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# Catalytic Asymmetric Piancatelli Rearrangement: Brønsted Acid Catalyzed 4π Electrocyclization for the Synthesis of Multisubstituted Cyclopentenones

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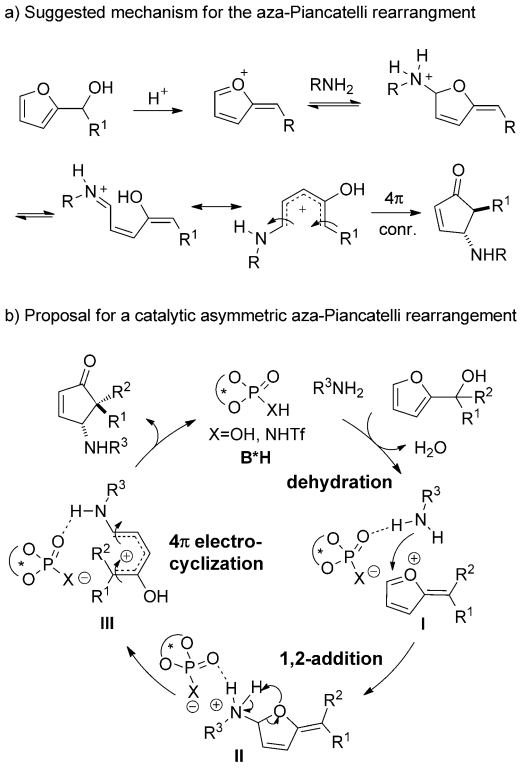
***Abstract:*** *The first catalytic asymmetric Piancatelli reaction is reported. Catalyzed by a chiral Brønsted acid, the rearrangement of a wide range of furylcarbinols with a series of aniline derivatives provides valuable aminocyclopentenones in high yields as well as excellent enantioselectivities and diastereoselectivities. The high value of the aza-Piancatelli rearrangement was demonstrated by the synthesis of a cyclopentane-based hNK1 antagonist analogue.*

The Piancatelli reaction,[1] an acid-catalyzed rearrangement of 2-furylcarbinols to cyclopentenone derivatives, was first reported in 1976 and has been widely applied to the synthesis of many natural products and biologically active molecules, including prostaglandins and phytoprostanes.[2,3] The transformation is believed to proceed through acid-promoted protonation–dehydration of the 2-furylcarbinol to form a highly reactive oxocarbenium ion intermediate, which, upon water attack and ring opening, generates a pentadienyl carbocation. Subsequent 4π-electrocyclic ring closure affords a *trans*-substituted 4-hydroxy-5-aryl(alkyl)-cyclopentenone.[4] The use of amines instead of water as the nucleophile is known as the aza-Piancatelli reaction (Scheme 1a), which is typically catalyzed by Brønsted or Lewis acid catalysts.[5] The resulting 4-aminocyclopentenone scaffolds are potential precursors not only for aminocyclopentitol frameworks, which are present in a variety of bioactive molecules as represented by peramivir or trehazolin,[6] but also for the synthesis of pharmacologically valuable compounds such as hNK1 antagonist analogues.[7]

However, despite its synthetic utility and its discovery over 40 years ago, to date, no catalytic asymmetric approach has been reported for the Piancatelli reaction. The rearrangement still constitutes a major challenge for the following reasons: The chiral catalyst must 1) be acidic enough to facilitate the dehydration reaction to generate the oxocarbenium intermediate, 2) be able to control the regioselectivity of the nucleophilic attack towards the 1,2-addition, and 3) act as an enantioselectivity-inducing element in the key 4π electrocyclization step. When amines are used as nucleophiles, the addition to the 5′-position of the oxocarbenium is in competition with a rearrangement pathway (see the Supporting Information, Scheme S3a–c),[5a,8] which renders the development of a regio- and enantioselective reaction more difficult. Furthermore, the rearrangement is often restricted to secondary furylcarbinols as tertiary furylcarbinols bearing an alkyl substituent tend to undergo dehydration to give stable alkene side products, which severely decreases the yield of the rearrangement product (Scheme S3b).[5e,9] Given the challenges of the aza-Piancatelli rearrangement and the high value of the multisubstituted cyclopentenone products, the development of a catalytic enantioselective version of this important reaction would be highly desirable.




***Scheme 1.*** Asymmetric aza-Piancatelli rearrangement.

Herein, we report the development of the first catalytic asymmetric Piancatelli reaction employing chiral Brønsted acid catalysis. Our strategy is outlined in Scheme 1b. We envisioned that chiral Brønsted acids,[10] especially the more acidic *N*-triflylphosphoramides, NTPAs[11] (X = NHTf),

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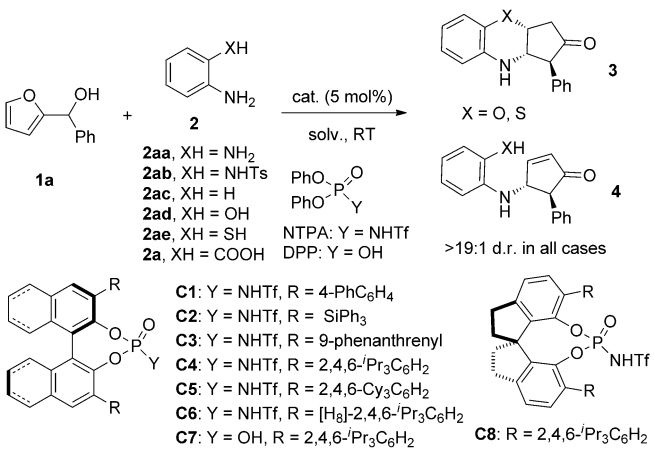
would enable the dehydration of the furylcarbinol,[12] generating the chiral anion stabilized oxocarbenium intermediate **I**. Subsequent nucleophilic attack by the amine would provide hemiaminal **II**, which yields pentadienyl carbocation **III** upon ring opening. The ensuing chiral anion controlled enantioselective 4π electrocyclic ring closure provides the desired optically active 4-aminocyclopentenones. Based on our previous work on asymmetric Brønsted acid catalysis involving oxonium ions, we realized that the choice of the nucleophile, as well as the catalyst framework (3,3 substitution pattern of the BINOL skeleton) and acidity, would be critical for the successful realization of the first asymmetric aza-Piancatelli rearrangement.

With these considerations in mind, we began our investigation of the Brønsted acid catalyzed Piancatelli reaction by evaluating various amine nucleophiles as well as catalysts with different acidities. Initial experiments showed that the combination of a more acidic triflylphosphoramide with anilines resulted in a less acidic salt that suppressed both the decomposition of the highly reactive oxonium intermediate as well as the direct dehydration of alkyl-substituted tertiary furylcarbinols to the corresponding alkenes.

Thus we studied the *N*-triflyldiphenylphosphoramide (NTPA) catalyzed aza-Piancatelli rearrangement of furan-2-yl(phenyl)methanol (**1a**) with a series of aniline derivatives (Scheme 2 and Table S1). Whereas the use of *ortho*-hydroxy- and *ortho*-mercaptoanilines resulted in the corresponding



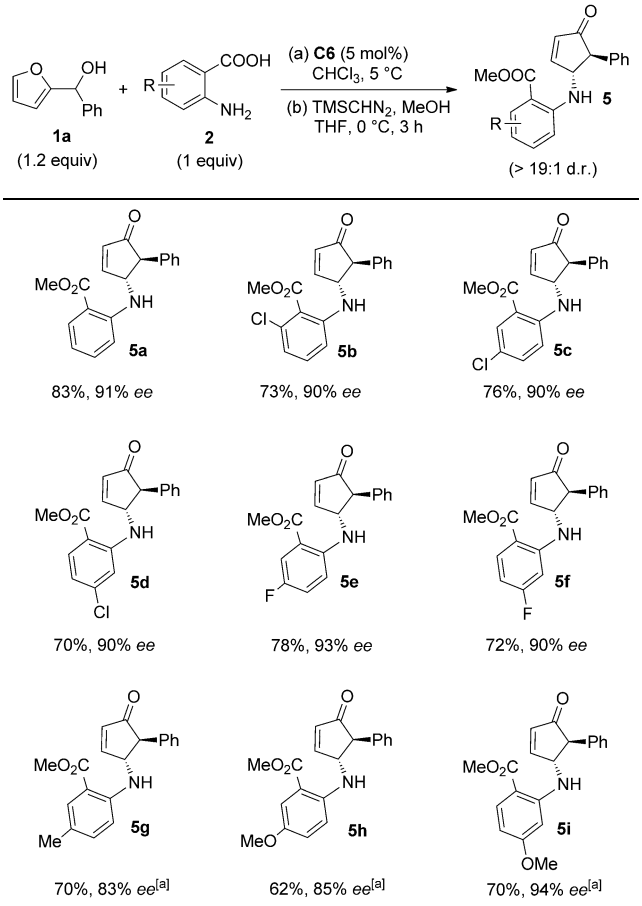

***Scheme 2.*** Optimization of the reaction conditions.

addition product **3a**, the use of *ortho*-aminobenzoic acid **2a** provided the desired rearrangement product **4a** in quantitative yield with excellent diastereoselectivity (>19:1 d.r.). Encouraged by these results, a variety of chiral NTPAs were surveyed. Gratifyingly, the sterically congested 3,3′-bis(2,4,6-$^{i}Pr_3C_6H_2$)-substituted NTPA **C4** and [$H_8$]-NTPA **C6** gave promising results in terms of reactivity and selectivity, affording the desired product **4a** in nearly quantitative yield with 75% *ee* and >19:1 d.r. (Table S1, entries 8 and 10). Use of the corresponding phosphoric acid **C7** as the catalyst delivered **4a** in 91% yield. However, this reaction required a prolonged reaction time and suffered from low enantioselectivity (opposite enantiomer, 30% *ee*; entry 11). Further reaction optimization with regard to the use of different solvents, concentrations, and temperatures led to further improvement and revealed that the product could be isolated in good yields and with high enantioselectivity provided that the reaction was conducted in chloroform at 5°C (96% yield, 91% *ee*, >19:1 d.r.; entry 17).

We first explored the generality of this reaction with respect to *ortho*-aminobenzoic acids. To simplify the purification process and HPLC analysis to determine the *ee*, all acid products **4** were transformed into the corresponding methyl esters **5** without loss of enantioselectivity using (trimethylsilyl)diazomethane as the reagent.[13] As shown in Table 1, the reaction of furylcarbinol **1a** with a variety of *ortho*-aminobenzoic acids, including those that bear electron-withdrawing or -donating substituents at various positions on the aryl ring, proceeded smoothly, affording the corresponding rearrangement products **5a**–**5i** in moderate to good yields with high levels of enantio- and diastereoselectivity (62–83%, 83–94% *ee*, >19:1 d.r.).

To further expand the substrate scope, we investigated the generality of this rearrangement with various anilines as well as carbinols (Table 2). In general, the rearrangements proceeded well, and the Brønsted acid rendered the asymmetric

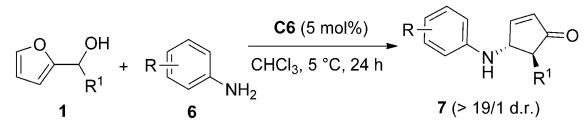
***Table 1:*** Catalytic asymmetric aza-Piancatelli rearrangement of secondary furylcarbinols with α-aminobenzoic acids.

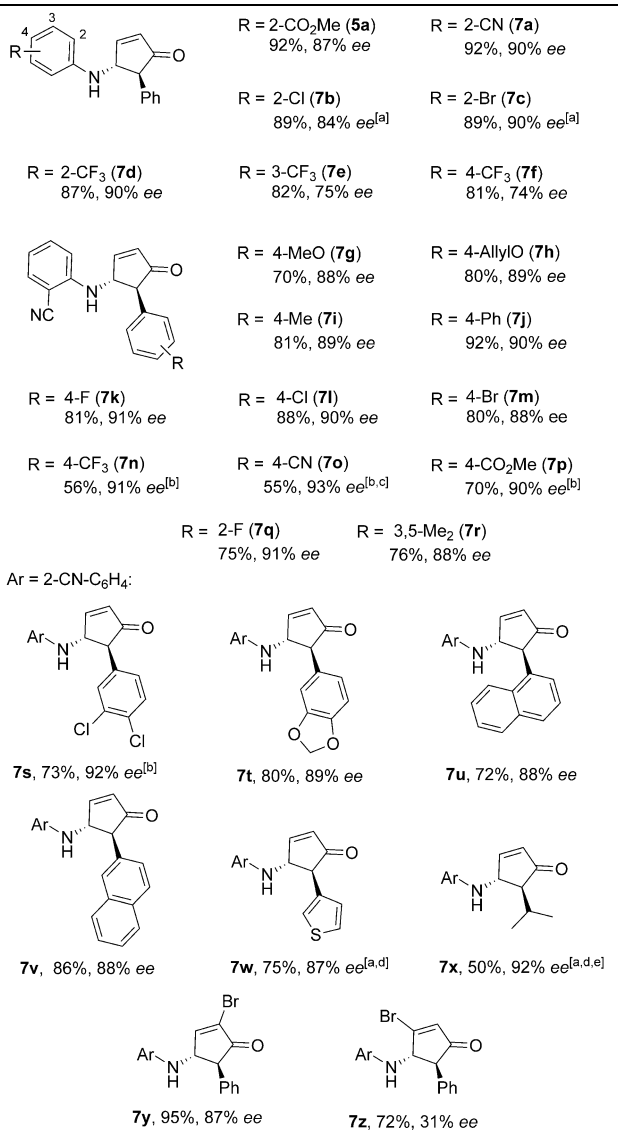



[a] The reaction in step (a) was conducted at room temperature.

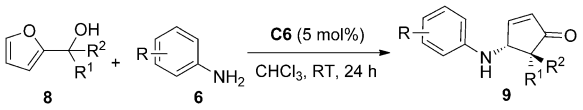
***Table 2:*** Catalytic asymmetric aza-Piancatelli rearrangement of secondary furylcarbinols with anilines.

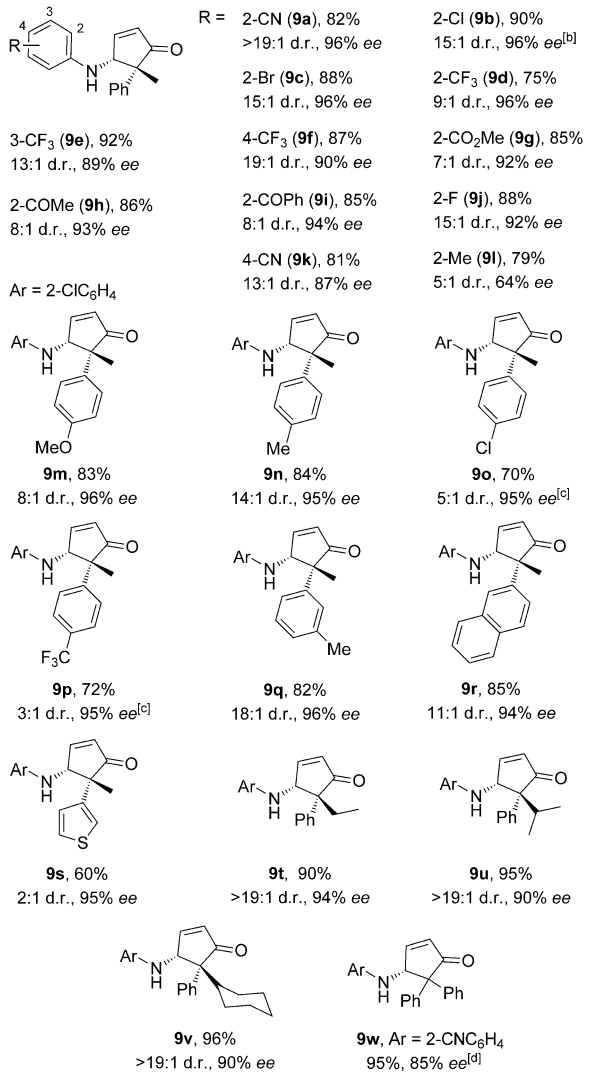



[a] At RT. [b] At 15 °C. [c] 13:1 d.r. [d] **1** (2 equiv). [e] 48 h.

***Table 3:*** Catalytic asymmetric aza-Piancatelli rearrangement of tertiary furylcarbinols with anilines.[a]




[a] Isolated yield of the major *cis* product. [b] The absolute configuration of **9b** was determined by X-ray crystallography as shown, and the configurations of all other products were assigned by analogy. [c] 36 h. [d] **8** (1.2 equiv), 5 °C.

4π electrocyclization[14] highly enantioselective, providing the 2,3-substituted cyclopentenones **7a**–**7z**. First attempts to vary the furan moiety in the 4-position did not result in the desired rearrangement product.[15]

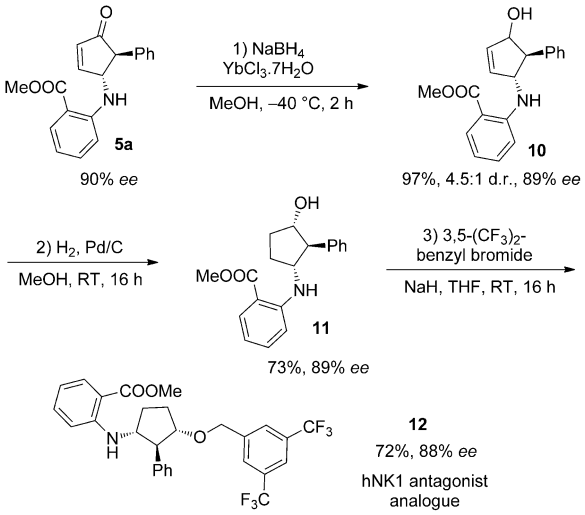
Additionally, we evaluated the generality of our aza-Piancatelli rearrangement with regard to tertiary furylcarbinols, which provide cyclopentenones with two consecutive stereocenters, one of which being quaternary. Again, various carbinols **8** as well as anilines **6** could be applied as substrates, and the desired β-amino-α,α-substituted cyclopentenones **9a**–**9w** were obtained in good yields and excellent enantioselectivities (Table 3). It is particularly noteworthy that under the rather mild reaction conditions, different alkyl-substituted tertiary furylcarbinols were tolerated. Compared to the rearrangement of secondary furylcarbinols (Table 2), the use of tertiary furylcarbinols generally delivered the corresponding products with higher enantioselectivities (Table 3).

To highlight the synthetic utility of this approach, we showed that the reactions of both secondary furylcarbinol **1a** and tertiary furylcarbinol **8a** with aniline derivatives can be scaled up to gram scale or preparative scale with comparable yields and efficiency without compromising the enantiomeric purity (**5a**: 1.01 g over two steps, 83%, 90% *ee*, >19:1 d.r.;

**9b**: 0.51 g, 86%, 96% *ee*, 15:1 d.r.; after one recrystallization: 72%, >99% *ee*, >99:1 d.r.; Scheme S2).

The 1,2-*trans*-2,3-*trans*-4-aminocyclopentane-based scaffolds (see Scheme S1b) were found to be comparable to Aprepitant in structure–activity relationship (SAR) studies with regard to hNK1 inhibition. In particular, the optically pure molecules showed enhanced binding affinity.[7] Therefore, we decided to apply our new method to the synthesis of human NK1 antagonist **12**. As shown in Scheme 3, the optically active product **5a** obtained with our method could be successfully transformed into hNK1 antagonist **12** with a high level of enantioselectivity in only three steps (Luche reduction, alkene hydrogenation, and alkylation of the hydroxy group). This clearly demonstrates the utility of this enantioselective aza-Piancatelli reaction as an expedient means to synthesize various chiral 4-aminocyclopentenones, which are highly useful in synthetic and medicinal chemistry.




***Scheme 3.*** Enantioselective synthesis of a cyclopentane-based hNK1 antagonist analogue.

In summary, we have developed the first catalytic asymmetric Piancatelli reaction. The Brønsted acid catalyzed reaction shows broad substrate scope and proceeds well with various amine nucleophiles, as well as secondary and tertiary carbinols, to give a range of 4-aminocyclopentenones (60 examples) in good yields and with excellent diastereo- and enantiocontrol. Under the mild reaction conditions, even alkyl-substituted tertiary furylcarbinols, which previously proved to be challenging substrates for Piancatelli reactions, were tolerated and provided the desired products with a quaternary stereocenter. To demonstrate the value of our new approach, the protocol was applied to the enantioselective synthesis of a cyclopentane-based hNK1 antagonist. The aza-Piancatelli reaction reported here not only provides fast access to valuable compounds but also constitutes a good basis for the development of further Brønsted acid catalyzed rearrangements and electrocyclization reactions.

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**Keywords:** alcohols · Brønsted acids · organocatalysis · quaternary stereocenters · rearrangements

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*Angew. Chem.* **2016**, *128*, 14332–14336

[1] G. Piancatelli, A. Scettri, S. Barbadoro, *Tetrahedron Lett.* **1976**, *17*, 3555–3558.
[2] a) G. Stork, C. Kowalski, G. Garcia, *J. Am. Chem. Soc.* **1975**, *97*, 3258–3260; b) J. H. Dygos, J. P. Adamek, K. A. Babiak, J. R. Behling, J. R. Medich, J. S. Ng, J. J. Wieczorek, *J. Org. Chem.* **1991**, *56*, 2549–2552; c) A. Rodríguez, M. Nomen, B. W. Spur, J. J. Godfroid, *Eur. J. Org. Chem.* **1999**, 2655–2662; d) J. P. Henschke, Y. L. Liu, X. H. Huang, Y. F. Chen, D. C. Meng, L. Z. Xia, X. Q. Wei, A. P. Xie, D. H. Li, Q. Huang, T. Sun, J. Wang, X. B. Gu, X. Y. Huang, L. H. Wang, J. Xiao, S. H. Qiu, *Org. Process Res. Dev.* **2012**, *16*, 1905–1916; e) A. R. Rodríguez, B. W. Spur, *Tetrahedron Lett.* **2003**, *44*, 7411–7415; f) W. T. Spencer III, T. Vaidya, A. J. Frontier, *Eur. J. Org. Chem.* **2013**, 3621–3633; g) D. J. Aitken, H. Eijsberg, A. Frongia, J. Ollivier, P. P. Piras, *Synthesis* **2014**, 1–24; h) S. P. Simeonov, J. P. M. Nunes, K. Guerra, V. B. Kurteva, C. A. M. Afonso, *Chem. Rev.* **2016**, *116*, 5744–5893.
[3] a) L. I. Palmer, J. R. de Alaniz, *Org. Lett.* **2013**, *15*, 476–479; b) D. Fisher, L. I. Palmer, J. E. Cook, J. E. Davis, J. R. de Alaniz, *Tetrahedron* **2014**, *70*, 4105–4110.
[4] a) O. Nieto Faza, C. Silva López, R. Álvarez, Á. R. de Lera, *Chem. Eur. J.* **2004**, *10*, 4324–4333; b) M. J. Palframan, G. Pattenden, *Chem. Commun.* **2014**, *50*, 7223–7242; c) G. Piancatelli, M. Dauria, F. Donofrio, *Synthesis* **1994**, 867–889; d) C. Piutti, F. Quartieri, *Molecules* **2013**, *18*, 12290–12312; e) R. R. Naredla, D. A. Klumpp, *Chem. Rev.* **2013**, *113*, 6905–6948.
[5] For selected examples, see: a) G. K. Veits, D. R. Wenz, J. R. de Alaniz, *Angew. Chem. Int. Ed.* **2010**, *49*, 9484–9487; *Angew. Chem.* **2010**, *122*, 9674–9677; b) L. I. Palmer, J. R. de Alaniz, *Angew. Chem. Int. Ed.* **2011**, *50*, 7167–7170; *Angew. Chem.* **2011**, *123*, 7305–7308; c) B. Yin, G. Zeng, C. Cai, F. Ji, L. Huang, Z. Li, H. Jiang, *Org. Lett.* **2012**, *14*, 616–619; d) D. R. Wenz, J. R. de Alaniz, *Org. Lett.* **2013**, *15*, 3250–3253; e) D. Lebceuf, E. Schulz, V. Gandon, *Org. Lett.* **2014**, *16*, 6464–6467.
[6] a) D. A. Boltz, N. A. Ilyushina, C. S. Arnold, Y. S. Babu, R. G. Webster, E. A. Govorkova, *Antiviral Res.* **2008**, *80*, 150–157; b) F. Jia, J. Hong, P. H. Sun, J. X. Chen, W. M. Chen, *Synth. Commun.* **2013**, *43*, 2641–2647; c) A. Boiron, P. Zillig, D. Faber, B. Giese, *J. Org. Chem.* **1998**, *63*, 5877–5882; d) M. T. Crimmins, E. A. Tabet, *J. Org. Chem.* **2001**, *66*, 4012–4018; e) I. Storch de Gracia, S. Bobo, M. D. Martin-Ortega, J. L. Chiara, *Org. Lett.* **1999**, *1*, 1705–1708.
[7] a) L. C. Meurer, P. E. Finke, K. A. Owens, N. N. Tsou, R. G. Ball, S. G. Mills, M. MacCoss, S. Sadowski, M. A. Cascieri, K. L. Tsao, G. G. Chicchi, L. A. Egger, S. Luell, J. M. Metzger, D. E. MacIntyre, N. M. J. Rupniak, A. R. Williams, R. J. Hargreaves, *Bioorg. Med. Chem. Lett.* **2006**, *16*, 4504–4511; b) P. E. Finke, L. C. Meurer, D. A. Levorse, S. G. Mills, M. MacCoss, S. Sadowski, M. A. Cascieri, K. L. Tsao, G. G. Chicchi, J. M. Metzger, D. E. MacIntyre, *Bioorg. Med. Chem. Lett.* **2006**, *16*, 4497–4503.
[8] a) D. Yu, V. T. Thai, L. I. Palmer, G. K. Veits, J. E. Cook, J. R. de Alaniz, J. E. Hein, *J. Org. Chem.* **2013**, *78*, 12784–12789;

  

b) R. Chung, D. Yu, V. T. Thai, A. F. Jones, G. K. Veits, J. R. de Alaniz, J. E. Hein, *ACS Catal.* **2015**, *5*, 4579 – 4585.
[9] M. Dauria, F. Donofrio, G. Piancatelli, A. Scettri, *Gazz. Chim. Ital.* **1986**, *116*, 173 – 175.
[10] For selected reviews, see: a) T. Akiyama, *Chem. Rev.* **2007**, *107*, 5744 – 5758; b) M. Terada, *Chem. Commun.* **2008**, 4097 – 4112; c) D. Kampen, C. M. Reisinger, B. List, *Top. Curr. Chem.* **2009**, *291*, 395 – 456; d) A. Zamfir, S. Schenker, M. Freund, S. B. Tsogoeva, *Org. Biomol. Chem.* **2010**, *8*, 5262 – 5276; e) M. Rueping, A. Kuenkel, I. Atodiresei, *Chem. Soc. Rev.* **2011**, *40*, 4539 – 4549; f) M. Terada, *Curr. Org. Chem.* **2011**, *15*, 2227 – 2256; g) M. Rueping, B. J. Nachtsheim, W. Ieawsuwan, I. Atodiresei, *Angew. Chem. Int. Ed.* **2011**, *50*, 6706 – 6720; *Angew. Chem.* **2011**, *123*, 6838 – 6853; h) J. Yu, F. Shi, L. Z. Gong, *Acc. Chem. Res.* **2011**, *44*, 1156 – 1171; i) D. Parmar, E. Sugiono, S. Raja, M. Rueping, *Chem. Rev.* **2014**, *114*, 9047 – 9153.
[11] a) K. Kaupmees, N. Tolstoluzhsky, S. Raja, M. Rueping, I. Leito, *Angew. Chem. Int. Ed.* **2013**, *52*, 11569 – 11572; *Angew. Chem.* **2013**, *125*, 11783 – 11786; b) M. Fleischmann, D. Drettwan, E. Sugiono, M. Rueping, R. M. Gschwind, *Angew. Chem. Int. Ed.* **2011**, *50*, 6364 – 6369; *Angew. Chem.* **2011**, *123*, 6488 – 6493; c) M. Rueping, B. J. Nachtsheim, R. M. Koenigs, W. Ieawsuwan, *Chem. Eur. J.* **2010**, *16*, 13116 – 13126; d) H. Kim, E. Sugiono, Y. Nagata, M. Wagner, M. Bonn, M. Rueping, J. Hunger, *ACS Catal.* **2015**, *5*, 6630 – 6633.
[12] For examples of phosphoric acid catalyzed reactions proceeding by dehydration, see: a) M. Rueping, B. N. Nachtsheim, S. A. Moreth, M. Bolte, *Angew. Chem. Int. Ed.* **2008**, *47*, 593 – 596; *Angew. Chem.* **2008**, *120*, 603 – 606; b) Q. X. Guo, Y. G. Peng, J. W. Zhang, L. Song, Z. Feng, L. Z. Gong, *Org. Lett.* **2010**, *11*, 4620 – 4623; c) M. Rueping, B. N. Nachtsheim, *Synlett* **2010**, 119 – 122; d) D. Wilcke, E. Herdtweck, T. Bach, *Synlett* **2011**, 1235 – 1238; e) M. Rueping, U. Uria, M.-Y. Lin, I. Atodiresei, *J. Am. Chem. Soc.* **2011**, *133*, 3732 – 3735; f) Q. X. Guo, J. Song, J.-Z. Huang, P.-H. Chen, S.-W. Luo, L.-Z. Gong, *Angew. Chem. Int. Ed.* **2012**, *51*, 1046 – 1050; *Angew. Chem.* **2012**, *124*, 1070 – 1074; g) L. Song, Q. X. Guo, X. C. Li, J. Tian, Y. G. Peng, *Angew. Chem. Int. Ed.* **2012**, *51*, 1899 – 1902; *Angew. Chem.* **2012**, *124*, 1935 – 1938; h) T. Courant, S. Kumarn, L. He, P. Retailleau, G. Masson, *Adv. Synth. Catal.* **2013**, *355*, 836; i) O. El-Sepelgy, S. Haseloff, S. K. Alamsetti, C. Schneider, *Angew. Chem. Int. Ed.* **2014**, *53*, 7923 – 7927; *Angew. Chem.* **2014**, *126*, 8057 – 8061; j) C.-C. Hsiao, H.-H. Liao, M. Rueping, *Angew. Chem. Int. Ed.* **2014**, *53*, 13258 – 13263; *Angew. Chem.* **2014**, *126*, 13474 – 13479; k) S. Saha, C. Schneider, *Chem. Eur. J.* **2015**, *21*, 2348 – 2352; l) S. Saha, C. Schneider, *Org. Lett.* **2015**, *17*, 648 – 651; m) S. Saha, S. K. Alamsetti, C. Schneider, *Chem. Commun.* **2015**, *51*, 1461 – 1464; n) H.-H. Liao, A. Chatupheeraphat, C.-C. Hsiao, I. Atodiresei, M. Rueping, *Angew. Chem. Int. Ed.* **2015**, *54*, 15540 – 15544; *Angew. Chem.* **2015**, *127*, 15760 – 15765; o) W. Zhao, Z. Wang, B. Chu, J. Sun, *Angew. Chem. Int. Ed.* **2015**, *54*, 1910 – 1913; *Angew. Chem.* **2015**, *127*, 1930 – 1933; p) J.-J. Zhao, S.-B. Sun, S.-H. He, Q. Wu, F. Shi, *Angew. Chem. Int. Ed.* **2015**, *54*, 5460 – 5464; *Angew. Chem.* **2015**, *127*, 5550 – 5554; q) Z. Wang, F. Ai, Z. Wang, W. Zhao, G. Zhu, Z. Lin, J. Sun, *J. Am. Chem. Soc.* **2015**, *137*, 383 – 389; r) C.-C. Hsiao, S. Raja, H.-H. Liao, I. Atodiresei, M. Rueping, *Angew. Chem. Int. Ed.* **2015**, *54*, 5762 – 5765; *Angew. Chem.* **2015**, *127*, 5854 – 5857; s) A. Chatupheeraphat, H.-H. Liao, S. Mader, M. Sako, H. Sasai, I. Atodiresei, M. Rueping, *Angew. Chem. Int. Ed.* **2016**, *55*, 4803 – 4807; *Angew. Chem.* **2016**, *128*, 4882 – 4887; t) S. K. Alamsetti, M. Spanka, C. Schneider, *Angew. Chem. Int. Ed.* **2016**, *55*, 2392 – 2396; *Angew. Chem.* **2016**, *128*, 2438 – 2442; u) M. Kretzschmar, T. Hodik, C. Schneider, *Angew. Chem. Int. Ed.* **2016**, *55*, 9788 – 9792; *Angew. Chem.* **2016**, *128*, 9941 – 9946.
[13] E. Kühnel, D. D. P. Laffan, G. C. Lloyd-Jones, T. Martínez del Campo, I. R. Shepperson, J. L. Slaughter, *Angew. Chem. Int. Ed.* **2007**, *46*, 7075 – 7078; *Angew. Chem.* **2007**, *119*, 7205 – 7208.
[14] a) S. Thompson, A. G. Coyne, P. C. Knipe, M. D. Smith, *Chem. Soc. Rev.* **2011**, *40*, 4217 – 4231; b) N. Shimada, C. Stewart, M. A. Tius, *Tetrahedron* **2011**, *67*, 5851 – 5870; c) T. Vaidya, R. Eisenberg, A. J. Frontier, *ChemCatChem* **2011**, *3*, 1531 – 1548; for examples of asymmetric organocatalyzed electrocyclizations, see: d) M. Rueping, W. Ieawsuwan, A. P. Antonchick, B. J. Nachtsheim, *Angew. Chem. Int. Ed.* **2007**, *46*, 2097 – 2100; *Angew. Chem.* **2007**, *119*, 2143 – 2146; e) M. Rueping, W. Ieawsuwan, *Adv. Synth. Catal.* **2009**, *351*, 78 – 84; f) M. Rueping, A. P. Antonchick, *Angew. Chem. Int. Ed.* **2008**, *47*, 10090 – 10093; *Angew. Chem.* **2008**, *120*, 10244 – 10247; g) A. K. Basak, N. Shimada, W. F. Bow, D. A. Vicic, M. A. Tius, *J. Am. Chem. Soc.* **2010**, *132*, 8266 – 8267; h) N. Shimada, B. O. Ashburn, A. K. Basak, W. F. Bow, D. A. Vicic, M. A. Tius, *Chem. Commun.* **2010**, *46*, 3774 – 3775; i) M. Rueping, W. Ieawsuwan, *Chem. Commun.* **2011**, *47*, 11450 – 11452; j) A. Das, C. M. R. Volla, I. Atodiresei, W. Bettray, M. Rueping, *Angew. Chem. Int. Ed.* **2013**, *52*, 8008 – 8011; *Angew. Chem.* **2013**, *125*, 8166 – 8169; k) A. Jolit, P. M. Walleser, G. P. A. Yap, M. Tius, *Angew. Chem. Int. Ed.* **2014**, *53*, 6180 – 6183; *Angew. Chem.* **2014**, *126*, 6294 – 6297; l) S. Raja, M. Nakajima, M. Rueping, *Angew. Chem. Int. Ed.* **2015**, *54*, 2762 – 2765; *Angew. Chem.* **2015**, *127*, 2801 – 2804.
[15] A substrate with a substituent at the 4-position of the furan moiety, (5-methylfuran-2-yl)(phenyl)methanol, did not deliver the rearrangement product under the optimized reaction conditions.

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