ee (entry 2). Next, the effect of the amount of acid on the enantioselectivity and reactivity was investigated (entries 3 and 4). When the amount of Brønsted acid was reduced to 10 mol %, the highest yield was obtained (entry 3). The study of the solvent effect suggested that only TFE gave the desired product (entries 3 and 5–7). When benzoic acid was introduced as the additive, the first step of the reaction could not occur (entry 8). Evaluation of various commercially available axially chiral diphosphine ligands (entries 9–11) showed that (*S*)-SegPhos (**L3**) was the most favorable in view of enantioselectivity and reactivity (entry 10).

Table 1. Optimization of the Reaction Parameters[a]



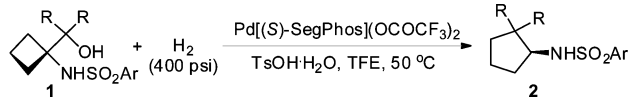
entry	ligand	solvent	equiv of TsOH·H$_2$O	yield (%)[b]	ee (%)[c]
1	**L1**	TFE	2.00	–	–
2	**L1**	TFE	0.20	51	91 (–)
3	**L1**	TFE	0.10	80	92 (–)
4	**L1**	TFE	0.05	33	92 (–)
5	**L1**	DCM	0.10	NR[d]	–
6	**L1**	toluene	0.10	NR[d]	–
7	**L1**	THF	0.10	NR[d]	–
8[e]	**L1**	TFE	0.10	NR[d]	–
9	**L2**	TFE	0.10	80	94 (–)
10	**L3**	TFE	0.10	81	94 (–)
11[f]	**L4**	TFE	0.10	74	93 (+)



[a]Reaction conditions: **1a** (0.125 mmol), Pd(**L***)(OCOCF$_3$)$_2$ (2.0 mol %), TsOH·H$_2$O (0.1 equiv), H$_2$ (400 psi), solvent (3 mL), 50 °C, 14–24 h. [b]Isolated yields. [c]Determined by chiral HPLC. [d]NR = no reactivity. [e]Benzoic acid was used instead of TsOH. [f]The opposite enantiomer was obtained.

With a set of optimized conditions in hand, the substrate scope was studied (Table 2). Generally, alkyl-substituted substrates performed very well, and the alkyl chain length had little influence on the enantioselectivity (entries 1–4). The aryl-substituted substrates were all good partners for the reaction, and the corresponding products were obtained with 94–96% ee (entries 5–8). Moreover, electron-donating and electron-withdrawing groups in the arylsulfonyl moiety exhibited little influence on the enantioselectivity (entries 9–11). Interestingly, substrates **1m** and **1l** bearing a five- or six-membered cyclic alcohol motif performed smoothly, giving the corresponding amines bearing spirocyclic skeletons with excellent enantioselectivity (entries 12 and 13).

Table 2. Palladium-Catalyzed Asymmetric Hydrogenation of Cyclic *N*-Sulfonyl Amino Alcohols 1[a]

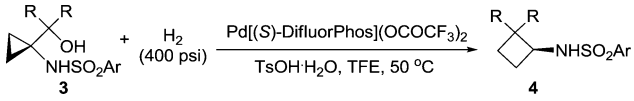


entry	R	Ar	yield (%)[b]	ee (%)[c]
1	Me	4-MeC$_6$H$_4$	81 (**2a**)	94 (*R*)[d]
2	Et	4-MeC$_6$H$_4$	86 (**2b**)	96 (+)
3	*n*-Pr	4-MeC$_6$H$_4$	89 (**2c**)	96 (–)
4	*n*-hexyl	4-MeC$_6$H$_4$	81 (**2d**)	97 (–)
5[e]	Ph	4-MeC$_6$H$_4$	95 (**2e**)	96 (+)
6	4-MeC$_6$H$_4$	4-MeC$_6$H$_4$	97 (**2f**)	96 (+)
7	3-MeC$_6$H$_4$	4-MeC$_6$H$_4$	85 (**2g**)	94 (+)
8	4-MeOC$_6$H$_4$	4-MeC$_6$H$_4$	72 (**2h**)	94 (+)
9[e]	Ph	4-FC$_6$H$_4$	87 (**2i**)	93 (+)
10[e]	Ph	4-MeOC$_6$H$_4$	79 (**2j**)	96 (+)
11	Ph	Ph	79 (**2k**)	94 (+)
12	(CH$_2$)$_4$	4-MeC$_6$H$_4$	69 (**2l**)	96 (–)
13	(CH$_2$)$_5$	4-MeC$_6$H$_4$	51 (**2m**)	93 (–)

[a]Reaction conditions: **1** (0.125 mmol), Pd[(*S*)-SegPhos](OCOCF$_3$)$_2$ (2.0 mol %), TsOH·H$_2$O (0.1 equiv), H$_2$ (400 psi), TFE (3 mL), 50 °C, 24 h. [b]Isolated yields. [c]Determined by chiral HPLC. [d]The absolute configuration was determined by X-ray analysis. [e]A 3/1 TFE/CH$_2$Cl$_2$ mixed solvent (4 mL) was added.

In addition, we also studied three-membered cyclic *N*-sulfonyl amino alcohols **3** (Table 3). It was found that excellent enantioselectivities were obtained regardless of the length of the alkyl substituent (entries 1–4), and the *n*-hexyl group proved to be optimal with respect to the yield. Tolerance with respect to variation of the aryl group was also investigated. All aryl-substituted substrates gave high ee values and yields (entries 5 and 6). The electronic properties of the sulfonyl group exhibited little influence on the enantioselectivity (entries 7–9). It is noteworthy that the direct synthesis of these sterically hindered *N*-tosyl imine or *N*-tosyl enamine intermediates is very difficult

Table 3. Palladium-Catalyzed Asymmetric Hydrogenation of Cyclic *N*-Sulfonyl Amino Alcohols 3[a]



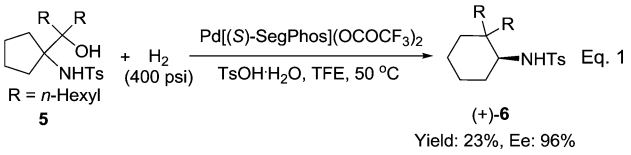
entry	R	Ar	yield (%)[b]	ee (%)[c]
1[d]	Et	4-MeC$_6$H$_4$	52 (**4a**)	98 (–)
2[d]	*n*-Pr	4-MeC$_6$H$_4$	68 (**4b**)	98 (–)
3	*n*-Bu	4-MeC$_6$H$_4$	63 (**4c**)	98 (–)
4	*n*-hexyl	4-MeC$_6$H$_4$	76 (**4d**)	98 (–)
5	Ph	4-MeC$_6$H$_4$	90 (**4e**)	89 (+)
6	4-MeC$_6$H$_4$	4-MeC$_6$H$_4$	91 (**4f**)	89 (+)
7	*n*-hexyl	Ph	71 (**4g**)	98 (–)
8	*n*-hexyl	4-MeOC$_6$H$_4$	66 (**4h**)	98 (–)
9	*n*-hexyl	4-FC$_6$H$_4$	69 (**4i**)	97 (–)

[a]Reaction conditions: **3** (0.125 mmol), Pd[(*S*)-DifluorPhos]-(OCOCF$_3$)$_2$ (2.0 mol %), TsOH·H$_2$O (0.1 equiv), H$_2$ (400 psi), TFE (3 mL), 50 °C, 24 h. [b]Isolated yields. [c]Determined by chiral HPLC. [d]40 °C.

dx.doi.org/10.1021/ja5075745 | J. Am. Chem. Soc. XXXX, XXX, XXX–XXX

using cyclic sterically hindered α,α-dialkyl ketones as starting materials. For *N*-tosyl imines from cyclobutanones, no report has appeared in the literature. This transformation provided a clever detour to the synthesis of enantioenriched α,α-dialkyl cyclic amine derivatives.[13]

This methodology was also suitable for five-membered cyclic *N*-toluenesulfonyl amino alcohol **5** (eq 1), providing the desired



product **6** with excellent enantioselectivity in a low 23% yield using Pd[(*S*)-SegPhos](OCOCF$_3$)$_2$ as the catalyst. The low yield might be due to the relatively weak driving force from ring strain release.[14]

The absolute configuration of the product **2a**[15] was determined to be *S* on the basis of single-crystal X-ray analysis after recrystallization from dichloromethane and hexanes (Figure 1). The absolute configurations of the other products were assigned by analogy.

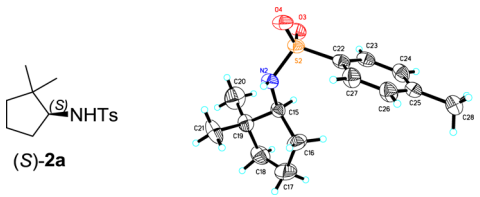
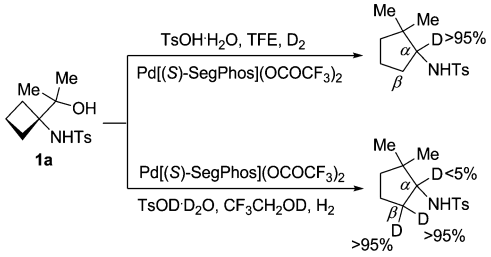


Figure 1. X-ray crystallographic analysis of product **2a**.

To investigate the detailed reaction pathway, two isotopic labeling experiments were carried out. When **1a** was subjected to the reaction conditions with D_2, the deuterium atoms were fully incorporated at the α-position (Scheme 3). When the reaction

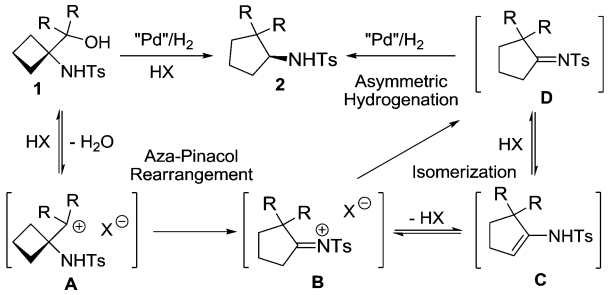
Scheme 3. Isotopic Labeling Experiments Using D_2 and TFE-d_1



was carried out in TFE-d_1 with H_2, ^{1}H NMR analysis of the product showed that two deuterium atoms were taken up at the β-position with >95% incorporation, suggesting that a reversible process of Brønsted acid-catalyzed enesulfonamide/*N*-sulfonylimine isomerization via protonation and deprotonation exists and that the equilibrium is faster than the following asymmetric hydrogenation.

On the basis of the above experimental results and the putative pinacol rearrangement mechanism,[4,5] a plausible reaction pathway is proposed (Scheme 4). First, Brønsted acid-catalyzed dehydration and aza-pinacol rearrangement of the cyclic *N*-sulfonyl amino alcohol forms iminium ion intermediate **B**, and

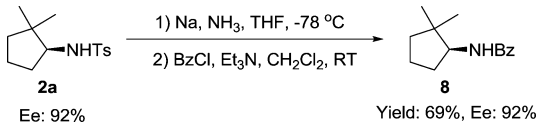
Scheme 4. Plausible Reaction Pathway



subsequent deprotonation affords enesulfonamide **C** and *N*-sulfonylimine **D**. Meanwhile, a fast and reversible process of enesulfonamide/*N*-sulfonylimine isomerization by Brønsted acid-catalyzed protonation and deprotonation exists. The final step is the Pd-catalyzed asymmetric hydrogenation of *N*-sulfonylimine **D** to give the chiral amine.

It should be noted that the *p*-toluenesulfonyl group could be easily removed without racemization by treatment with sodium/ammonia (Scheme 5).

Scheme 5. Removal of the *p*-Toluenesulfonyl Group in 2a



Generally, because of poor selectivity, unpredictable side reactions, and instability of the products, the aza-pinacol rearrangement is rarely applied in organic synthesis. By the combination of asymmetric hydrogenation and the aza-pinacol rearrangement, convergent asymmetric hydrogenation of several active intermediates leads to a single product, and the side reactions can also be inhibited. This strategy extends the scope of application of the aza-pinacol rearrangement and asymmetric hydrogenation in organic synthesis.

In summary, we have successfully developed the first highly enantioselective Pd-catalyzed hydrogenation via capture of active intermediates generated in situ from Brønsted acid-catalyzed aza-pinacol rearrangement of *N*-sulfonyl amino alcohols, providing efficient access to chiral exocyclic amine derivatives with up to 98% ee. This study opens a completely new window to the application of asymmetric hydrogenation and provides some useful hints for the design of new reactions. Future work will focus on mechanistic studies and applications in the synthesis of optically active drugs and natural products.

■ ASSOCIATED CONTENT

Supporting Information

Procedures and characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

ygzhou@dicp.ac.cn

Notes

The authors declare no competing financial interest.

dx.doi.org/10.1021/ja5075745 | *J. Am. Chem. Soc.* XXXX, XXX, XXX−XXX

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (21032003 and 21125208) and the National Basic Research Program of China (2010CB833300).

■ REFERENCES

(1) (a) *Handbook of Homogeneous Hydrogenation*; De Vries, J. G., Elsevier, C. J., Eds.; Wiley-VCH: Weinheim, Germany, 2007. (b) Thayer, A. M. *Chem. Eng. News* **2005**, *83* (36), 40. (c) Tang, W.; Zhang, X. *Chem. Rev.* **2003**, *103*, 3029. (d) Wang, D.-S.; Chen, Q.-A.; Lu, S.-M.; Zhou, Y.-G. *Chem. Rev.* **2012**, *112*, 2557.

(2) (a) Keinan, E.; Greenspoon, N. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: New York, 1991; Vol. *III*, p 523. (b) Molander, G. A.; Hoberg, J. O. *J. Am. Chem. Soc.* **1992**, *114*, 3123. (c) Kokubo, K.; Miura, M.; Nomura, M. *Organometallics* **1995**, *14*, 4521. (d) Jang, H.-Y.; Huddleston, R. R.; Krische, M. J. *J. Am. Chem. Soc.* **2002**, *124*, 15156. (e) Jang, H.-Y.; Krische, M. J. *Acc. Chem. Res.* **2004**, *37*, 653. (f) Skucas, E.; Nagi, M.-Y.; Komanduri, V.; Krische, M. J. *Acc. Chem. Res.* **2007**, *40*, 1394. (g) Bower, J.; Skucas, E.; Patman, R. L.; Krische, M. J. *J. Am. Chem. Soc.* **2007**, *129*, 15134. (h) Ngai, M.-Y.; Barchuk, A.; Krische, M. J. *J. Am. Chem. Soc.* **2007**, *129*, 280. (i) Shibahara, F.; Bower, J. F.; Krische, M. J. *J. Am. Chem. Soc.* **2008**, *130*, 6338. (j) Hassan, A.; Krische, M. J. *Org. Process Res. Dev.* **2011**, *15*, 1236. (k) Park, B. Y.; Montgomery, T. P.; Garza, V.; Krische, M. J. *J. Am. Chem. Soc.* **2013**, *135*, 16320. (l) Geary, L. M.; Chen, T.-Y.; Montgomery, T. P.; Krische, M. J. *J. Am. Chem. Soc.* **2014**, *136*, 5920. (m) McInturff, E. L.; Nguyen, K. D.; Krische, M. J. *Angew. Chem., Int. Ed.* **2014**, *53*, 3232.

(3) Enantioselective access to chiral 2,3-disubstituted indoline derivatives through consecutive Brønsted acid/Pd-complex-promoted reductive alkylation/hydrogenation was reported by us. The intermediate via Brønsted acid-catalyzed C−C bond-forming Friedel−Crafts reaction between indole and aldehyde is stable and separable. See: Duan, Y.; Chen, M.-W.; Ye, Z.-S.; Wang, D.-S.; Chen, Q.-A.; Zhou, Y.-G. *Chem.—Eur. J.* **2011**, *17*, 7193.

(4) (a) Fittig, R. *Liebigs Ann. Chem.* **1860**, *114*, 54. (b) Rickborn, B. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, U.K., 1991; p 721. (c) Kürti, L.; Czakó, B. In *Strategic Applications of Named Reactions in Organic Synthesis*; Elsevier Academic Press: Burlington, MA, 2005; p 350. (d) Goess, B. In *Name Reactions for Homologations*; Li, J. J., Ed.; Wiley: Hoboken, NJ, 2009; p 319. (e) Snape, T. J. *Chem. Soc. Rev.* **2007**, *36*, 1823. (f) Snyder, S. A.; Thomas, S. B.; Mayer, A. C.; Breazzano, S. P. *Angew. Chem., Int. Ed.* **2012**, *51*, 4080.

(5) (a) Song, Z.-L.; Fan, C.-A.; Tu, Y.-Q. *Chem. Rev.* **2011**, *111*, 7523. (b) Seiser, T.; Saget, T.; Tran, D. N.; Cramer, N. *Angew. Chem., Int. Ed.* **2011**, *50*, 7740. (c) Schweinitz, A.; Chtchemelinine, A.; Orellana, A. *Org. Lett.* **2011**, *13*, 232. (d) Wang, B.-M.; Tu, Y.-Q. *Acc. Chem. Res.* **2011**, *44*, 1207. (e) Grainger, R. S.; Betou, M.; Male, L.; Pitak, M. B.; Coles, S. J. *Org. Lett.* **2012**, *14*, 2234. (f) Plummer, C. W.; Soheili, A.; Leighton, J. L. *Org. Lett.* **2012**, *14*, 2462. (g) Chen, Z.-M.; Bai, W.; Wang, S.-H.; Yang, B.-M.; Tu, Y.-Q.; Zhang, F.-M. *Angew. Chem., Int. Ed.* **2013**, *52*, 9781. (h) Romanov-Michailidis, F.; Guénée, L.; Alexakis, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 9266. (i) Yin, Q.; You, S.-L. *Org. Lett.* **2014**, *16*, 1810. (j) Guo, B.-J.; Fu, C.-L.; Ma, S.-M. *Chem. Commun.* **2014**, *50*, 4445.

(6) (a) Stevens, C. L.; Elliott, R. D.; Winch, B. L. *J. Am. Chem. Soc.* **1963**, *85*, 1464. (b) Razavi, H.; Polt, R. *J. Org. Chem.* **2000**, *65*, 5693. (c) Sugihara, Y.; Iimura, S.; Nakayama, J. *Chem. Commun.* **2002**, 134. (d) Rono, L. J.; Yayla, H. G.; Wang, D. Y.; Armstrong, M. F.; Knowles, R. R. *J. Am. Chem. Soc.* **2013**, *135*, 17735.

(7) (a) Wang, D.-S.; Chen, Q.-A.; Li, W.; Yu, C.-B.; Zhou, Y.-G.; Zhang, X. *J. Am. Chem. Soc.* **2010**, *132*, 8909. (b) Wang, D.-S.; Tang, J.; Zhou, Y.-G.; Chen, M.-W.; Yu, C.-B.; Duan, Y.; Jiang, G.-F. *Chem. Sci.* **2011**, *2*, 803. (c) Wang, D.-S.; Ye, Z.-S.; Chen, Q.-A.; Zhou, Y.-G.; Yu, C.-B.; Fan, H.-J.; Duan, Y. *J. Am. Chem. Soc.* **2011**, *133*, 8866. (d) Duan, Y.; Chen, M.-W.; Chen, Q.-A.; Yu, C.-B.; Zhou, Y.-G. *Org. Biomol. Chem.* **2012**, *10*, 1235. (e) Chen, Q.-A.; Ye, Z.-S.; Duan, Y.; Zhou, Y.-G. *Chem. Soc. Rev.* **2013**, *42*, 497. (f) Duan, Y.; Li, L.; Chen, M.-W.; Yu, C.-B.; Fan, H.-J.; Zhou, Y.-G. *J. Am. Chem. Soc.* **2014**, *136*, 7688.

(8) (a) Wang, Y.-Q.; Lu, S.-M.; Zhou, Y.-G. *Org. Lett.* **2005**, *7*, 3235. (b) Zhou, X.-Y.; Wang, D.-S.; Bao, M.; Zhou, Y.-G. *Tetrahedron Lett.* **2011**, *52*, 2826. (c) Chen, J.-Z.; Liu, D.-L.; Butt, N.; Li, C.; Fan, D.-Y.; Liu, Y.-G.; Zhang, W.-B. *Angew. Chem., Int. Ed.* **2013**, *52*, 11632.

(9) (a) Abe, H.; Amii, H.; Uneyama, K. *Org. Lett.* **2001**, *3*, 313. (b) Yang, Q.; Shang, G.; Gao, W.-Z.; Deng, J.-G.; Zhang, X. *Angew. Chem., Int. Ed.* **2006**, *45*, 3832. (c) Wang, Y.-Q.; Lu, S.-M.; Zhou, Y.-G. *J. Org. Chem.* **2007**, *72*, 3729. (d) Chen, M.-W.; Duan, Y.; Chen, Q.-A.; Wang, D.-S.; Yu, C.-B.; Zhou, Y.-G. *Org. Lett.* **2010**, *12*, 5075. (e) Zhou, X.-Y.; Bao, M.; Zhou, Y.-G. *Adv. Synth. Catal.* **2011**, *353*, 84. (f) Goulioukina, N. S.; Shergold, I. A.; Bondarenko, G. N.; Ilyin, M. M.; Davankov, V. A.; Beletskaya, I. P. *Adv. Synth. Catal.* **2012**, *354*, 2727. (g) McLaughlin, M.; Belyk, K.; Chen, C.-Y.; Linghu, X.; Pan, J.; Qian, G.; Reamer, R. A.; Xu, Y.-J. *Org. Process. Res. Dev.* **2013**, *17*, 1052.

(10) (a) Yu, C.-B.; Gao, K.; Wang, D.-S.; Shi, L.; Zhou, Y.-G. *Chem. Commun.* **2011**, *47*, 5052. (b) Yu, C.-B.; Gao, K.; Chen, Q.-A.; Chen, M.-W.; Zhou, Y.-G. *Tetrahedron Lett.* **2012**, *53*, 2560.

(11) Yu, C.-B.; Zhou, Y.-G. *Angew. Chem., Int. Ed.* **2013**, *52*, 13365.

(12) (a) Rengasamy, R.; Curtis-Long, M. J.; Seo, W. D.; Jeong, S. H.; Jeong, I. Y.; Park, K. H. *J. Org. Chem.* **2008**, *73*, 2898. (b) Watanuki, S.; Matsuura, K.; Tomura, Y.; Okada, M.; Okazaki, T.; Ohta, M.; Tsukamoto, S. I. *Chem. Pharm. Bull.* **2011**, *59*, 1376. (c) Ordónez, M.; Cruz-Cordero, R. D.; Fernández-Zertuche, M.; Munoz-Hernández, M. A.; García-Barradas, O. *Tetrahedron: Asymmetry* **2004**, *15*, 3035.

(13) (a) Trost, B. M.; Silverman, S. M. *J. Am. Chem. Soc.* **2012**, *134*, 4941. (b) Jennings, W. B.; Lovely, C. J. *Tetrahedron* **1991**, *47*, 5561.

(14) When linear *N*-(2-hydroxy-2-methyl-1-phenylpropyl)-4-methylbenzenesulfonamide was used as the substrate under the standard conditions, a complex mixture was obtained, which might be due to a weak driving force because there is no ring strain release as well as the good leaving ability of the *p*-toluenesulfonyl group. When the secondary alcohol *N*-(1-(hydroxy(phenyl)methyl)cyclobutyl)-4-methylbenzenesulfonamide was used for synthesis of chiral amines with two contiguous stereogenic centers, no reaction occurred, which suggested that the secondary carbocation cannot be generated under the standard conditions.

(15) CCDC 975090 contains the supplementary crystallographic data for product **2a**. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.