

Enantioselective Prins cyclization: BINOL-derived phosphoric acid and CuCl synergistic catalysis.

Claudia Lalli, Pierre van de Weghe

► **To cite this version:**

Claudia Lalli, Pierre van de Weghe. Enantioselective Prins cyclization: BINOL-derived phosphoric acid and CuCl synergistic catalysis.. Chemical Communications, Royal Society of Chemistry, 2014, 50 (56), pp.7495-8. 10.1039/C4CC02826K . hal-01116325

HAL Id: hal-01116325

<https://hal-univ-rennes1.archives-ouvertes.fr/hal-01116325>

Submitted on 18 Dec 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Enantioselective Prins Cyclization: BINOL-Derived Phosphoric Acid and CuCl Synergistic Catalysis†

Claudia Lalli* and Pierre van de Weghe*

Université de Rennes 1, UMR 6226 CNRS, Institut des Sciences Chimiques de Rennes, Equipe PNSCM, UFR des Sciences Biologiques et Pharmaceutiques, 2 Avenue du Prof. Léon Bernard, 35043 Rennes Cedex, France

The first catalytic enantioselective Prins cyclization is disclosed. The reaction is catalyzed by the combination of a chiral BINOL-derived bis-phosphoric acid and CuCl. The process consists in a tandem Prins/Friedel-Crafts cyclization that affords the hexahydro-1*H*-benzo[*f*]isochromenes products with three new contiguous stereogenic centers in high yields, good enantio- and excellent diastereoselectivities.

The Prins cyclization reaction¹ between a homoallylic alcohol and an aldehyde in the presence of an acidic promoter or catalyst is a powerful C-C bond forming transformation and one of the most elegant approach to access highly substituted tetrahydropyrans with excellent diastereoselectivities.² Despite the recent advances and the increasing interest in the stereochemical outcome and the mechanism of the Prins cyclization,³ to date, to our knowledge, no asymmetric version has been reported.⁴ The main drawback associated with the development of the enantioselective Prins cyclization is the racemization due to the Oxonia Cope rearrangement, the allyl transfer or the solvolysis.⁵ Recently Feng and coworkers succeeded in the synthesis of optically pure 4-OH-tetrahydropyrans by the meaning of a catalytic asymmetric ene reaction followed by a FeCl₃ Prins cyclization.^{3d} However so far direct access to tetrahydropyrans by catalytic enantioselective Prins cyclization has not been achieved and it is therefore highly required.

Since the seminal independent reports of Akiyama⁶ and Terada,⁷ the ability of BINOL-derived chiral phosphoric acids to direct the enantioselective addition to imines is well established.⁸ Nevertheless the enantioselective addition to oxocarbenium ion is much less developed.⁹ We recently reported the unprecedented synergistic effect in Prins cyclization between non-reactive Brønsted and Lewis acids that lack to catalyze the reaction if used alone, such as *p*-TSA and MgBr₂.¹⁰ Inspired by the successful examples on the enantioselective addition to oxocarbenium ions and in continuation of our interest in the Prins cyclization reaction,¹¹ we reasoned that the combination of the chiral Brønsted acid with an achiral Lewis acid¹² could promote the reaction and we envisioned that chiral phosphoric acids could activate the oxonium ion intermediate and ensure the enantioselectivity.

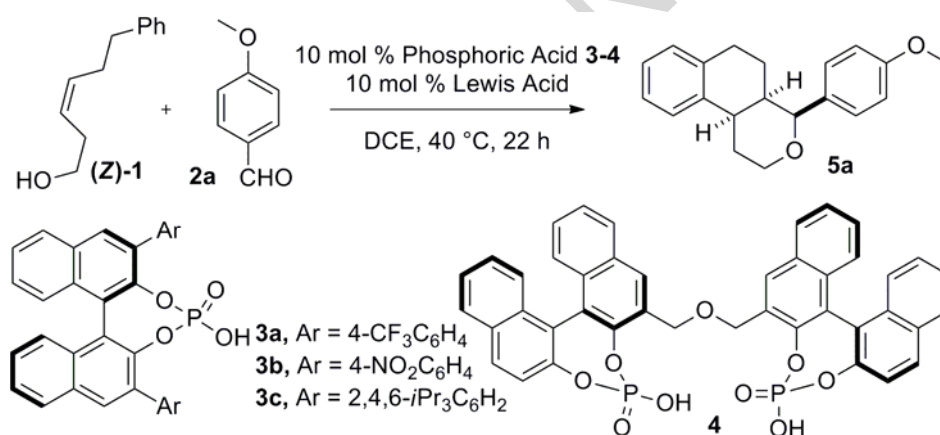
Herein we report our preliminary results for the first catalytic enantioselective Prins cyclization.

We chose as model substrates homoallylic alcohols such as 6-phenylhex-3-en-1-ol **1** containing a tethered nucleophile.¹³ The advantage in using those kind of substrates consists in a simplified reaction system to study. Indeed, most of the Prins cyclization reactions are promoted by stoichiometric amounts of Lewis acid that play a double role, promoter and nucleophile source to trap the carbocation species which is formed after the cyclization. The embedded phenyl moiety prevents the use of a stoichiometric external nucleophile which can interfere with the catalytic system, and moreover allows a tandem Prins/Friedel-Crafts process to take place.^{13e}

We began our studies by investigating the reaction between (*Z*)-6-phenylhex-3-en-1-ol (*Z*)-1 and *p*-methoxybenzaldehyde 2a in DCE (1,2-dichloroethane) at 40 °C, leading to the hexahydro-1*H*-benzo[*f*]isochromenes product 5a with three new contiguous stereogenic centers.

A screening of known chiral phosphoric acids 3-4 (Table 1, entries 1-4) gave only disappointing results summarized in a lack of reactivity. We hypothesized that the Brønsted acid alone is not prone to activate the electrophilic carbonyl group. We reasoned that a catalytic system integrating a phosphoric acid and a metal catalyst should synergistically enable our reaction. To confirm our hypothesis we first examined the combination of phosphoric acids 3 with different achiral Lewis acids. As shown in Table 1, MgBr₂ is completely inactive (entry 5), on the contrary first row transition metal salts such as Cu(OTf)₂ and FeCl₃ (entries 6-9) could catalyze the reaction with up to 45% yield, unfortunately without any enantioselection. The association between the bis-phosphoric acid¹⁴ 4 and FeCl₃ (entry 10) also failed to selectively promote the reaction. To our delight the combination of 4 and Cu(OTf)₂ (entry 11) afforded the desired product 5a with an exciting 80:20 enantiomeric ratio (e.r.) and as single diastereomer (d.r. > 95:5), the *cis*-fused hexahydro-1*H*-benzo[*f*]isochromene dictated by the *Z* geometry of the double bond, even if in moderated yields (24%). Different trifluoromethanesulfonates such as Zn(OTf)₂, Ni(OTf)₂, Bi(OTf)₃, AgOTf or LiOTf failed to give better results, on the contrary the variation of the copper source (CuCl₂ and CuCl entries 12-13 respectively) improved the yield up to 70% (see Supporting Information). Finally the effect of the alkene geometry was evaluated and it was observed that changing the double bond to *E* resulted in a dramatic loss in reactivity and selectivity (entry 14), thus the *trans*-fused hexahydro-1*H*-benzo[*f*]isochromene was obtained with only 29% yield and 67:33 e.r.. An exploration of different reaction conditions was set out to optimize the selectivity. A solvent screening revealed chlorinated solvents to be superior (see Supporting Information), in particular DCE gave slightly better yields and enantiomeric ratios than CH₂Cl₂. Decreasing the temperature was detrimental for the reactivity. The increase of the phosphoric acid loading to 20 mol % did not benefit to the enantioselectivity.

Table 1 Catalysts identification and reaction optimization of the Enantioselective Prins Cyclization.^a

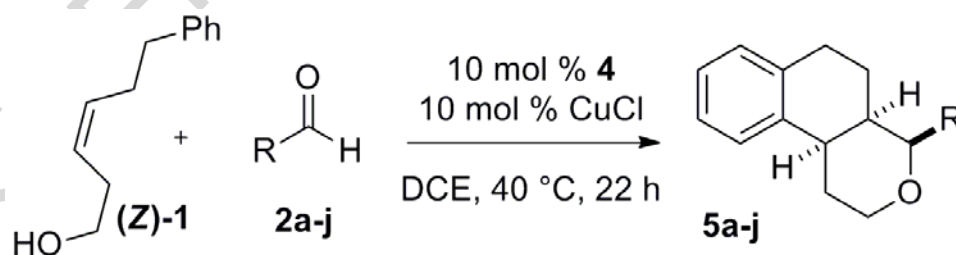


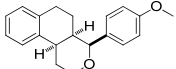
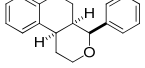
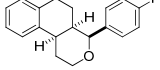
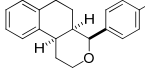
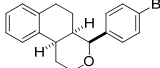
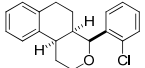
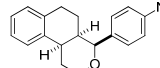
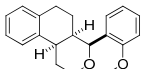
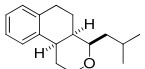
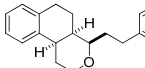
Entry	catalyst	Lewis Acid	yield 5a (%) ^{[b],[c]}	e.r. 5a ^{[d],[e]}
1	3a	-	n.r.	-
2	3b	-	n.r.	-
3	3c	-	n.r.	-
4	4	-	n.r.	-
5	3a	MgBr ₂	n.r.	-
6	3a	Cu(OTf) ₂	20	53:47
7	3b	FeCl ₃	45	50:50
8	3b	Cu(OTf) ₂	28	50:50
9	3c	Cu(OTf) ₂	34	50:50
10	4	FeCl ₃	52	50:50
11	4	Cu(OTf) ₂	24	80:20
12	4	CuCl ₂	65	79:21
13	4	CuCl	70	80:20
14	4 ^[f]	CuCl	29	67:33

[a] General conditions: (**Z**)-**1** (0.1 mmol), **2a** (0.12 mmol), **3-4** (10 mol%), Lewis Acid (10 mol%) in DCE (*c* = 0.1 M) at 40 °C for 22 h. [b] Yields refer to isolated products. [c] n.r. = no reaction. [d] Enantiomeric ratio was determined by chiral HPLC analysis. [e] d.r. > 95:5. [f] The (**E**)-**1** isomer was used.

Encouraged by the promising level of enantiocontrol, our catalytic system was tested on different substituted aromatic aldehydes (Table 2, entries 1-8). Gratifyingly benzaldehyde **2b** (entry 2) smoothly participated to the reaction leading to the desired product **5b** with 73% yield, 80:20 e.r. and as a single diastereomer. The substitution of the aromatic ring in the *ortho* or *para* position with halogens (entries 3-6) is tolerated as in all the cases enantioenriched hexahydro-1*H*-benzo[*f*]isochromenes were obtained with the same range of yields and e.r. values. The *p*-NO₂ benzaldehyde also participated with a slight erosion of enantioselectivity (entry 7). The catalytic system proved to be efficient for aromatic aldehydes substituted with an electron donating group in the *para* position (entry 1) but it is less selective for the *o*-MeO substitution probably because of the steric hindrance (entry 8). Aliphatic aldehydes undergo Prins cyclization with high yields, excellent diastereoselectivities but moderate enantiocontrol (entries 9-10).

Table 2 Scope of the Enantioselective Prins Cyclization.^a



Entry	Product 5	yield (%) ^[b]	e.r. ^{[c],[d]}
1	 5a	70	80:20
2	 5b	73	80:20
3	 5c	78	77:23
4	 5d	76	76:24
5	 5e	62	80:20
6	 5f	62	72:28
7	 5g	63	67:33
8	 5h	76	60:40
9	 5i	63	65:35
10	 5j	72	60:40

[a] General conditions: (Z)-1 (0.1 mmol), 2 (0.12 mmol), 4 (10 mol%), CuCl (10mol %) in DCE (*c* = 0.1 M) at 40 °C for 22 h. [b] Yields refer to isolated products. [c] Enantiomeric ratio was determined by chiral HPLC analysis. [d] d.r. > 95:5.

The absolute configuration of **5e** was unambiguously determined to be 4*S*,4*aR*,10*bR* by single crystal X-ray analysis¹⁵ (Figure 1). The three new contiguous stereogenic centers formed are issue of an attack of the alkene on the *Si* face of the oxocarbenium ion, followed by a completely diastereoselective Friedel-Crafts reaction.

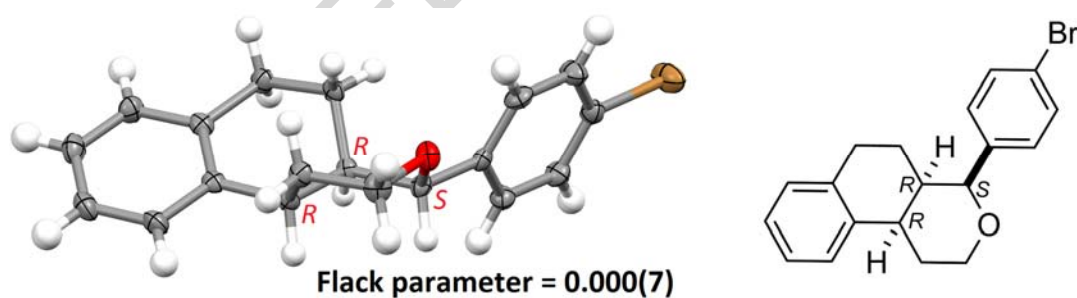


Fig. 1 ORTEP representation of the hexahydro-1*H*-benzo[*f*]isochromene product **5e**. The thermal ellipsoids are shown at 50% probability.

In conclusion, we have disclosed the first enantioselective Prins cyclization catalyzed by a synergistic combination of chiral BINOL-derived bis-phosphoric acid and CuCl under mild conditions. The present method demonstrates the feasibility of the asymmetric condensation between a homoallylic alcohol and an aldehyde and provides an efficient route to enantiomerically enriched tetrahydropyrans containing three contiguous stereogenic centers. Further research on the substrate scope and investigations to gain insight on the reaction mechanism are underway and will be reported in due course.

We thank Université de Rennes 1, CNRS, Rennes Métropole and Région Bretagne for financial support. Thierry Roisnel and the Centre de Diffractométrie X (CDIFX) de l'Institut des Sciences Chimiques de Rennes are gratefully acknowledged for crystallographic analysis and the CRMPO for mass measurement. Part of this work has been performed using the PRISM core facility (Biogenouest©, UMS Biosit, Université de Rennes 1- Campus de Villejean- 35043 RENNES Cedex, FRANCE).

Notes and references

Université de Rennes 1, UMR 6226 CNRS, Institut des Sciences Chimiques de Rennes, Equipe PNSCM, UFR des Sciences Biologiques et Pharmaceutiques, 2 Avenue du Prof. Léon Bernard, 35043 Rennes Cedex, France. E-mail: claudia.lalli@univ-rennes1.fr and pierre.van-de-weghe@univ-rennes1.fr

† Electronic Supplementary Information (ESI) available. For ESI and crystallographic data in CIF see DOI: 10.1039/c000000x/

- 1 For reviews on the Prins cyclization reaction see: (a) E. Arundale and L. A. Mikeska, *Chem. Rev.*, 1952, **52**, 505-555; (b) D. R. Adams and S. P. Bhatnagar, *Synthesis*, 1977, 661-672; (c) B. B. Snider In *The Prins Reaction and Carbonyl Ene Reactions*, Vol. 2; B. M. Trost, I. Fleming, C. H. Heathcock, Eds.; Pergamon Press: New York, 1991, 527-561; (d) L. E. Overman and L. D. Pennington, *J. Org. Chem.*, 2003, **68**, 7143-7157; (e) P. A. Clarke and S. Santos, *Eur. J. Org. Chem.*, 2006, 2045-2053; (f) I. M. Pastor and M. Yus, *Curr. Org. Chem.*, 2007, **11**, 925-957; (g) C. Olier, M. Kaafarani, S. Gastaldi and M. P. Bertrand, *Tetrahedron*, 2010, **66**, 413-445; (h) I. M. Pastor and M. Yus, *Curr. Org. Chem.*, 2012, **16**, 1277-1312; (i) X. Han, G.-R. Peh and P. E. Floreancig, *Eur. J. Org. Chem.*, 2013, 1193-1208.
- 2 (a) C. St. J. Barry, S. R. Crosby, J. R. Harding, R. A. Hughes, C. D. King, G. D. Parker and C. L. Willis, *Org. Lett.*, 2003, **5**, 2429-2432; (b) V. K. Yadav and N. V. Kumar, *J. Am. Chem. Soc.*, 2004, **126**, 8652-8653; (c) R. Jasti, J. Vitale and S. D. Rychnovsky, *J. Am. Chem. Soc.*, 2004, **126**, 9904-9905; (d) O. L. Epstein and T. Rovis, *J. Am. Chem. Soc.*, 2006, **128**, 16480-16481; (e) P. O. Miranda, M. A. Ramirez, V. S. Martin and J. I. Padrón, *Org. Lett.*, 2006, **8**, 1633-1636; (f) R. B. Miles, C. E. Davis and R. M. Caotes, *J. Org. Chem.*, 2006, **71**, 1493-1501; (g) L. E. Overman and E. J. Velthuisen, *J. Org. Chem.*, 2006, **71**, 1581-1587; (h) A. Puglisi, A.-L. Lee, R. R. Schrock and A. H. Hoveyda, *Org. Lett.*, 2006, **8**, 1871-1874; (i) K.-P. Chan, A.-H. Seow and T.-P. Loh, *Tetrahedron Lett.*, 2007, **48**, 37-41; (j) U. Biermann, A. Lützen and J. O. Metzger, *Eur. J. Org. Chem.*, 2006, 2631-2637; (k) J. S. Yadav, B. V. Subba Reddy, T. Maity and G. G. K. S. Narayana Kumarn, *Tetrahedron Lett.*, 2007, 7155-7159; (l) J. S. Yadav, B. V. Subba Reddy, G. G. K. S. Narayana Kumarn and S. Aravind, *Synthesis*, 2008, 395-400; (m) U. C. Reddy, S. Bondalapati and A. K. Saika, *J. Org. Chem.*, 2009, **74**, 2605-2608; (n) A. K. Ghosh and D. R. Nicponski, *Org. Lett.*, 2011, **13**, 4328-4331; (o) B. B. Parida, I. L. Lysenko and J. K. Cha, *Org. Lett.*, 2012, **14**, 6258-6261; (p) K. Indukuri, S. Bondalapati, T. Kotipalli, P. Gogoi and A. K. Saika, *Synlett*, 2012, **23**, 233-238; (q) Q. Dai, N. K. Rana and J. C.-G. Zhao, *Org. Lett.*, 2013, **15**, 2922-2925; (r) S. Sultana, K. Indukuri, M. J. Deka and A. K. Saika, *J. Org. Chem.*, 2013, **78**, 12182-12188; (s) Y. Xie and P. E. Floreancig, *Angew. Chem., Int. Ed.*, DOI: 10.1002/anie.201402010.
- 3 (a) R. W. Alder, J. N. Harvey and M. T. Oakley, *J. Am. Chem. Soc.*, 2002, **124**, 4960-4961; (b) C. St. J. Barry, N. Bushby, J. R. Harding, R. A. Hughes, G. D. Parker, R. Roe and C. L. Willis, *Chem. Commun.*, 2005, 3727-3729; (c) R. Jasti, C. D. Anderson and S. D. Rychnovsky, *J. Am. Chem. Soc.*, 2005, **127**, 9939-9945; (d) K. Zheng, X. Liu, S. Qin, M. Xie, L. Lin, C. Hu and X. Feng, *J. Am. Chem. Soc.*, 2012, **134**, 17564-17573; For recent examples of enantioselective formation of tetrahydropyrans via Brønsted acid oxacarbenium ion activation see: (e) V. M. Lombardo, C. D. Thomas and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2013, **52**, 12910-12914; (f) E. Ascic, R. G. Ohm, R. Petersen, M. R. Hansen, C. L. Hansen, D. Madsen, D. Tanner and T. E. Nielsen, *Chem.-Eur. J.*, 2014, **20**, 3297-3300.
- 4 For a seminal example of the enantioselective nucleophilic addition of an alkene to an aldehyde see: C. A. Mullen and M. R. Gagné, *Org. Lett.*, 2006, **8**, 665-668.
- 5 (a) S. D. Rychnovsky, S. Marumoto and J. J. Jaber, *Org. Lett.*, 2001, **3**, 3815-3818; (b) S. R. Crosby, J. R. Harding, C. D. King, G. D. Parker and C. L. Willis, *Org. Lett.*, 2002, **4**, 577-580; (c) S. R. Crosby, J. R. Harding, C. D. King, G. D. Parker and C. L. Willis, *Org. Lett.*, 2002, **4**, 3407-3410; (d) S. Marumoto, J. J. Jaber, J. P. Vitale and S. D. Rychnovsky, *Org. Lett.*, 2002, **4**, 3919-3922; (e) R. Jasti and S. D. Rychnovsky, *J. Am. Chem. Soc.*, 2006, **128**, 13640-13648.
- 6 T. Akiyama, J. Itoh, K. Yokota and K. Fuchibe, *Angew. Chem. Int. Ed.*, 2004, **43**, 1566-1568.
- 7 D. Uraguchi and M. Terada, *J. Am. Chem. Soc.*, 2004, **126**, 5356-5357.
- 8 For recent reviews on Brønsted acid catalysis: (a) T. Akiyama, J. Itoh and K. Fuchibe, *Adv. Synth. Catal.*, 2006, **348**, 999-1010; (b) T. Akiyama, *Chem. Rev.*, 2007, **107**, 5744-5758; (c) M. Terada, *Chem. Commun.*, 2008, 4097-4112; (d) H. Yamamoto and N. Payette, in *Hydrogen Bonding in Organic Synthesis*, ed. P. M. Pihko, Wiley-VCH, Weinheim 2009, 73-140; (e) D. Kampen, C. M. Reisinger and B. List, *Top. Curr. Chem.*, 2010, **291**, 395-456; (f) M. Terada,

- Synthesis*, 2010, 1929-1982; (g) M. Terada, *Bull. Chem. Soc. Jpn.*, 2010, **83**, 101-119 (h) A. Zamfir, S. Schenker, M. Freud, S. B. Tsogoeva, *Org. Biomol. Chem.*, 2010, **8**, 5262-5276; (i) M. Terada, *Curr. Org. Chem.*, 2011, **15**, 2227-2256; (j) S. Schenker, A. Zamfir, M. Freud and S. B. Tsogoeva, *Eur. J. Org. Chem.*, 2011, 2209-2222; (k) M. Rueping, A. Kuenkel and I. Atodiresei, *Chem. Soc. Rev.*, 2011, **40**, 4539-4549.
- 9 (a) S. E. Reisman, A. G. Doyle and E. N. Jacobsen, *J. Am. Chem. Soc.*, 2008, **130**, 7198-7199; (b) M. Terada, H. Tanaka and K. Sorimachi, *J. Am. Chem. Soc.*, 2009, **131**, 3430-3431; (c) Q.-W. Zhang, C.-A. Fan, H.-J. Zhang, Y.-Q. Tu, Y.-M. Zhao, P. Gu and Z.-M. Chen, *Angew. Chem., Int. Ed.*, 2009, **48**, 8572-8574; (d) I. Čorić, S. Vellalath and B. List, *J. Am. Chem. Soc.*, 2010, **132**, 8536-8537; (e) I. Čorić, S. Müller and B. List, *J. Am. Chem. Soc.*, 2010, **132**, 17370-17373; (f) I. Čorić and B. List, *Nature*, 2012, **483**, 315-319; (g) Z. Sun, G. A. Winschel, A. Borovika and P. Nagorny, *J. Am. Chem. Soc.*, 2012, **134**, 8074-8077; (h) M. Rueping, C. M. R. Volla and I. Atodiresei, *Org. Lett.*, 2012, **14**, 4642-4645; (i) J. H. Kim, I. Čorić, S. Vellalath and B. List, *Angew. Chem., Int. Ed.*, 2013, **52**, 4474-4477; (j) C. Lu, X. Su and P. E. Floreancig, *J. Org. Chem.*, 2013, **78**, 9366-9376; (k) C.-C Hsiao, H.-H. Liao, E. Sugiono, I. Atodiresei and M. Rueping, *Chem.-Eur. J.*, 2013, **19**, 9775-9779.
- 10 (a) P. Bokar, P. van de Weghe, B. V. Subba Reddy, J. S. Yadav and R. Grée, *Chem. Commun.*, 2012, **48**, 9316-9318; It has been recently demonstrated that the synergy between a Brønsted and a Lewis acid results in an enhancement of the Brønsted acidity, see: (b) M. Breugst, R. Grée and K. N. Houk, *J. Org. Chem.*, 2013, **78**, 9892-9897.
- 11 M. Jacolot, M. Jean, N. Levoine and P. van de Weghe, *Org. Lett.*, 2012, **14**, 58-61.
- 12 For reviews combining organocatalysis and transition metals see: (a) Y. J. Park, J.-W. Park and C.-H. Jun, *Acc. Chem. Res.*, 2008, **41**, 222-234; (b) Z. Shao and H. Zhang, *Chem. Soc. Rev.*, 2009, **38**, 2745-2755; (c) C. Zhong and X. Shi, *Eur. J. Org. Chem.*, 2010, 2999-3025; (d) J. Zhou, *Chem. Asian J.*, 2010, **5**, 422-434; (e) L. Stegbauer, F. Sladojevich and D. J. Dixon, *Chem. Sci.*, 2012, **3**, 942-958; (f) Z. Du and Z. Shao, *Chem. Soc. Rev.*, 2013, **42**, 1337-1378; for reviews combining organocatalysis and alkaline earth metals see: (g) S. Kobayashi and Y. Yamashita, *Acc. Chem. Res.*, 2011, **44**, 58-71; (h) Y. Yamashita, T. Tsubogo and S. Kobayashi, *Chem. Sci.*, 2012, **3**, 967-975; for selected recent examples of chiral alkaline earth metal phosphates see: (i) M. Hatano, K. Moriyama, T. Maki and K. Ishihara *Angew. Chem., Int. Ed.*, 2010, **49**, 3823-3826; (j) J. Lv, X. Li, L. Zhong, S. Luo and J.-P. Cheng, *Org. Lett.*, 2010, **12**, 1096-1099; (k) Z. Zhang, W. Zheng and J. C. Antilla, *Angew. Chem., Int. Ed.*, 2011, **50**, 1135-1138; (l) W. Zheng, Z. Zhang, M. J. Kaplan and J. C. Antilla, *J. Am. Chem. Soc.*, 2011, **133**, 3339-3341; (m) G. K. Ingle, Y. Liang, M. G. Mormino, G. Li, F. R. Fronczek and J. C. Antilla, *Org. Lett.*, 2011, **13**, 2054-2057; (n) S. E. Larson, G. Li, G. B. Rowland, D. Junge, R. Huang, H. R. Woodcock and J. C. Antilla, *Org. Lett.*, 2011, **13**, 2188-2191; (o) F. Drouet, C. Lalli, H. Liu, G. Masson and J. Zhu, *Org. Lett.*, 2011, **13**, 94-97; (p) A. Alix, C. Lalli, P. Retailleau and G. Masson, *J. Am. Chem. Soc.*, 2012, **134**, 10389-10392; (q) M. Rueping, T. Bootwicha, S. Kambutong and E. Sugiono, *Chem. Asian J.*, 2012, **7**, 1195-1198; (r) G. Li, T. Liang, L. Woitas and J. C. Antilla, *Angew. Chem., Int. Ed.*, 2013, **52**, 4628-4632; for a review on organophosphate metal salts: (s) A. Parra, S. Reboredo, A. M. Martín Castro and J. Alemán, *Org. Biomol. Chem.*, 2012, **10**, 5001-5020; for a review combining phosphoric acids and Lewis acids see: (t) J. Lv and S. Luo, *Chem. Commun.*, 2013, **49**, 847-858.
- 13 (a) Y. S. Cho, H. Y. Kim, J. H. Cha, A. N. Pae, N. Y. Koh, Y. H. Choi and M. H. Chang, *Org. Lett.*, 2002, **4**, 2025-2028; (b) J. D. Elsworth and C. L. Willis, *Chem. Commun.*, 2008, 1587-1589; (c) J. S. Yadav, P. P. Chakravarthy, P. Borkar, B. V. Subba Reddy and A. V. S. Sarma, *Tetrahedron Lett.*, 2009, **50**, 5998-6000; (d) J. S. Yadav, P. Borkar, P. P. Chakravarthy, B. V. Subba Reddy, A. V. S. Sarma, S. J. Basha, B. Sridhar and R. Grée, *J. Org. Chem.*, 2010, **75**, 2081-2084; (e) B. V. Subba Reddy, P. Borkar, J. S. Yadav, B. Sridhar and R. Grée, *J. Org. Chem.*, 2011, **76**, 7677-7690; (f) B. V. Subba Reddy, P. Borkar, J. S. Yadav, P. P. Reddy, A. C. Kunwar, B. Sridhar and R. Grée, *Org. Biomol. Chem.*, 2012, **10**, 1349-1358; (g) B. V. Subba Reddy, S. Jalal, P. Borkar, J. S. Yadav, P. P. Reddy, A. C. Kunwar and B. Sridhar, *Org. Biomol. Chem.*, 2012, **10**, 6562-6568; (h) B. V. Subba Reddy, A. Venkateswarlu, P. Borkar, J. S. Yadav, M. Kanakaraju, A. C. Kunwar and B. Sridhar, *J. Org. Chem.*, 2013, **78**, 6303-6308; (i) B. V. Subba Reddy, D. Medaboina, B. Sridhar and K. K. Singarapu, *J. Org. Chem.*, 2013, **78**, 8161-8168.
- 14 (a) X.-H. Chen, W.-Q. Zhang and L.-Z. Gong, *J. Am. Chem. Soc.*, 2008, **130**, 5652-5653; (b) J. Yu, L. He, X.-H. Chen, J. Song, W.-J. Chen and L.-Z. Gong, *Org. Lett.*, 2009, **11**, 4946-4949; (c) J. Yu, W.-J. Chen and L.-Z. Gong, *Org. Lett.*, 2010, **12**, 4050-4053; (d) L. He, X.-H. Chen, D.-N. Wang, S.-W. Luo, W.-Q. Zhang, J. Yu, R. Lei and L.-Z. Gong, *J. Am. Chem. Soc.*, 2011, **133**, 13504-13518; (e) N. Momiyama, T. Konno, Y. Furiya, T. Iawamoto and M. Terada, *J. Am. Chem. Soc.*, 2011, **133**, 19294-19297; (f) J. Yu, F. Shi and L.-Z. Gong, *Acc. Chem. Res.*, 2011, **44**, 1156-1171; (g) L. Hong, M. Kai, C. Wu, W. Sun, G. Zhu, G. Li, X. Yao and R. Wang, *Chem. Commun.*, 2013, **49**, 6713-6715.
- 15 See Supporting Information.