ChemPubSoc Europe

DOI: 10.1002/chem.201304835

CHEMISTRY
A European Journal
Communication

Asymmetric Synthesis

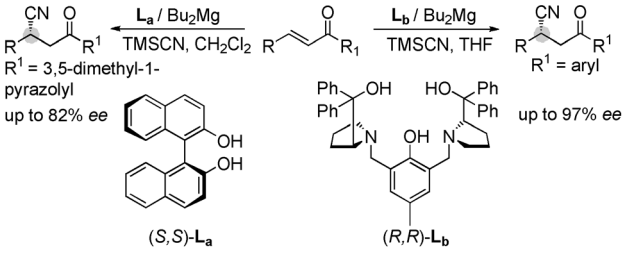
Magnesium Complexes as Highly Effective Catalysts for Conjugate Cyanation of α,β-Unsaturated Amides and Ketones

Jinlong Zhang, Xihong Liu, and Rui Wang*[a]

Abstract: Asymmetric cyanation of trimethylsilyl cyanide (TMSCN) with α,β-unsaturated amides and ketones, respectively, catalyzed by bifunctional mononuclear 1,1′-bi-2-naphthol (BINOL)–Mg and binuclear bis(prophenol)–Mg catalysts was realized. A series of synthetically important 1,4-cyano products were obtained with good to high enantioselectivities (up to 97% *ee*).

The asymmetric conjugate cyanide addition is certainly one of the most efficient and practical methods to afford optically active β-cyano adducts, which can be readily converted into important compounds, including γ-aminobutyric acids (GABA analogues) and 1,2-dicarboxylic acids.[1] As a result of the importance of these enantioenriched derivatives, particularly in biological and pharmaceutical chemistry, the asymmetric conjugate cyanation of α,β-unsaturated carbonyl compounds has attracted much attention from biological and synthetic chemists.[2] In 2003, Jacobsen and co-workers reported the first chiral Salen–Al[3] catalytic system for the enantioselective conjugate cyanation between α,β-unsaturated imides and trimethylsilyl cyanide (TMSCN). Since then, a varied of elegant works on those reactions have been disclosed. Generally speaking, chiral organic–metal complexes involving Ti, Al, Gd, and Sr,[4] phase-transfer catalysts,[5] or organocatalysts[6] have been developed for this kind of reaction. It is undoubted that further advances in practical methods are still desirable. In this context, we are interested in the development of readily accessible magnesium catalysts for catalyzing the 1,4-addition of trimethylsilyl cyanide in high enantioselectivity.

The alkaline earth metal is among the most common elements on earth, and in contrast to the transition metals it is vastly abundant and relatively nontoxic. However, applications of these catalysts to catalyze chemical transformations, especially the asymmetric synthetic reactions, have been rarely revealed. Thus, we turned our attention to the alkaline earth metal magnesium as an easy to handle catalyst.[7] When chiral alcohols or phenol ligands, such as BINOL derivatives[8] and bis(prophenol) ligands[9] are used, magnesium base[10] can deprotonate the hydroxyl moiety of the ligand to form a rigid chiral complex, in which the particularly low electronegativity of the metal center usually results in stronger Brøsted basicity of the oxygen atoms. Both the Lewis acidity of the magnesium and Brøsted basicity of the oxygen atom are very important for the chemical activity and selectivity of the bifunctional acid–base magnesium catalyst, which simultaneously activates both a substrate and an acidic pronucleophile. Until now, only a few catalytic methods for the asymmetric phenol–Mg catalysis have been developed and most of these reaction processes are restricted to the additions of phosphorus nucleophiles,[8a] α- or γ-positions of carbonyl compounds[8b,c] to electrophilic acceptors. The conjugate cyanation of α,β-unsaturated compounds catalyzed by magnesium has never been reported. As part of our ongoing work on the magnesium catalysis, we explored the viability of this method for the conjugate cyanation reaction. Gratifyingly, the reaction proceeded smoothly to afford the desired 1,4-cyano adducts with good to excellent results catalyzed by mononuclear catalyst $\mathbf{L_a}$ and dinuclear catalyst $\mathbf{L_b}$ by using TMSCN as the cyanide source (Scheme 1).



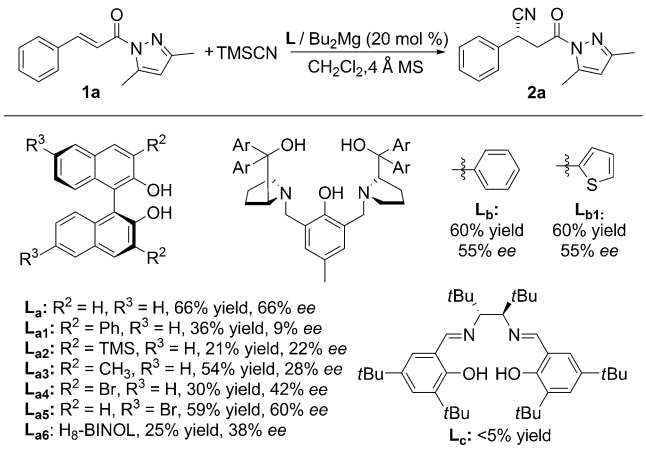
Scheme 1. Asymmetric conjugate cyanation with mononuclear or dinuclear magnesium salts.

The initial investigation began with the reaction between β-phenyl-substituted pyrazole **1a** and TMSCN in CH_2Cl_2 at room temperature with a 20 mol% catalyst loading (Scheme 2). Although chiral alcohol and phenol ligands have been widely used in asymmetric catalysis, their application for chiral modification of magnesium was less investigated. It should be noted that these types of metal salts could be easily obtained, a *divalent* magnesium center firmly bonded to both oxygen atoms, forming an effective chiral acid–base catalyst. We examined a series of phenol–Mg derivatives with 4 Å molecular sieves in the model reaction, and an excellent result in terms of both

[a] *J. Zhang,[+] X. Liu,[+] Prof. R. Wang*
Key Laboratory of Preclinical Study for New Drugs of Gansu Province, School of Basic Medical Science and Institute of Biochemistry and Molecular Biology School of Life Science Lanzhou University, Lanzhou, 730000 (P. R. China)
E-mail: wangrui@lzu.edu.cn

[+] *These authors contributed equally to this work.*

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201304835.



Scheme 2. Magnesium catalysts for the model reaction: The reactions were carried out with **1a** (0.1 mmol), TMSCN (0.3 mmol, 3.0 equiv) and **L**/Bu_2Mg (20 mol%) in 1.0 mL CH_2Cl_2 for 24 h. For $\mathbf{L_a}$, $\mathbf{L_{a1}}$–$\mathbf{L_{a6}}$, and $\mathbf{L_c}$, **L**/Bu_2Mg = 1:1; for $\mathbf{L_b}$ and $\mathbf{L_{b1}}$, **L**/Bu_2Mg = 1:2.

the enantioselectivity and yield was observed under the catalysis of catalyst $\mathbf{L_a}$. Surprisingly, no cyanide adduct was detected in the presence of protic additives, such as phenol, alcohol, or water. Structural information of the substrate suggested that the use of 3,5-dimethylpyrazole as an achiral auxiliary leads to an interaction between the trimethylsilane and acetylpyrazole group, and the chelating capacity was relatively weak to undergo rapid catalyst exchange.

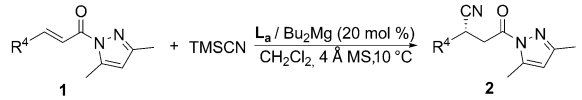
On the basis of the experimental results, we then tried to optimize the cyanation reaction with $\mathbf{L_a}$/Mg by changing other variables including temperature and solvent (Table 1). A significant influence of reaction temperature on the yield and enantioselectivity was found. The reaction proceeded at 10 °C and resulted in a higher enantioselectivity without an obvious sacrifice of reaction rate (Table 1, entries 1–4). Further screening of the solvents revealed that CH_2Cl_2 appeared to be the most suitable reaction media (entries 5–8). When the catalyst loading decreased to 10 mol% or no molecular sieves were added, low selectivity and yield were observed (entries 9–10).

Table 1. Reaction condition optimization of the model reaction.[a]

Entry	Solvent	*T* [°C]	Additive	*T* [h][b]	*ee* [%][c]
1	CH_2Cl_2	RT	4 Å MS	24	66
2	CH_2Cl_2	30	4 Å MS	24	52
3	CH_2Cl_2	10	4 Å MS	30	76
4	CH_2Cl_2	0	4 Å MS	>72	80
5	THF	10	4 Å MS	n.d.	n.d.
6	Et_2O	10	4 Å MS	>72	34
7	toluene	10	4 Å MS	>72	45
8	CCl_4	10	4 Å MS	48	24
9[d]	CH_2Cl_2	10	4 Å MS	>72	68
10	CH_2Cl_2	10	–	>72	50

[a] Unless otherwise specified, the reaction was performed on a 0.1 mmol scale in 1.0 mL of the solvent with a **1a**/TMSCN/**L**/Bu_2Mg molar ratio of 1:3:0.2. [b] Determined by TLC analysis. [c] Determined by HPLC analysis on a chiral stationary phase. [d] The reaction was performed at 10 mol% catalyst loading.

Table 2. Substrate scope for the asymmetric conjugate cyanation of α,β-unsaturated amides.[a]



Entry	R	Product	Yield [%][b]	*ee* [%][c]
1[d]	Ph (**1a**)	**2a**	61	76
2	2-MeC_6H_4 (**1b**)	**2b**	65	75
3	3-MeC_6H_4 (**1c**)	**2c**	68	70
4	4-MeC_6H_4 (**1d**)	**2d**	71	74
5	4-$ClPhC_6H_4$ (**1e**)	**2e**	68	70
6	2,4-$2ClC_6H_3$ (**1f**)	**2f**	63	82
7	4-BrC_6H_4 (**1g**)	**2g**	58	40
8	4-$CF_3C_6H_4$ (**1h**)	**2h**	75	72
9	4-CNC_6H_4 (**1i**)	**2i**	79	76
10	4-$MeOC_6H_4$ (**1j**)	**2j**	71	60
11	2-naphthyl (**1k**)	**2k**	76	64
12	PhCH=CH (**1l**)	**2l**	69	50
13	Me (**1m**)	**2m**	62	37
14[e]	3-*N*-Methylindol (**1n**)	**2n**	88	48

[a] Unless otherwise specified, the reaction was performed on 0.1 mmol scale with **1** (1.0 equiv), TMSCN (3.0 equiv), and catalyst $\mathbf{L_a}$/Bu_2Mg (20 mol%) in CH_2Cl_2 (1.0 mL) at 10 °C for 30 h. [b] Isolated yields. [c] Determined by HPLC analysis on a chiral stationary phase. [d] The absolute configuration of **2a** was determined to be *R* by comparison with literature data. For details, see the Supporting Information. [e] The reaction time was 72 h.

With the optimal reaction conditions as indicated in entry 3 of Table 1, we further examined the substrate scope (Table 2). A series of α,β-unsaturated *N*-acylimides with either electron-withdrawing or -donating groups on the aromatic ring were proved to be amenable and gave the corresponding cyanide adducts in high yields, and good to high enantioselectivities (except for **2g**, which was only obtained with 40% *ee*, **2a**–**k**). The use of diolefin substrate also afforded the product in 69% yield and with 50% *ee* (entry 12, **2l**). With aliphatic-substituted substrates, the enantioselectivity decreased to 37% (entry 13, **2m**). Because of the medicinal properties of many natural and non-natural compounds that contain an indole backbone, an indole heterocycle-substituted olefin was tested in this process and the corresponding adduct was obtained in 92% yield, although with 48% *ee* (entry 14, **2n**). The pyrazole motif is a good leaving group and these products can be easily converted into carboxylic acid derivatives.

Encouraged by the successful synthesis of cyanide adducts of α,β-unsaturated *N*-acylimides catalyzed by mononuclear BINOL–Mg complex as described above, we attempted to extend the substrate scope of α,β-unsaturated amides to α,β-unsaturated ketones. The model reaction was performed between chalcone **3a** and TMSCN at the optimized reaction conditions. Unfortunately, catalyst $\mathbf{L_a}$ was not a good choice because of the very poor catalytic activity and low stereoselectivity. The ESI-MS analysis suggested that a dimeric chiral complex might exist as a mixture of $\mathbf{L_a}$ and TMSCN (1:5 molar ratio) in CH_2Cl_2. We observed a peak at *m*/*z*: 743.42, which could be

identified as [2 BINOL–Mg+TMSCN+HCN+H]$^+$. Although other oligomeric candidates can still be considered, we proposed that the presence of α,β-unsaturated amides could promote the dissociation of dimeric complexes into highly active monomeric species under our reaction conditions. For the α,β-unsaturated *N*-acylimide with pyrazole as a achiral auxiliary,[11] stereocontrol would be much more favorable as illustrated in complex **A** (Figure 1).[12] While the rotatable monochelated

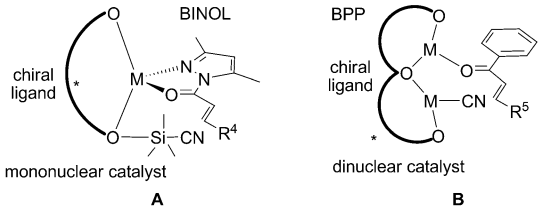


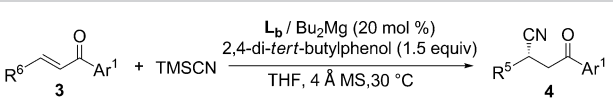
Figure 1. Proposed complexes **A** and **B**.

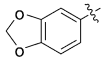
bond between the ketones and catalyst generated in the cyanation process might reduce the chemical enantioselectivity. In this case, a dinuclear catalyst might theoretically provide an effective asymmetric environment around the two metal atoms and the dual-mode coordination in complex **B** enabled the cyanation to undergo stereospecific addition.[13] To validate our hypothesis, a bis(prophenol)–Mg catalyst was synthesized. To our delight, compared to $\mathbf{L_a}$, the catalyst $\mathbf{L_b}$ gave the 1,4-adduct as the only detectable product with a much higher enantioselectivity and moderate yield. Afterward, 2,6-di-*tert*-butylphenol was added as a protic additive and both yield and enantioselectivity were dramatically enhanced (92% *ee*). Gratifyingly, the peak (*m/z*: 711.40) corresponding to [bis(prophenol)–Mg+HCN+H]$^+$ was observed by ESI-MS analysis of a mixture between bis(prophenol)–Mg and TMSCN (1:5 molar ratio) in THF, which led us to propose the hypothesis that the bis(prophenol)–Mg/CN complex was a more possible reaction intermediate. Thus, the combined use of catalyst $\mathbf{L_b}$ and protic additive 2,6-di-*tert*-butylphenol worked in a highly effective manner to give the cyanide addition products of α,β-unsaturated ketones in THF at 30 °C (for details, see the Supporting Information).

Evaluation of the reaction scope revealed that high yield and enantioinduction could be obtained for a range of enone substrates with the dinuclear catalyst $\mathbf{L_b}$. Various aromatic enones possessing both electron-donating and -withdrawing groups afforded the corresponding products in 70–97% yields with enantiomeric excesses up to 97% *ee* (Table 3, **4a**–**s**). In addition, β-heteroaromatic-substituted substrate was also tolerated and gave the desired product in high yield and *ee* value (entry 12, **4l**). It was worth noting that the β-aliphatic enone was also applicable to the present catalytic system (entry 14, **4n**).

Next, we examined the cyanation of chalcone **3a** with the use of *tert*-butyldimethylsilanecarbonitrile (TBDMSCN) or HCN as the cyanide source. To our delight, both cyanide compounds were amenable and the reaction proceeded smoothly

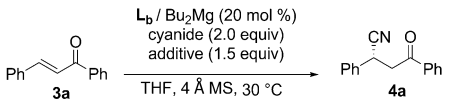
Table 3. Substrate scope for the asymmetric conjugate cyanation of α,β-unsaturated ketones.[a]



Entry	R^6, Ar^1	Product	Yield[b] [%]	*ee*[c] [%]
1[d]	Ph, Ph (**3a**)	**4a**	95	92
2	2-MeC_6H_4, Ph (**3b**)	**4b**	89	90
3	4-MeC_6H_4, Ph (**3c**)	**4c**	93	94
4	4-$ClPhC_6H_4$, Ph (**3d**)	**4d**	91	88
5	2-BrC_6H_4, Ph (**3e**)	**4e**	82	92
6	4-BrC_6H_4, Ph (**3f**)	**4f**	85	85
7	2-$MeOC_6H_4$, Ph (**3g**)	**4g**	91	93
8	3-$MeOC_6H_4$, Ph (**3h**)	**4h**	89	94
9	4-$MeOC_6H_4$, Ph (**3i**)	**4i**	90	95
10	 , Ph (**3j**)	**4j**	92	97
11	2-naphthyl, Ph (**3k**)	**4k**	83	94
12	2-furanyl, Ph (**3l**)	**4l**	79	88
13	PhCH=CH, Ph (**3m**)	**4m**	75	79
14	Hex, Ph (**3n**)	**4n**	85	82
15	Ph, 4-MeC_6H_4 (**3o**)	**4o**	93	95
16	Ph, 2-ClC_6H_4 (**3p**)	**4p**	84	77
17	Ph, 3-ClC_6H_4 (**3q**)	**4q**	87	89
18	Ph, 4-ClC_6H_4 (**3r**)	**4r**	90	90
19	Ph, 4-$MeOC_6H_4$ (**3s**)	**4s**	92	94

[a] Unless otherwise specified, the reaction was performed on 0.1 mmol scale with **3** (1.0 equiv), TMSCN (2.0 equiv), 2,4-di-*tert*-butylphenol (1.5 equiv), and catalyst $\mathbf{L_b}$/Bu_2Mg (20 mol%) in THF (1.0 mL) at 30 °C for 10 h. [b] Isolated yields. [c] Determined by HPLC analysis on a chiral stationary phase. [d] The absolute configuration of **2a** was determined to be *R* by comparison with literature data and the other products were assigned by analogy.

Table 4. Cyanation of chalcone **3a** with TBDMSCN or HCN as cyanide source.

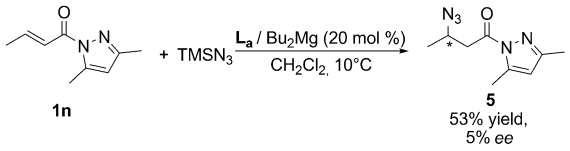


Entry	Cyanide	Additive	Yield [mol%]	*ee* [%]
1[a]	TMSCN	dibutylphenol	95	92
2[a]	TBDMSCN	dibutylphenol	64	93
3[b]	HCN	–	93	92

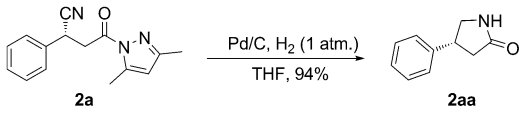
[a] The reaction was performed on 0.1 mmol scale with **3a** (1.0 equiv), cyanide (2.0 equiv), 2,4-di-*tert*-butylphenol (1.5 equiv), and catalyst $\mathbf{L_b}$/Bu_2Mg (20 mol%) in THF (1.0 mL) at 30 °C for 10 h. [b] The HCN solution was generated from equimolar amounts of TMSCN and MeOH at RT, and the reaction proceeded without addition of 2,4-di-*tert*-butylphenol. The product was isolated and the *ee* value was determined by HPLC analysis on a chiral stationary phase.

to give **4a** with high enantioselectivity from moderate to high yield (Table 4, entries 2–3).

Catalyst $\mathbf{L_a}$ could also be used in the conjugate addition of trimethylsilylazide to β-methyl α,β-unsaturated *N*-acylimide, providing the azide compound with 5% *ee* (Scheme 3).[14] The synthetic utility of cyanation product **2a** was demonstrated in



Scheme 3. Conjugate addition of trimethylsilylazide to α,β-unsaturated amide **1n**.



Scheme 4. Transformation of **2a** to pyrrolidin-2-one **2aa**.

the intramolecular cyclization to give product pyrrolidin-2-one **2aa** as a useful building block (Scheme 4).[15]

In summary, we have developed the asymmetric cyanation of TMSCN with α,β-unsaturated carboxylic compounds catalyzed by the bifunctional acid–base mononuclear BINOL–Mg and dinuclear bis(prophenol)–Mg salts, respectively. A series of synthetically important 1,4-cyano products were obtained with good to high enantioselectivities (up to 97% *ee*). Several noteworthy features of the magnesium catalyst include its vast abundance and relative nontoxicity should render this enantioselective chemical transformation a potentially very valuable addition to the asymmetric carbon–carbon bond formation methods. Further investigation of the bifunctional catalyst in asymmetric reactions is underway in our laboratory.

Experimental Section

Typical procedure for the cyanation of α,β-unsaturated amides 1

Bu_2Mg (0.5 M in heptane, 40 μL, 0.02 mmol) was added to a stirred solution of $\mathbf{L_a}$ (5.9 mg, 0.02 mmol) and well-dried 4 Å molecular sieves (20 mg) in CH_2Cl_2 (0.8 mL), under an argon atmosphere at 0 °C. The mixture was then stirred at 0 °C for 2 h to generate the bifunctional $\mathbf{L_a}$–Mg catalyst. After the addition of amides 1 (0.1 mmol) and TMSCN (3.0 equiv) in CH_2Cl_2 (0.2 mL), the resulting reaction mixture was stirred for 30 h at 10 °C until the reaction was accomplished (monitored by TLC analysis). The reaction was quenched by water and extracted with CH_2Cl_2 (10 mL×3). The mixture was washed by brine (10 mL) and dried over Na_2SO_4, and then concentrated under vacuum. The crude product was purified by silica gel column chromatography to give the desired product **2**.

Typical procedure for the cyanation of α,β-unsaturated ketones 3

Bu_2Mg (80 μL, 0.04 mmol) was added to a stirred solution of $\mathbf{L_b}$ (12.8 mg, 0.02 mmol) and well-dried 4 Å molecular sieves (20 mg) in THF (0.8 mL) under an argon atmosphere at 0 °C. The mixture was then stirred at 0 °C for 2 h to generate the bifunctional dinuclear $\mathbf{L_b}$–Mg catalyst. After the addition of ketones **3** (0.1 mmol), additive 2,4-di-*tert*-butylphenol (1.5 equiv) and TMSCN (2.0 equiv) in THF (0.2 mL), the resulting reaction mixture was stirred for 10 h at 30 °C until the reaction was accomplished (monitored by TLC analysis). The cyanide adducts **4** obtained by the following workup as above.

Acknowledgements

We are grateful for the grants from the National Natural Science Foundation of China (Nos. 91213302 and 21272102), the Key National S&T Program "Major New Drug Development" of the Ministry of Science and Technology of China (2012ZX09504001–003) and the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT: IRT1137).

Keywords: asymmetric catalysis · cyanation · magnesium · synthetic methods · unsaturated ketones

[1] a) E. Roberts, *Biochem. Pharmacol.* **1974**, *23*, 2637–2649; b) I. A. Sytinsky, A. T. Soldatenkov, A. Lajtha, *Prog. Neurobiol.* **1978**, *10*, 89–133; c) L. Sivilotti, A. Nistri, *Prog. Neurobiol.* **1991**, *36*, 35–39.

[2] a) L. N. Mander, R. J. Thomson, *J. Org. Chem.* **2005**, *70*, 1654–1670; b) K. C. Nicolaou, A. F. Stepan, T. Lister, A. Li, A. Montero, G. S. Tria, C. I. Turner, Y. Tang, J. Wang, J. R. M. Denton, D. J. Edmonds, *J. Am. Chem. Soc.* **2008**, *130*, 13110–13119; c) A. Vázquez-Romero, J. Rodríguez, A. Lledó, X. Verdaguer, A. Riera, *Org. Lett.* **2008**, *10*, 4509–4512.

[3] G. M. Sammis, E. N. Jacobsen, *J. Am. Chem. Soc.* **2003**, *125*, 4442–4443.

[4] For examples, see: a) G. M. Sammis, H. Danjo, E. N. Jacobsen, *J. Am. Chem. Soc.* **2004**, *126*, 9928–9929; b) T. Mita, K. Sasaki, M. Kanai, M. Shibasaki, *J. Am. Chem. Soc.* **2005**, *127*, 514–515; c) I. Fujimori, T. Mita, K. Maki, M. Shiro, A. Sato, S. Furusho, M. Kanai, M. Shibasaki, *Tetrahedron* **2007**, *63*, 5820–5831; d) C. Mazet, E. N. Jacobsen, *Angew. Chem.* **2008**, *120*, 1786–1789; *Angew. Chem. Int. Ed.* **2008**, *47*, 1762–1765; e) Y. Tanaka, M. Kanai, M. Shibasaki, *J. Am. Chem. Soc.* **2008**, *130*, 6072–6073; f) Y. Tanaka, M. Kanai, M. Shibasaki, *J. Am. Chem. Soc.* **2010**, *132*, 8862–8863; g) J. Wang, W. Li, Y. Liu, Y. Chu, L. Lin, X. Liu, X. Feng, *Org. Lett.* **2010**, *12*, 1280–1283; h) N. Kurono, N. Nii, Y. Sakaguchi, M. Uemura, T. Ohkuma, *Angew. Chem.* **2011**, *123*, 5655–5658; *Angew. Chem. Int. Ed.* **2011**, *50*, 5541–5544; i) S. Lin, Y. Wei, F. Liang, *Chem. Commun.* **2012**, *48*, 9879–9881; j) H. Kawai, S. Okusu, E. Tokunaga, H. Sato, M. Shiro, N. Shibata, *Angew. Chem. Int. Ed.* **2012**, *51*, 4959–4962; k) Y. Sakaguchi, N. Kurono, K. Yamauchi, T. Ohkuma, *Org. Lett.* **2014**, *16*, 808–811; for asymmetric conjugate cyanation of nitroalkenes, see: l) P. Bernal, R. Fernández, J. M. Lassaletta, *Chem. Eur. J.* **2010**, *16*, 7714–7718; m) L. Lin, W. Yin, X. Fu, J. Zhang, X. Ma, R. Wang, *Org. Biomol. Chem.* **2012**, *10*, 83–89; n) M. North, J. M. Watson, *ChemCatChem* **2013**, *5*, 2405–2409.

[5] For phase-transfer-catalyzed asymmetric conjugate cyanation, see: a) B. A. Provencher, K. J. Bartelson, Y. Liu, B. M. Foxman, L. Deng, *Angew. Chem.* **2011**, *123*, 10753–10757; *Angew. Chem. Int. Ed.* **2011**, *50*, 10565–10569; b) H. Kawai, S. Okusu, E. Tokunaga, H. Sato, M. Shiro, N. Shibata, *Angew. Chem. Int. Ed.* **2012**, *51*, 4959–4962; c) Y. Liu, S. Shirakawa, K. Maruoka, *Org. Lett.* **2013**, *15*, 1230–1233.

[6] Y.-F. Wang, W. Zeng, M. Sohail, J. Guo, S. Wu, F.-X. Chen, *Eur. J. Org. Chem.* **2013**, 4624–4633.

[7] For reviews in catalysis with alkaline earth-metal complexes: a) U. Kazmaier, *Angew. Chem.* **2009**, *121*, 5902–5904; *Angew. Chem. Int. Ed.* **2009**, *48*, 5790–5792; b) S. Harder, *Chem. Rev.* **2010**, *110*, 3852–3876; c) S. Kobayashi, Y. Mori, J. S. Fossey, M. M. Salter, *Chem. Rev.* **2011**, *111*, 2626–2704; d) S. Sarish, S. Nembenna, S. Nagendran, H. W. Roesky, *Acc. Chem. Res.* **2011**, *44*, 157–170; e) S. Kobayashi, Y. Yamashita, *Acc. Chem. Res.* **2011**, *44*, 58–71; f) W. Maudez, K. Fromm, *Z. Anorg. Allg. Chem.* **2012**, *638*, 1810–1819.

[8] Mg^{II}–BINOLates have received little attention in asymmetric catalysis. For pioneering reports, see: a) H. Du, X. Zhang, Z. Wang, H. Bao, T. You, K. Ding, *Eur. J. Org. Chem.* **2008**, 2248–2254; b) M. Hatano, T. Horibe, K. Ishihara, *Org. Lett.* **2010**, *12*, 3502–3505; c) L. Lin, J. Zhang, X. Ma, X. Fu,

R. Wang, *Org. Lett.* **2011**, *13*, 6410 – 6413; d) M. Hatano, T. Horibe, K. Ishihara, *Angew. Chem. Int. Ed.* **2013**, *52*, 1 – 6; e) M. Hatano, T. Horibe, K. Yamashita, K. Ishihara, *Asian J. Org. Chem.* **2013**, *2*, 952 – 956.

[9] For bis(prophenol)–Mg-catalyzed asymmetric reactions, see: a) B. M. Trost, S. Malhotra, B. A. Fried, *J. Am. Chem. Soc.* **2009**, *131*, 1674 – 1675; b) B. M. Trost, S. Malhotra, P. Koschker, P. Ellerbrock, *J. Am. Chem. Soc.* **2012**, *134*, 2075 – 2084; c) B. M. Trost, S. Malhotra, P. Ellerbrock, *Org. Lett.* **2013**, *15*, 440 – 443.

[10] For reviews in asymmetric catalysis with Mg complexes: a) Y. Motoyama, H. Nishiyama, In *Lewis Acids in Organic Synthesis* Vol. 1 (Ed: H. Yamamoto), Wiley-VCH, Weinheim, Germany, **2000**, Chapter 3; b) M. Hatano, K. Ishihara, In *Acid Catalysis in Modern Organic Synthesis* Vol. 1 (Eds: H. Yamamoto, K. Ishihara), Wiley-VCH: Weinheim, Germany, **2008**, Chapter 4; Mg^{II} complexes in Synthesis: Box – Mg, c) M. P. Sibi, K. Itoh, C. P. Jasperse, *J. Am. Chem. Soc.* **2004**, *126*, 5366 – 5367; d) G. A. Cutting, N. E. Stainforth, M. P. John, G. Kociok-Köhn, M. C. Willis, *J. Am. Chem. Soc.* **2007**, *129*, 10632 – 10633; e) C. Taillier, M. Lautens, *Org. Lett.* **2007**, *9*, 591 – 593; f) S. Murarka, I. Deb, C. Zhang, D. Seidel, *J. Am. Chem. Soc.* **2009**, *131*, 13226 – 13227; phophate – Mg, g) J. Lv, X. Li, L. Zhong, S. Luo, J.-P. Cheng, *Org. Lett.* **2010**, *12*, 1096 – 1099; h) G. K. Ingle, Y. Liang, M. G. Mormino, G. Li, F. R. Fronczek, J. C. Antilla, *Org. Lett.* **2011**, *13*, 2054 – 2057; i) S. E. Larson, G. Li, G. B. Rowland, D. Junge, R. Huang, H. L. Woodcock, J. C. Antilla, *Org. Lett.* **2011**, *13*, 2188 – 2191; j) G. Li, T. Liang, L. Wojtas, J. C. Antilla, *Angew. Chem.* **2013**, *125*, 4726 – 4730; *Angew Chem. Int. Ed.* **2013**, *52*, 4628 – 4632; salen – Mg, k) T. Yoshino, H. Morimoto, G. Lu. S. Matsunaga, M. Shibasaki, *J. Am. Chem. Soc.* **2009**, *131*, 17082 – 17083; l) D. Yang, L. Wang, F. Han, D. Zhao, B. Zhang, R. Wang, *Angew. Chem. Int. Ed.* **2013**, *125*, 6871 – 6874. Bis-sulfonamide-Mg, m) D. A. Evans, S. G. Nelson, *J. Am. Chem. Soc.* **1997**, *119*, 6452 – 6453. *N*,*N*′-Dioxide-Mg, n) C. Yin, W. Cao, L. Lin, X. Liu, X. Feng, *Adv. Synth. Catal.* **2013**, *355*, 1924 – 1930.

[11] a) M. P. Sibi, J. J. Shay, M. Liu, C. P. Jasperse, *J. Am. Chem. Soc.* **1998**, *120*, 6615 – 6616; b) K. Itoh, S. Kanemasa, *J. Am. Chem. Soc.* **2002**, *124*, 13394 – 13395; c) K. Itoh, S. Kanemasa, *Tetrahedron Lett.* **2003**, *44*, 1799 – 1802; d) K. Itoh, M. Hasegawa, J. Tanaka, S. Kanemasa, *Org. Lett.* **2005**, *7*, 979 – 981; e) K. Ishihara, M. Fushimi, *Org. Lett.* **2006**, *8*, 1921 – 1924; f) M. P. Sibi, K. Itoh, *J. Am. Chem. Soc.* **2007**, *129*, 8064 – 8065; g) A. Sakakura, M. Hori, M. Fushimi, K. Ishihara, *J. Am. Chem. Soc.* **2010**, *132*, 15550 – 15552; h) B. Tan, X. Zeng, W. W. Y. Leong, Z. Shi, C. F. Barbas, III, G. Zhong, *Chem. Eur. J.* **2012**, *18*, 63 – 67; i) X.-Q. Dong, X. Fang, H.-Y. Tao, X. Zhou, C.-J. Wang, *Chem. Commun.* **2012**, *48*, 7238 – 7240; j) X.-Q. Dong, X. Fang, H.-Y. Tao, X. Zhou, C.-J. Wang, *Adv. Synth. Catal.* **2012**, *354*, 1141 – 1147.

[12] M. Hatano, T. Ikeno, T. Miyamoto, K. Ishihara, *J. Am. Chem. Soc.* **2005**, *127*, 10776 – 10777.

[13] For examples, see: a) B. M. Trost, J. Hitce, *J. Am. Chem. Soc.* **2009**, *131*, 4572 – 4573; b) B. M. Trost, V. S. Chan, D. Yamamoto, *J. Am. Chem. Soc.* **2010**, *132*, 5186 – 5192; c) B. M. Trost, K. Hirano, *Angew. Chem. Int. Ed.* **2012**, *51*, 6480 – 6483; d) D. Zhao, L. Wang, D. Yang, Y. Zhang, R. Wang, *Angew. Chem. Int. Ed.* **2012**, *51*, 7523 – 7527; e) B. M. Trost, M. J. Bartlett, *Org. Lett.* **2012**, *14*, 1322 – 1325; f) B. M. Trost, K. Hirano, *Org. Lett.* **2012**, *14*, 2446 – 2449; g) B. M. Trost, D. J. Michaelis, M. I. Truica, *Org. Lett.* **2013**, *15*, 4516 – 4519.

[14] a) H. Uno, J. E. Baldwin, A. T. Russell, *J. Am. Chem. Soc.* **1994**, *116*, 2139 – 2140; b) G. Casiraghi, F. Zanardi, *Chem. Rev.* **2000**, *100*, 1929 – 1972; c) A. Gheorghe, M. Schulte, O. Reiser, *J. Org. Chem.* **2006**, *71*, 2173 – 2176; d) K. C. Nicolaou, S. M. Dalby, U. Majumder, *J. Am. Chem. Soc.* **2008**, *130*, 14942 – 14943; e) G. Casiraghi, F. Zanardi, L. Battistini, G. Rassu, *Synlett* **2009**, *10*, 1525 – 1542.

[15] For examples for azidation, see: a) J. K. Myers, E. N. Jacobsen, *J. Am. Chem. Soc.* **1999**, *121*, 8959 – 8960; b) D. J. Guerin, T. E. Horstmann, S. J. Miller, *Org. Lett.* **1999**, *1*, 1107 – 1109; c) D. J. Guerin, S. J. Miller, *J. Am. Chem. Soc.* **2002**, *124*, 2134 – 2136; d) L.-W. Xu, L. Li, C.-G. Xia, S.-L. Zhou, J.-W. Li, *Tetrahedron Lett.* **2004**, *45*, 1219 – 1221; e) M. S. Taylor, D. N. Zalatan, A. M. Lerchner, E. N. Jacobsen, *J. Am. Chem. Soc.* **2005**, *127*, 1313 – 1317; f) Y. Sawama, Y. Sawara, N. Krause, *Org. Lett.* **2009**, *11*, 5034 – 5037; g) T. Angelini, S. Bonollo, D. Lanari, F. Pizzo, L. Vaccaro, *Org. Lett.* **2012**, *14*, 4610 – 4613.

Received: December 10, 2013
Revised: January 24, 2014
Published online on March 18, 2014