Organic LETTERS

Letter

pubs.acs.org/OrgLett

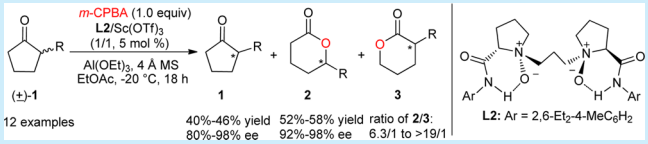
Regio- and Enantioselective Baeyer–Villiger Oxidation: Kinetic Resolution of Racemic 2-Substituted Cyclopentanones

Lin Zhou, Xiaohua Liu, Jie Ji, Yuheng Zhang, Wangbin Wu, Yangbin Liu, Lili Lin, and Xiaoming Feng*

Key Laboratory of Green Chemistry & Technology, Ministry of Education, College of Chemistry, Sichuan University, Chengdu 610064, P. R. China

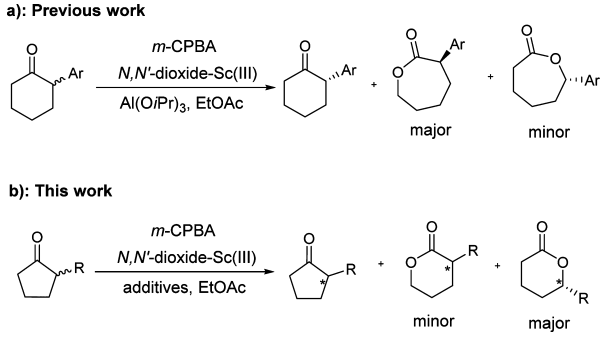
Supporting Information

ABSTRACT: A kinetic resolution of racemic 2-substituted cyclopentanones via highly regio- and enantioselective Baeyer–Villiger oxidation has been successfully developed. The reaction could afford the normal 6-substituted δ-lactones in up to 98% ee and >19/1 regioselectivity. Meanwhile, the unreacted ketones were recovered in excellent ee values (up to 98%). It represents the best results of the kinetic resolution of racemic 2-substituted cyclopentanones via nonenzymic asymmetric BV oxidation.



The Baeyer–Villiger (BV) oxidation[1] plays an important role in organic synthesis since it provides a straightforward access to esters or lactones from ketones. Especially, the asymmetric BV oxidation of substituted cyclic ketones is highly valuable for the synthesis of optically active lactones.[2−7] Impressive results have been achieved for the asymmetric BV oxidations of prochiral cyclic ketones with biocatalysts,[3] chiral metal complexes,[4] or organocatalysts.[5] Notably, the asymmetric BV oxidation of racemic 2-substituted cyclic ketones results in a kinetic resolution leading to optically active lactones and 2-substituted cyclic ketones. The related nonenzymatic catalytic system remains still elusive.[6] In 1994, Bolm[8a] and Strukul[8b] reported the discovery of chiral bisoxazoline-Cu(II) and diphosphine-Pt(II) catalyzed asymmetric BV oxidation of 2-substituted cyclic ketones, respectively. Hitherto, the progress of this process is the chiral *N,N′*-dioxide–Sc(III) catalyzed BV oxidation of 2-arylcyclohexanones by our group, and it is interesting to note that abnormal regioselectivity occurred in this case (Scheme 1a).[9] Unfortunately, the kinetic resolution of 2-substituted cyclopentanones via asymmetric BV oxidation has not been accomplished in these contexts, and the enantiomeric excess of the resulted δ-lactones was no less than 58% ee.[8b] Herein, we would like to report an enantioselective BV oxidation and kinetic resolution of 2-substituted cyclopentanones. The regio- and enantioselectivity of the reaction are well addressed. In the presence of a chiral *N,N′*-dioxide–Sc(III) complex catalyst[10] and additives, optically active δ-lactones generated preferentially from a normal CHR-group migration, and the unreactive 2-substituted cyclopentanones were recovered in high enantioselectivities (Scheme 1b).

Scheme 1. Regio- and Enantioselective BV Oxidation of Racemic 2-Substituted Cyclohexanones and 2-Substituted Cyclopentanones

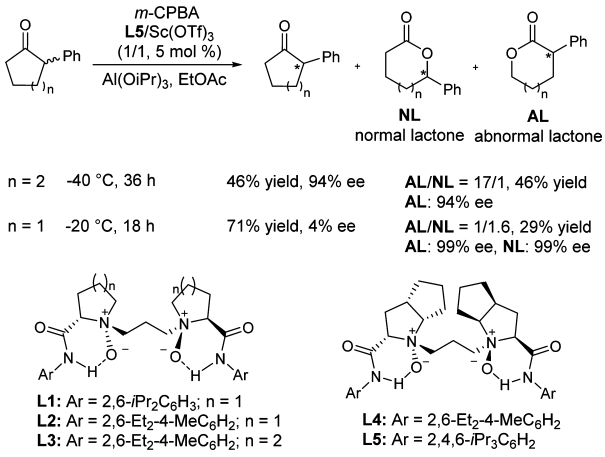


At the beginning, the catalytic system that is efficient for the asymmetric BV oxidation of 2-arylcyclohexanones was subjected to the reaction of 2-phenylcyclopentanone **1a**. Although high enantioselectivities were achieved for both the normal δ-lactone **2a** and the abnormal δ-lactone **3a**, the regioselectivity (rs) and yield were poor (29% yield, 1/1.6 rs; Scheme 2). We then restarted to optimize the reaction conditions using 2-phenylcyclopentanone **1a** and *m*-chlorobenzoperoxoic acid (*m*-CPBA) as the model substrate and oxidant,[11] respectively. Performing the reaction in EtOAc at 0 °C without a catalyst afforded the racemic lactone **2a** in 25% yield as a single isomer (Table 1, entry 1), whereas only a trace amount of the products was observed in the presence of the chiral *N,N′*-dioxide **L1**–$Sc(OTf)_3$ complex catalyst (Table 1, entry 2). To improve the reactivity, the efficiency of additives was then examined. Delightedly, when the reaction was carried out with 1.0 equiv of $Al(O^iPr)_3$ as the additive, the **L1**–$Sc(OTf)_3$ complex could give the δ-lactones in 17% yield. The ratio of the normal δ-lactone **2a** to the abnormal δ-lactone **3a** reached 5/1, and the ee value of the major δ-lactone **2a** was excellent (99% ee, Table 1, entry 3). The addition of 4 Å molecular sieves (MS) could further enhance the yield to 26% with the regio- and enantioselectivity maintained (Table 1, entry 4). Compara-

Received: June 16, 2014
Published: July 16, 2014

dx.doi.org/10.1021/ol501737a | *Org. Lett.* 2014, 16, 3938–3941

Scheme 2. Chiral *N,N′*-Dioxide−Sc(III) Complex Catalyzed Kinetic Resolution of Racemic 2-Phenyl Cyclic Ketones via Asymmetric BV Oxidation and *N,N′*-Dioxide Ligands Used in This Study

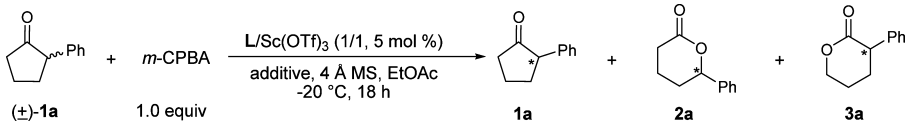


tively, a low yield was obtained in the presence of 4 Å MS without $Al(O^iPr)_3$ (Table 1, entry 5).

Further optimization of the reaction conditions was then aimed at exploring the efficiency of other aluminum alkoxides as the additives (Table 1, entries 6−7). Fortunately, improved reactivity, as well as regio- and enantioselectivity, was observed when $Al(OEt)_3$ was employed as an additive (Table 1, entry 7). The 2-phenylcyclopentanone **1a** was recovered in 60% conversion with 40% ee, and δ-lactone **2a** was given in 99% ee. It is not possible to clearly rationalize the role of $Al(OEt)_3$ in the catalytic process at present. The primary IR spectrum of the mixture of $Al(OEt)_3$ and *m*-CPBA gives new peaks (see Supporting Information). We proposed that $Al(OEt)_3$ prior reacts with *m*-CPBA to generate an activate species which has enhanced the oxidative ability so that the reactivity was obviously improved. Next, the efficiency of other *N,N′*-dioxide ligands was explored (Scheme 2). When the ligand **L2** containing 2,6-diethyl-4-methylaniline was introduced, 56% conversion of the products with a 9.6/1 ratio of **2a** to **3a** was achieved. The major δ-lactone **2a** was yielded in 98% ee, and the unreacted ketone **1a** was recovered in 44% yield with 90% ee (Table 1, entry 8).[12] As for the chiral backbone moiety, the *N,N′*-dioxide **L2** derived from L-proline acid exhibited superiority in enantiocontrol toward this reaction compared with the ones derived from (*S*)-pipecolic acid (**L3**) and (*S*)-ramipril acid (**L4**) (Table 1, entry 8 vs entries 9 and 10). The relationship between the enantioselectivity of the recovered ketone and the regioselectivity of the δ-lactones indicated that the two products primarily resulted from each enantiomer of the racemic ketone (entries 9 and 10). Therefore, the optimized conditions were identified as 5 mol % of the chiral *N,N′*-dioxide **L2**−$Sc(OTf)_3$ catalyst, $Al(OEt)_3$, and 4 Å MS as the additives in EtOAc at −20 °C.

Under the optimal conditions (Table 1, entry 8), the asymmetric BV oxidation and kinetic resolution of a series of 2-substituted cyclopentanones **1** was examined. As shown in Table 2, the stereocontrol of the reaction was not sensitive to the electronic property of substituents on the phenyl ring of 2-arylcyclopentanones **1**. Generally, the normal δ-lactones **2** as the major products were obtained with a good to excellent ratio of **2** to **3** (6.3/1−>19/1 rs). Good to excellent enantiomeric excesses were achieved for the major products **2** (92−98% ee) and unreacted ketones **1** (80−98% ee; entries 1−11). The regioselectivity and reactivity were sensitive to the substituted position on 2-aryl group of the substrates rather than the electronic property. The substrates with 3-substituents on the phenyl ring afforded the lactones with decreased regioselectivity and were recovered partly in lower ee values compared with those containing 4-substituted ones (entries 2, 4, and 8 vs 3, 5, and 9). Especially, the racemic 2-([1,1′-biphenyl]-4-yl)cyclopentanone **1f** underwent the oxidation reaction well, affording the major δ-lactone **2f** in 98% ee with up to 13/1 ratio of **2f** to **3f**. And the unreacted ketone **1f** was isolated in 95% ee and 44% yield (entry 6). Moreover, 2-naphthyl substituted cyclopentanone **1k** was also tolerable, and the major product **2k** and unreacted ketone **1k** were obtained in 94% ee and 92% ee, respectively (entry 11). Besides, the absolute configuration of **2h** was determined to be *S* by X-ray analysis,[13] and the recovered ketone **1d** was assigned as *R* by comparison of the

Table 1. Optimization of the Reaction Conditions for the Kinetic Resolution of Racemic 2-Phenylcyclopentanone 1a

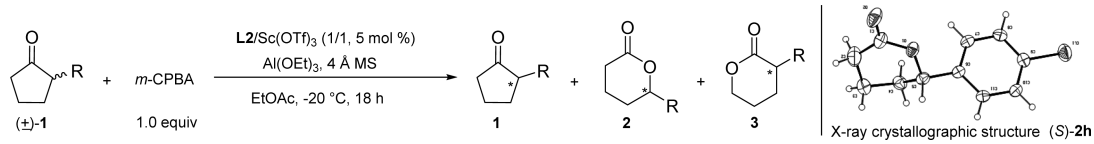


				conversion (%)[b]		ee (%)[c]		rs[b]
entry[a]	ligand	additive	MS	**1a**	**2a** + **3a**	**1a**	**2a**	**2a**/**3a**
1	−	−	−	75	25 (**2a**)	−	−	−
2	**L1**	−	−	97	trace	−	−	−
3	**L1**	$Al(O^iPr)_3$	−	83	17	4	99	5/1
4	**L1**	$Al(O^iPr)_3$	4 Å MS	74	26	20	99	6.2/1
5	**L1**	−	4 Å MS	90	10	3	99	4.6/1
6	**L1**	$Al(O^tBu)_3$	4 Å MS	87	13	8	99	5/1
7	**L1**	$Al(OEt)_3$	4 Å MS	60	40	40	99	5.8/1
8	**L2**	$Al(OEt)_3$	4 Å MS	44	56	90	98	9.6/1
9	**L3**	$Al(OEt)_3$	4 Å MS	39	61	60	97	2.8/1
10	**L4**	$Al(OEt)_3$	4 Å MS	31	69	70	97	2.3/1

[a]Unless otherwise noted, all reactions were performed with **1a** (0.1 mmol), **L** (5 mol %), $Sc(OTf)_3$ (5 mol %), $Al(OR)_3$ (0.1 mmol), and 4 Å MS (30.0 mg) in EtOAc (1.0 mL) at −20 °C, and then *m*-CPBA (0.1 mmol in 1.0 mL of EtOAc) was added at −20 °C. The reaction mixture was stirred at −20 °C for 18 h. [b]The conversion and the ratio of **2a**/**3a** were determined by ^1H NMR. [c]Determined by chiral HPLC analysis.

dx.doi.org/10.1021/ol501737a | *Org. Lett.* 2014, 16, 3938−3941

Table 2. Substrate Scope for the Kinetic Resolution of Racemic 2-Substituted Cyclopentanones



		yield (%)[b]		ee (%)[c]		rs[d]
entry[a]	a-l: R	1	2 + 3	1	2	2/3
1	**a**: Ph	42	53	90	98	9.6/1
2	**b**: 4-MeC_6H_4	45	55	90	94	>19/1
3	**c**: 3-MeC_6H_4	46	52	85	98	12/1
4	**d**: 4-MeOC_6H_4	40	58	98 (*R*)[e]	94	15/1
5	**e**: 3-MeOC_6H_4	43	56	80	92	7/1
6	**f**: 4-PhC_6H_4	44	54	95	98	13/1
7	**g**: 4-FC_6H_4	46	53	95	97	15.6/1
8	**h**: 4-ClC_6H_4	46	53	92	97 (*S*)[f]	11.5/1
9	**i**: 3-ClC_6H_4	41	56	87	98	6.3/1
10	**j**: 4-BrC_6H_4	43	54	86	96	11/1
11	**k**: 2-naphthyl	44	56	92	94	9.5/1
12	**l**: benzyl	57	41	14	87 (62)[g]	1.33/1
13	**d**: 4-MeOC_6H_4	42	55	90 (*R*)	95[h]	13/1

[a]Unless otherwise noted, the reactions were performed with **1** (0.1 mmol), **L2** (5 mol %), $Sc(OTf)_3$ (5 mol %), $Al(OEt)_3$ (0.1 mmol, 16.2 mg), and 4 Å MS (30.0 mg) in EtOAc (1.0 mL) at −20 °C, and then *m*-CPBA (0.1 mmol in 1.0 mL of EtOAc) was added at −20 °C. The reaction mixture was stirred at −20 °C for 18 h. [b]Isolated yield. [c]Determined by chiral HPLC analysis. [d]The regioselectivity of **2**/**3** was determined by ^{1}H NMR. [e]The absolute configuration of **1d** was confirmed to be *R* by comparison of the optical rotation with this reported in the literature. [f]The absolute configuration of **2h** was determined to be *S* by X-ray analysis. [g]The ee of the δ-lactone **3l** was 62%. [h]Using 3.0 mmol of **1d** as the substrate.

optical rotation with the literature.[14] It indicated that the (*S*)-ketone preferred to be oxidized to δ-lactone **2** in the asymmetric catalytic system and the migration proceeded with retention of configuration at the migrating carbon atom. Optically active 2-arylcyclopentanones did not racemize under the asymmetric catalytic system but suffered slight racemization by column chromatography via silica at higher temperature.[12] When 2-benzylcyclopentanone **1l** was subjected to the BV oxidation, the regioselectivity and reactivity decreased obviously. The corresponding mixed δ-lactones **2l** and **3l** were obtained with 1.33/1 rs, as well as 87% and 62% ee, respectively. As a result, the unreacted ketone **1l** was recovered with only 14% ee (entry 12).[15] Furthermore, by treatment of 3.0 mmol of the racemic **1d**, the product **2d** was produced smoothly in 55% yield with up to 95% ee and 13/1 rs, and the unreacted ketone **1d** was recovered in 42% yield with 90% ee, which showed the synthetic utility of the catalytic system (entry 13).

Next, the catalytic system was explored for the BV oxidations of the racemic 2-phenylcyclobutanone **4** and 2-phenylcyclohexanone **7**.[16] The product distribution and enantioselectivities changed obviously. As shown in Figure 1, the BV oxidation of the racemic 2-phenylcyclobutanone **4** gave the mixed γ-lactones **5** and **6** with only 1.33/1 rs. The normal lactone **5** and the unreacted ketone **4** were isolated in 50% and 42% ee, respectively. The racemic 2-phenylcyclohexanone **7** generated the abnormal ε-lactone **9** slightly more than the normal ε-lactone **8**. The normal ε-lactone **8** and the unreacted ketone **7** were isolated in low ee values, albeit ε-lactone **9** was given in 93% ee. It was proposed that the different ring strain and conformations of the 2-substituted cyclic ketones, and the steric hindrance created by a chiral catalyst as well, would account for the migratory aptitude in the circumstances.

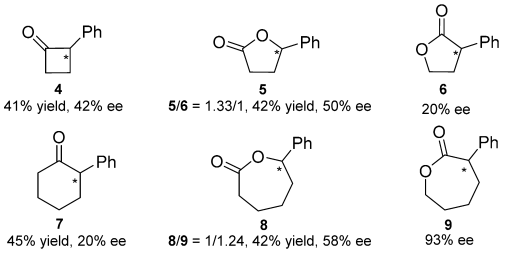


Figure 1. Asymmetric BV oxidations of the racemic 2-phenylcyclobutanone **4** and 2-phenylcyclohexanone **7**.

In summary, we have successfully developed a highly regio- and enantioselective BV oxidation of racemic 2-substituted cyclopentanones using the highly efficient *N,N′*-dioxide−Sc^{III} complex catalyst. The asymmetric BV oxidation could afford the desired δ-lactones in 87−98% ee and moderate to good regioselectivities. Moreover, the kinetic resolution process gave optically active ketones in excellent ee (up to 98%). To the best of our knowledge, it represents the best example of the kinetic resolution of 2-substituted cyclopentanones via nonenzymatic asymmetric BV oxidation to date. Further study on the reaction mechanism and extensive exploration of the methodology to other cyclic ketones are underway.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures, spectral and analytical data for the products. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: xmfeng@scu.edu.cn.

dx.doi.org/10.1021/ol501737a | *Org. Lett.* 2014, 16, 3938−3941

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the National Natural Science Foundation of China (21321061, 21290182, and 21172151), the National Basic Research Program of China (973 Program: 2010CB833300), and the Ministry of Education (20110181130014) for financial support.

■ REFERENCES

(1) (a) Baeyer, A.; Villiger, V. *Ber. Dtsch. Chem. Ges.* **1899**, *32*, 3625. For selected reviews, see: (b) Krow, G. R. *Org. React.* **1993**, *43*, 251. (c) Renz, M.; Meunier, B. *Eur. J. Org. Chem.* **1999**, 737. (d) Strukul, G. *Angew. Chem.* **1998**, *110*, 1256; *Angew. Chem., Int. Ed.* **1998**, *37*, 1198. (e) ten Brink, G.-J; Arends, I. W. C. E.; Sheldon, R. A. *Chem. Rev.* **2004**, *104*, 4105.

(2) For selected books, see: (a) Bolm, C. In *Asymmetric Synthesis—The Essentials*; Christmann, M., Bräse, S., Eds.; Wiley-VCH: Weinheim, 2006; p 57. (b) Bolm, C.; Beckmann, O. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999, Vol. 2; p 803. (c) Bolm, C. In *Advances in Catalytic Processes*; Doyle, M. P., Ed.; JAI Press: Greenwich, 1997; Vol. 2, p 43.

(3) For selected examples for the asymmetric BV oxidation of prochiral cyclic ketones catalyzed by biocatalysts, see: (a) Taschner, M. J.; Black, D. J.; Chen, Q. Z. *Tetrahedron: Asymmetry* **1993**, *4*, 1387. (b) Stewart, J. D.; Reed, K. W.; Martinez, C. A.; Zhu, J.; Chen, G.; Kayser, M. M. *J. Am. Chem. Soc.* **1998**, *120*, 3541. (c) Mihovilovic, M. D.; Chen, G.; Wang, S.; Kyte, B.; Rochon, F.; Kayser, M. M.; Stewart, J. D. *J. Org. Chem.* **2001**, *66*, 733. (d) Rial, D. V.; Bianchi, D. A.; Kapitanova, P.; Lengar, A.; van Beilen, J. B.; Mihovilovic, M. D. *Eur. J. Org. Chem.* **2008**, 1203. (e) Reetz, M. T.; Brunner, B.; Schneider, T.; Schulz, F.; Clouthier, C. M.; Kayser, M. M. *Angew. Chem.* **2004**, *116*, 4167; *Angew. Chem., Int. Ed.* **2004**, *43*, 4075. (f) Schwarz-Linek, U.; Krödel, A.; Ludwig, F.-A.; Schulze, A.; Rissom, S.; Kragl, U.; Tishkov, V. I.; Vogel, M. *Synthesis* **2001**, *6*, 947. (g) Rudroff, F.; Rydz, J.; Ogink, F. H.; Fink, M.; Mihovilovic, M. D. *Adv. Synth. Catal.* **2007**, *349*, 1436.

(4) For selected examples for the asymmetric BV oxidation of prochiral cyclic ketones catalyzed by chiral metal complexes, see: (a) Bolm, C.; Luong, T. K. K.; Schlingloff, G. *Synlett* **1997**, 1151. (b) Sugimura, T.; Fujiwara, Y.; Tai, A. *Tetrahedron Lett.* **1997**, *38*, 6019. (c) Shinohara, T.; Fujioka, S.; Kotsuki, H. *Heterocycles* **2001**, *55*, 237. (d) Uchida, T.; Katsuki, T. *Tetrahedron Lett.* **2001**, *42*, 6911. (e) Bolm, C.; Beckmann, O.; Cosp, A.; Palazzi, C. *Synlett* **2001**, 1461. (f) Bolm, C.; Frison, J.-C.; Zhang, Y.; Wulff, W. D. *Synlett* **2004**, 1619. (g) Frison, J.-C.; Palazzi, C.; Bolm, C. *Tetrahedron* **2006**, *62*, 6700. (h) Paneghetti, C.; Gavagnin, R.; Pinna, F.; Strukul, G. *Organometallics* **1999**, *18*, 5057. (i) Cavarzan, A.; Bianchini, G.; Sgarbossa, P.; Lefort, L.; Gladiali, S.; Scarso, A.; Strukul, G. *Chem.—Eur. J.* **2009**, *15*, 7930. (j) Colladon, M.; Scarso, A.; Strukul, G. *Synlett* **2006**, 3515.

(5) For selected examples for the asymmetric BV oxidation of prochiral cyclic ketones catalyzed catalyzed by organocatalysts, see: (a) Murahashi, S.-I.; Ono, S.; Imada, Y. *Angew. Chem.* **2002**, *114*, 2472; *Angew. Chem., Int. Ed.* **2002**, *41*, 2366. (b) Xu, S.; Wang, Z.; Zhang, X.; Zhang, X.; Ding, K. *Angew. Chem.* **2008**, *120*, 2882; *Angew. Chem., Int. Ed.* **2008**, *47*, 2840. (c) Xu, S.; Wang, Z.; Li, Y.; Zhang, X.; Wang, H.; Ding, K. *Chem.—Eur. J.* **2010**, *16*, 3021.

(6) For selected examples for the asymmetric BV oxidation of racemic cyclic ketones catalyzed by biocatalysts, see: (a) Alphand, V.; Archelas, A.; Furstoss, R. *J. Org. Chem.* **1990**, *55*, 347. (b) Kayser, M. M.; Chen, G.; Stewart, J. D. *J. Org. Chem.* **1998**, *63*, 7103. (c) Berezina, N.; Alphand, V.; Furstoss, R. *Tetrahedron: Asymmetry* **2002**, *13*, 1953. (d) Bocola, M.; Schulz, F.; Leca, F.; Vogel, A.; Fraaije, M. W.; Reetz, M. T. *Adv. Synth. Catal.* **2005**, *347*, 979. (e) Hollmann, F.; Taglieber, A.; Schulz, F.; Reetz, M. T. *Angew. Chem.* **2007**, *119*, 2961; *Angew. Chem., Int. Ed.* **2007**, *46*, 2903. (f) Reetz, M. T.; Wu, S. *Chem. Commun. (Cambridge, U. K.)* **2008**, 5499. (g) Reetz, M. T.; Wu, S. *J. Am. Chem. Soc.* **2009**, *131*, 15424. (h) Stewart, J. D.; Reed, K. W.; Zhu, J.; Chen, G.; Kayser, M. M. *J. Org. Chem.* **1996**, *61*, 7652.

(7) For selected examples for the asymmetric BV oxidation of bicyclic cyclobutanones, see: (a) Alphand, V.; Furstoss, R. *J. Org. Chem.* **1992**, *57*, 1306. (b) Alphand, V.; Furstoss, R. *J. Mol. Catal. B: Enzymatic* **2000**, *9*, 209. (c) Schulz, F.; Leca, F.; Hollmann, F.; Reetz, M. T. *Beilstein J. Org. Chem.* **2005**, *1*, 10. (d) Watanabe, A.; Uchida, T.; Irie, R.; Katsuki, T. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5737. (e) Bolm, C.; Schlingloff, G. *J. Chem. Soc., Chem. Commun.* **1995**, 1247. (f) Lopp, M.; Paju, A.; Kanger, T.; Pehk, T. *Tetrahedron Lett.* **1996**, *37*, 7583. (g) Kanger, T.; Kriis, K.; Paju, A.; Pehk, T.; Lopp, M. *Tetrahedron: Asymmetry* **1998**, *9*, 4475. (h) Bolm, C.; Beckmann, O. *Chirality* **2000**, *12*, 523. (i) Colladon, M.; Scarso, A.; Strukul, G. *Synlett* **2006**, 3515. (j) Xu, S.; Wang, Z.; Zhang, X.; Ding, K. *Eur. J. Org. Chem.* **2011**, 110.

(8) (a) Bolm, C.; Schlingloff, G.; Weickhardt, K. *Angew. Chem.* **1994**, *106*, 1944; *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1848. (b) Gusso, A.; Baccin, C.; Pinna, F.; Strukul, G. *Organometallics* **1994**, *13*, 3442. (c) Peng, Y. G.; Feng, X. M.; Yu, K. B.; Li, Z.; Jiang, Y. Z.; Yeung, C.-H. *J. Organomet. Chem.* **2001**, *619*, 204.

(9) Zhou, L.; Liu, X. H.; Ji, J.; Zhang, Y. H.; Hu, X. L.; Lin, L. L.; Feng, X. M. *J. Am. Chem. Soc.* **2012**, *134*, 17023.

(10) (a) Liu, X. H.; Lin, L. L.; Feng, X. M. *Acc. Chem. Res.* **2011**, *44*, 574. (b) Shen, K.; Liu, X. H.; Lin, L. L.; Feng, X. M. *Chem. Sci.* **2012**, *3*, 327. (c) Feng, X. M.; Liu, X. H. In *Scandium: Compounds, Productions and Applications*; Greene, V. A., Ed.; Nova Science, New York, 2011; p 1. (d) Huang, S.; Ding, K. *Angew. Chem.* **2011**, *123*, 7878; *Angew. Chem., Int. Ed.* **2011**, *50*, 7734. (e) Liu, X. H.; Lin, L. L.; Feng, X. M. *Org. Chem. Front.* **2014**, *1*, 298.

(11) Using H_2O_2 or TBHP as the oxidant, no BV product was observed.

(12) The optically active 2-arylcyclopentanones suffer slow racemization by column chromatography on silica gel at high temperature.

(13) CCDC 998771 (**2h**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

(14) Shen, Y.-M.; Wang, B.; Shi, Y. *Angew. Chem.* **2006**, *118*, 1457; *Angew. Chem., Int. Ed.* **2006**, *45*, 1429.

(15) The BV reaction of 2-methylcyclopentanone was tested, but the method of determination of the ee value is not established.

(16) Under the optimal reaction conditions, no BV product was observed for 2-phenylcycloheptanone.