

Cite this: *Chem. Sci.*, 2020, 11, 3862

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 29th January 2020

Accepted 11th March 2020

DOI: 10.1039/d0sc00542h

rsc.li/chemical-science

A chiral cobalt(II) complex catalyzed enantioselective aza-Piancatelli rearrangement/Diels–Alder cascade reaction†

Bin Shen,  Qianwen He,  Shunxi Dong,  Xiaohua Liu * and Xiaoming Feng *

A chiral *N,N'*-dioxide/cobalt(II) complex catalyzed highly diastereoselective and enantioselective tandem aza-Piancatelli rearrangement/intramolecular Diels–Alder reaction has been disclosed. Various valuable hexahydro-2*a*,5-epoxycyclopenta[*cd*]isoindoles bearing six contiguous stereocenters have been obtained in good yields with excellent diastereo- and enantio-selectivities from a wide range of both readily available 2-furylcarbinols and *N*-(furan-2-ylmethyl)anilines.

Introduction

The Piancatelli reaction and its variants,¹ a kind of acid-catalyzed rearrangement of 2-furylcarbinols, allow straightforward access to a large array of 2-substituted cyclopentenones and other structurally complex molecules. Due to the prevalence of cyclopentane structures in major natural product families, as well as in a wealth of biologically active molecules,² this reaction has gained great interest in the past decade.^{3–7} Although a range of catalytic aza-Piancatelli reactions along with related cascade processes have been developed,^{4–6} only a few examples are catalytic enantioselective versions, which are dominated by chiral Brønsted acid catalysts (Scheme 1a). For instance, Rueping's group and Sun's group reported the first catalytic asymmetric aza-Piancatelli reaction with aniline derivatives by using a chiral *N*-triflyl phosphoramidate catalyst^{6a} and chiral phosphoric acid catalyst,^{6b} respectively. Recently, Jiang and coworkers employed chiral phosphoramidate to promote an enantioselective aza-Piancatelli rearrangement/Friedel–Crafts alkylation cascade reaction.^{6d} In these cases, the chiral Brønsted acids enabled dehydration and regioselective nucleophilic addition, and then the resulting bifunctional chiral anion ensured stereoselection in the key 4π conrotatory electrocyclization of the pentadienyl cation (Scheme 1a). Piancatelli-type reactions are mechanistic analogous to Nazarov cyclization.⁸ Although Lewis acids are efficient to accelerate those rearrangements and the following cascade reactions as well,⁵ the chiral metal complex catalyzed asymmetric version is

still void. Even the well-developed enantioselective Nazarov reaction is usually limited to strong-coordinated bidentate substrates.⁹ The major challenge in the asymmetric Piancatelli rearrangement might come from the elusive interaction between chiral metal/ligand and cyclopentadienyl cation, which makes it hard to define the stereochemistry.^{6b}

Given the difficulties of aza-Piancatelli rearrangement and its initiated cascade reaction in the synthesis of multicyclic cores, and in connection with our long endeavor in chiral Lewis acid catalysis, we attempt to develop chiral metal complex catalysts to expand the enantioselective aza-Piancatelli-initiated cascade reactions. Chiral *N,N'*-dioxide–metal complexes are able to promote a number of asymmetric transformations with high efficiency and stereoselectivity,¹⁰ and are tolerant to water,¹¹ which is generated in the dehydration step of Piancatelli rearrangement. Very recently, Baskaran disclosed an interesting Yb(OTf)₃-catalyzed aza-Piancatelli rearrangement/[4+2] cycloaddition cascade to construct an octahydro-1*H*-cyclopenta[*cd*]isoindole structure, an aza-tricyclic core of a gracilamine alkaloid.^{5b} We proposed that the well-characterized chiral pocket of *N,N'*-dioxide–metal complex might be able to adopt the hydrocyclopentadienyl cation from 2-furylcarbinol, delivering 3-amino substituted cyclopentenone, which undergoes a Lewis acid-promoted diastereoselective intramolecular Diels–Alder reaction (Scheme 1b). Herein, we report a new chiral *N,N'*-dioxide-cobalt(II) complex¹² catalyzed diastereo- and enantioselective aza-Piancatelli rearrangement/Diels–Alder reaction, allowing efficient and direct construction of a number of hexahydro-2*a*,5-epoxycyclopenta[*cd*]isoindole derivatives. The metal salt and the ligand framework were found to be critical for the realization of enantiocontrol.

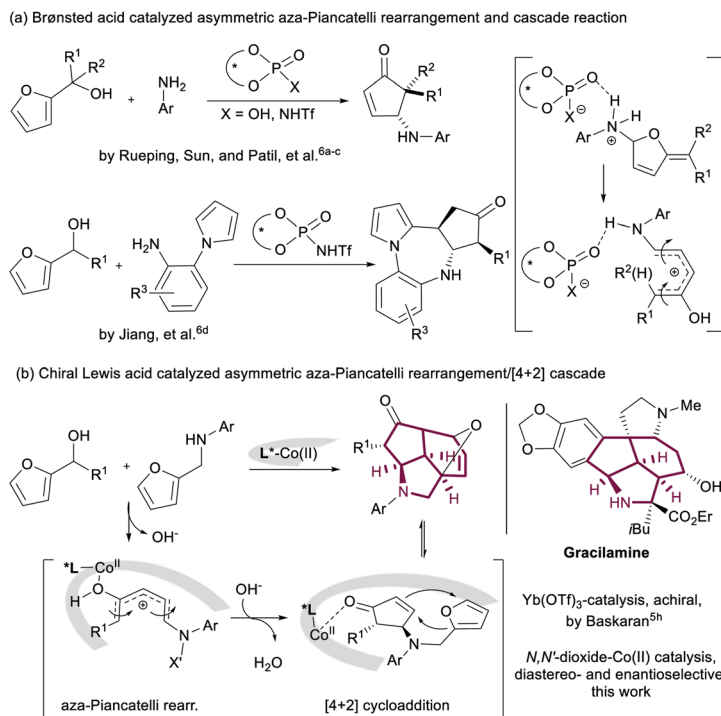
Results and discussion

In our preliminary investigation, we chose furan-2-yl(phenyl)methanol **1a** and *N*-(furan-2-ylmethyl)aniline **2a** as the model

Key Laboratory of Green Chemistry & Technology, Ministry of Education, College of Chemistry, Sichuan University, Chengdu 610064, China. E-mail: liuxh@scu.edu.cn; xmfeng@scu.edu.cn

† Electronic supplementary information (ESI) available: ¹H, ¹³C{¹H} and ¹⁹F{¹H} NMR, HPLC spectra, and CD spectra (PDF). X-ray crystallographic data for **3m** (CIF). CCDC 1971783. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0sc00542h





Scheme 1 Asymmetric catalytic aza-Piancatelli rearrangement and cascade reaction.

substrates to optimize the reaction conditions. Various metal salts, including Yb(OTf)₃, Dy(OTf)₃, and In(OTf)₃ as well, which were proven effective for aza-Piancatelli rearrangement, were screened in toluene at 80 °C upon coordination with the chiral *N,N'*-dioxide ligand **L**₃-PrPr₂. Disappointingly, the corresponding product **3a** was obtained as a nearly racemate with poor to moderate yields, lower reactivity and a longer reaction time than the achiral version^{4b,5a,c,h} (Table 1, entries 1–3). We proposed that rare earth metal salts bear large ionic radii and multiple-coordination manners,¹³ which might be disadvantageous to create a tight pocket to confine the hydrocyclopentadienyl cation to deliver enantiocontrol in the competition of amine **2**.¹⁴ The existence of water generated in the rearrangement step will accelerate the formation of a poor-enantioselective OH-bridged dimer when indium(III) salt was used.¹⁵ After examining other metal salts, we found that the reaction could be achieved with medium yield and enantioselectivity (36% yield, >19 : 1 dr, 65% ee; Table 1, entry 5) in the presence of Co(BF₄)₂·6H₂O, where the center metal ion Co(II) is soft and bears a small ionic radius, reducing the bonding of the amine nucleophile and forming a suitable chiral pocket with the ligand to define the stereochemistry in the rearrangement of the hydrocyclopentadienyl intermediate. Encouraged by this result, the structure of *N,N'*-dioxide ligands was evaluated. It was revealed that the *L*-proline derived ligand **L**₃-PrPr₂ gives better enantioselectivity than other amino acid derived ligands (see the ESI† for details). The steric hindrance of the aniline subunits of the ligand has a dramatic influence on the enantioselectivity (Table 1, entries 5–9). Decreasing the steric hindrance, such

Table 1 Optimization of the reaction conditions^a

1a: Ar = Ph
1b: Ar = 4-MeOC₆H₄

2a

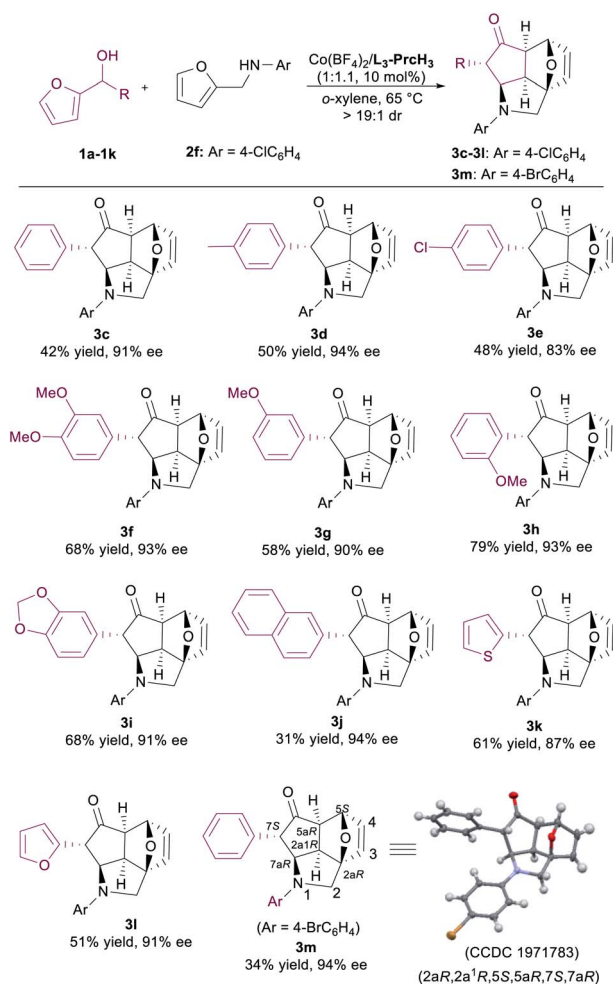
3a: Ar = Ph
3b: Ar = 4-MeOC₆H₄

L₃-PrEt₂: Ar = 2,6-Et₂C₆H₃
L₃-PrPr₂: Ar = 2,6-*i*Pr₂C₆H₃
L₃-PrPr₃: Ar = 2,4,6-*i*Pr₃C₆H₂
L₃-PrPr₂Ad: Ar = 2,6-*i*Pr₂-4-AdC₆H₂
L₃-PrCH₃: Ar = 2,4,6-Cy₃C₆H₂

Entry	Metal salt	Ligand	Yield ^b (%)	ee ^c (%)
1	Yb(OTf) ₃	L ₃ -PrPr ₂	14	0
2	Dy(OTf) ₃	L ₃ -PrPr ₂	<10	-3
3	In(OTf) ₃	L ₃ -PrPr ₂	47	4
4	Co(OTf) ₂	L ₃ -PrPr ₂	10	57
5	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrPr ₂	36	65
6	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrEt ₂	60	8
7	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrPr ₃	14	81
8	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrPr ₂ Ad	42	82
9 ^d	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrCH ₃	55	83
10 ^{d,e}	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrCH ₃	63	85
11 ^{d,e,f}	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrCH ₃	20	92
12 ^{d,e,f,g}	Co(BF ₄) ₂ ·6H ₂ O	L ₃ -PrCH ₃	88	90

^a Unless otherwise noted, the reactions were performed with metal salt/ligand (1 : 1.1, 5 mol%), **1a** (0.10 mmol), and **2a** (1.0 equiv.) in toluene (1.0 mL) at 80 °C for 16 h. ^b Isolated yield, and >19/1 dr was obtained. ^c Determined by HPLC analysis on a chiral stationary phase. ^d Co(II)/ligand (1 : 1.1, 10 mol%). ^e *o*-Xylene (1.0 mL) was used instead of toluene. ^f 65 °C for 16 h. ^g **1b** was used instead of **1a**.



Table 2 Substrate scope of 2-furylcarbinols^a

^a Unless otherwise noted, the reactions were performed with Co(BF₄)₂·6H₂O/L₃-PrCp*H₃ (1 : 1.1, 10 mol%), **1** (0.10 mmol), and **2** (1.0 equiv.), in *o*-xylene (1.0 mL) at 65 °C. >19/1 dr.

as L₃-PrEt₂ containing 2,6-diethyl aniline substituent (Table 1, entry 6).

Bulkier 2,4,6-substitutions, such as L₃-PrCp*H₃, bearing a 2,4,6-cyclohexyl aniline moiety, improved the yield to 55% and the ee value to 83% with 10 mol% catalyst loading (Table 1, entry 9). After careful investigation of the solvents, *o*-xylene was proven to be the best choice, and the desired product could be obtained in 63% yield with 85% ee (Table 1, entry 10). When the reaction temperature was reduced to 65 °C, the ee value had an obvious increase (92% ee), but the reaction activity was depressed (Table 1, entry 11). When furan-2-yl(4-methoxyphenyl)methanol **1b** was used as the model substrate instead of **1a**, the related product **3b** could be obtained in 88% yield with 90% ee (Table 1, entry 12). The reason of dramatically increased reactivity might be that the *para*-methoxy group on phenyl of 2-furylcarbinol makes the cyclopentadienyl cation more stable. It is noteworthy that there is a dynamic equilibrium between the desired products **3** and the uncyclized intermediates in the solvent (see the ESI† for

details).^{5b} Finally, we established the optimized reaction conditions as Co(BF₄)₂·6H₂O/L₃-PrCp*H₃ (1 : 1.1, 10 mol%) in *o*-xylene at 65 °C for 16 h.

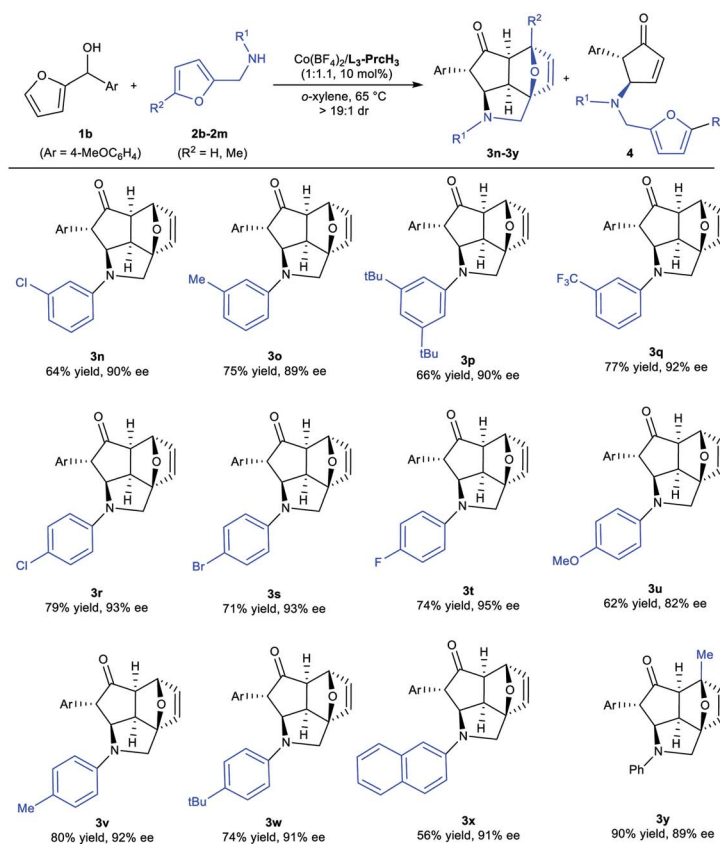
With the optimized conditions in hand, we turned our attention to the scope of 2-furylcarbinols (Table 2). The 2-furylcarbinols containing electron-withdrawing or electron-neutral groups on the aryl moiety had lower reactivity than the standard substrate **1b** in the reaction. The corresponding products **3c–3e** were only achieved in medium yields with excellent ee values after the reaction time was prolonged. The phenyl ring of 2-furylcarbinols bearing electron-donating groups at the *para*, *meta*, or *ortho* position were converted to the desired products **3f–3i** with good yields and enantioselectivities (58–79% yields and 90–93% ee). We were also pleased to find that the reaction was compatible with 2-naphthyl, 2-furyl, and 2-thienyl groups to furnish **3j–3l** in 31–61% yields with 87–94% ee. Moreover, the absolute configuration of the product **3m** was determined to be (2*a*R,2*a*'*R*,5*S*,5*a*R,7*S*,7*a*R) by X-ray crystallography analysis.¹⁶ It is noteworthy that only one diastereoisomer of the epoxy-cyclopenta[*cd*]isoindole products was isolated in all cases. The absolute configuration of the other products was determined to be uniform by comparing the circular-dichroism spectra with that of **3m**.

Subsequently, we assessed the scope of *N*-(furan-2-ylmethyl)anilines in the reaction with furan-2-yl(4-methoxyphenyl)methanol **1b**, and the results are summarized in Table 3. The electronic properties or steric hindrance of the substituents on the aromatic ring had a little effect on the stereoselectivity of the tandem reaction, and the desired epoxy-cyclopenta[*cd*]isoindoles **3n–3w** were obtained in good to excellent yields (62–88% yields) with excellent enantioselectivities (82–95% ee). Of note, a 2-naphthyl containing amine was also a suitable substrate, giving the product **3x** in 56% yield with 91% ee. Furthermore, *N*-((5-methylfuran-2-yl)methyl)aniline was converted to the corresponding product **3y** with 90% yield and 89% ee as well.

To show the practicability of this methodology, a gram scale synthesis of the product **3b** was carried out. In the presence of 10 mol% of Co(BF₄)₂·6H₂O/L₃-PrCp*H₃, 2-furylcarbinol **1b** (4 mmol) reacted with *N*-(furan-2-ylmethyl)aniline **2a** (4 mmol) smoothly, and delivered **3b** in 79% yield, >19 : 1 dr with 91% ee (Scheme 2a). We also carried out some product derivatization (Scheme 2b–d). For example, the compound **3b** could undergo diastereoselective 1,2-addition with an allyl Grignard reagent or reduction of the carbonyl group, affording the corresponding alcohols in 91% yield with 94% ee (**5**) and 95% yield with 97% ee (**7**). Moreover, phenyloctahydro-2*a*,5-epoxycyclopenta[*cd*]isoindole **6** could be isolated in 90% yield with 95% ee through hydrogenation.

In addition, we tested other amine-type nucleophiles to probe the aza-Piancatelli rearrangement process (Scheme 3). When the substrate *N*-(thiophen-2-ylmethyl)aniline **2n** was used, only the uncyclized product **4bn** could be achieved in 95% yield with 89% ee. It indicates that the high diastereo- and enantio-selectivity come from the 4π conrotatory electrocyclicization step. If amine **2o** embodying a 2-furyl substituent

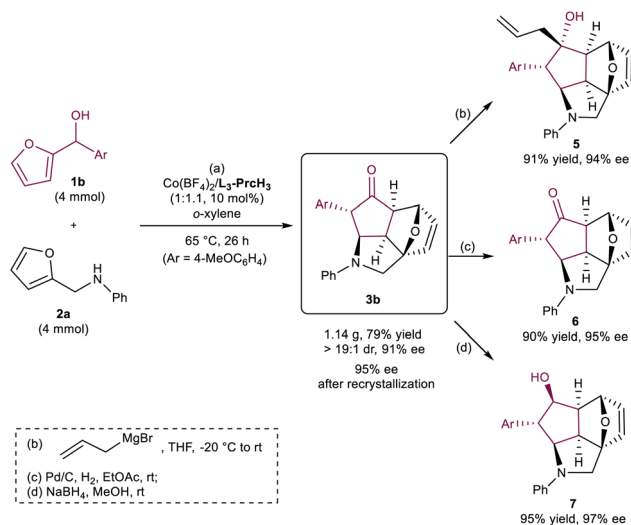


Table 3 Substrate scope of *N*-(furan-2-ylmethyl)anilines^a

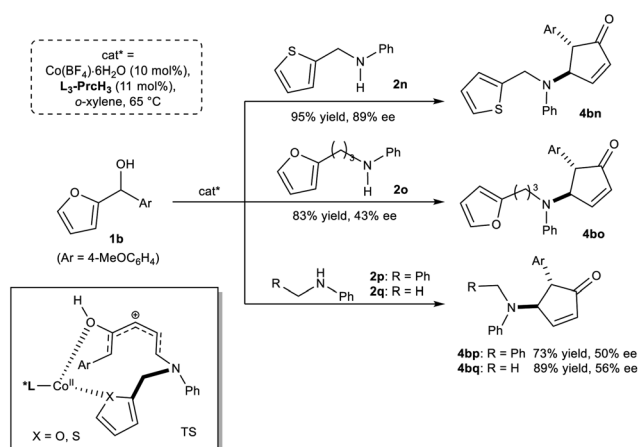
^a Unless otherwise noted, the reactions were performed with Co(BF₄)₂·6H₂O/L₃-PrCH₃ (1 : 1.1, 10 mol%), **1b** (0.10 mmol), and **2** (1.0 equiv.) in o-xylene (1.0 mL) at 65 °C. >19/1 dr.

with a longer chain was subjected to the reaction, the corresponding aza-Piancatelli rearrangement product **4bo** was isolated in high yield with a medium ee value. Other secondary

amines as the nucleophiles yielded the *trans*-substituted cyclopentenone derivatives **4bp** and **4bq** with moderate enantioselectivity, implying that hetero-atoms in furyl or thienyl might also participate in cooperation with the metal center to enhance the enantioselection.



Scheme 2 Gram scale experiment and product derivatization.



Scheme 3 Other amine-type nucleophiles.



Conclusions

We have presented an efficient chiral Lewis acid catalyzed asymmetric aza-Piancatelli rearrangement/Diels–Alder cascade reaction of 2-furylcarbinols with *N*-(furan-2-ylmethyl)anilines. The use of a chiral *N,N'*-dioxide-Co(BF₄)₂·6H₂O complex enabled the construction of a series of hexahydro-2*a*,5-epoxycyclopenta[*cd*]isoindoles bearing six contiguous stereocenters in a wonderful diastereo- and enantio-selective manner. Further investigations on chiral Lewis acid catalyzed other types of rearrangement and electrocyclization reactions as well as the study to probe the secret of enantiocontrol are underway.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank the National Natural Science Foundation of China (U19A2014) for financial support.

Notes and references

- (a) G. Piancatelli, A. Scettri and S. Barbadoro, *Tetrahedron Lett.*, 1976, **17**, 3555; (b) G. Piancatelli, A. Scettri, G. David and M. D'auria, *Tetrahedron*, 1978, **34**, 2775; (c) G. Piancatelli, M. D'auria and F. D'Onofrio, *Synthesis*, 1994, 867; (d) C. Piutti and F. Quartieri, *Molecules*, 2013, **18**, 12290; (e) L. I. Palmer and J. R. de Alaniz, *Synlett*, 2014, **25**, 8; (f) R. F. A. Gomes, J. A. S. Coelho and C. A. M. Afonso, *Chem.–Eur. J.*, 2018, **24**, 9170; (g) C. Verrier, S. M. Sanchez, Y. Queneau and F. Popowycz, *Org. Biomol. Chem.*, 2018, **16**, 676; (h) H. Wu, Q. Wang and J. P. Zhu, *Eur. J. Org. Chem.*, 2019, 1964.
- (a) G. Liu, M. E. Shirley, K. N. Van, R. L. Mcfarlin and D. Romo, *Nat. Chem.*, 2013, **5**, 1049; (b) B. Heasley, *Curr. Org. Chem.*, 2014, **18**, 641.
- For some selected examples of oxa-Piancatelli rearrangement: (a) M. D'auria, *Heterocycles*, 2000, **52**, 185; (b) B. L. Yin, Y. L. Wu and J. Q. Lai, *Eur. J. Org. Chem.*, 2009, 2695; (c) K. Ulbrich, P. Kreitmeier and O. Reiser, *Synlett*, 2010, 2037; (d) L. I. Palmer, G. K. Veits and J. R. de Alaniz, *Eur. J. Org. Chem.*, 2013, 6237; (e) L. I. Palmer and J. R. de Alaniz, *Org. Lett.*, 2013, **15**, 476; (f) D. Fisher, L. I. Palmer, J. E. Cook, J. E. Davis and J. R. de Alaniz, *Tetrahedron*, 2014, **70**, 4105; (g) K. Michalak and J. Wicha, *Tetrahedron*, 2014, **70**, 5073; (h) A. Bredihhin, S. Luiga and L. Vares, *Synthesis*, 2016, **48**, 4181; (i) G. L. Goff, E. Adelin, G. Arcile and J. Ouazzani, *Tetrahedron Lett.*, 2017, **58**, 2337.
- For some selected examples of aza-Piancatelli rearrangement: (a) S. W. Li and R. Batey, *Chem. Commun.*, 2007, 3759; (b) G. K. Veits, D. R. Wenz and J. R. de Alaniz, *Angew. Chem., Int. Ed.*, 2010, **49**, 9484; (c) L. I. Palmer and J. R. de Alaniz, *Angew. Chem., Int. Ed.*, 2011, **50**, 7167; (d) B. V. Reddy, G. Narasimhulu, P. S. Lakshumma, Y. V. Reddy and J. S. Yadav, *Tetrahedron Lett.*, 2012, **53**, 1776; (e) D. R. Wenz and J. R. de Alaniz, *Org. Lett.*, 2013, **15**, 3250; (f) D. Leboeuf, E. Schulz and V. Gandon, *Org. Lett.*, 2014, **16**, 6464; (g) G. K. Veits, D. R. Wenz, L. I. Palmer, A. H. S. Amant, J. E. Hein and J. R. de Alaniz, *Org. Biomol. Chem.*, 2015, **13**, 8465; (h) D. Leboeuf, L. Marin, B. Michelet, A. Perez-Luna, R. Guillot, E. Schulz and V. Gandon, *Chem.–Eur. J.*, 2016, **22**, 16165; (i) M. S. Estevão and C. A. M. Afonso, *Tetrahedron Lett.*, 2017, **58**, 302; (j) Z. L. Xu, P. Xing and B. Jiang, *Org. Lett.*, 2017, **19**, 1028; (k) R. F. A. Gomes, N. R. Esteves, J. A. S. Coelho and C. A. M. Afonso, *J. Org. Chem.*, 2018, **83**, 7509.
- For some examples of aza-Piancatelli-initiated cascade reactions: (a) B. V. S. Reddy, Y. V. Reddy, P. S. Lakshumma, G. Narasimhulu, J. S. Yadav, B. Sridhar, P. P. Reddy and A. C. Kunwar, *RSC Adv.*, 2012, **2**, 10661; (b) J. Q. Liu, Q. Shen, J. J. Yu, M. Y. Zhu, J. W. Han and L. M. Wang, *Eur. J. Org. Chem.*, 2012, 6933; (c) B. V. S. Reddy, Y. V. Reddy and K. K. Singarapu, *Org. Biomol. Chem.*, 2016, **14**, 1111; (d) L. Marin, V. Gandon, E. Schulz and D. Leboeuf, *Adv. Synth. Catal.*, 2017, **359**, 1157; (e) K. Nayani, R. Cinsani, A. Hussaini, P. S. Mainkar and S. Chandrasekhar, *Eur. J. Org. Chem.*, 2017, 5671; (f) L. Marin, R. Guillot, V. Gandon, E. Schulz and D. Leboeuf, *Org. Chem. Front.*, 2018, **5**, 640; (g) B. Baldé, G. Force, L. Marin, R. Guillot, E. Schulz, V. Gandon and D. Leboeuf, *Org. Lett.*, 2018, **20**, 7405; (h) S. Gouse, N. R. Reddy and S. Baskaran, *Org. Lett.*, 2019, **21**, 3822; (i) S. D. Wang, R. Guillot, J. F. Carpentier, Y. Sarazin, C. Bour, V. Gandon and D. Leboeuf, *Angew. Chem., Int. Ed.*, 2020, **59**, 1134.
- For some examples of asymmetric aza-Piancatelli rearrangement: (a) Y. F. Cai, Y. R. Tang, I. Atodiresei and M. Rueping, *Angew. Chem., Int. Ed.*, 2016, **55**, 14126; (b) H. L. Li, R. B. Tong and J. W. Sun, *Angew. Chem., Int. Ed.*, 2016, **55**, 15125; (c) A. B. Gade and N. T. Patil, *Synlett*, 2017, **28**, 1096; (d) Z. Wei, J. L. Zhang, H. M. Yang and G. X. Jiang, *Org. Lett.*, 2019, **21**, 2790; (e) G. R. Hammersley, M. F. Nichol, H. C. Steffens, J. M. Delgado, G. K. Veits and J. R. de Alaniz, *Beilstein J. Org. Chem.*, 2019, **15**, 1569.
- For some selected examples of carbo-Piancatelli rearrangement: (a) B. L. Yin, L. Huang, X. Y. Zhang, F. H. Ji and H. F. Jiang, *J. Org. Chem.*, 2012, **77**, 6365; (b) B. L. Yin, L. Huang, X. J. Wang, J. C. Liu and H. F. Jiang, *Adv. Synth. Catal.*, 2013, **355**, 370; (c) L. Huang, X. Y. Zhang, J. Li, K. Ding, X. H. Li, X. W. Zheng and B. L. Yin, *Eur. J. Org. Chem.*, 2014, 338; (d) C. Y. Wang, C. Y. Dong, L. K. Kong, Y. L. Li and Y. Z. Li, *Chem. Commun.*, 2014, **50**, 2164; (e) J. F. Xu, Y. Luo, H. P. Xu, Z. K. Chen, M. Z. Miao and H. J. Ren, *J. Org. Chem.*, 2017, **82**, 3561.
- (a) O. N. Faza, C. S. López, R. Álvarez and Á. R. de Lera, *Chem.–Eur. J.*, 2004, **10**, 4324; (b) A. B. G. Pérez, P. Villar and Á. R. de Lera, *Eur. J. Org. Chem.*, 2019, 2539.
- For some selected asymmetric Nazarov reactions: (a) V. K. Aggarwal and A. J. Belfield, *Org. Lett.*, 2003, **5**, 5075; (b) I. Walz and A. Togni, *Chem. Commun.*, 2008, 4315; (c) P. Cao, C. Deng, Y. Y. Zhou, X. L. Sun, J. C. Zheng, Z. W. Xie and Y. Tang, *Angew. Chem., Int. Ed.*, 2010, **49**, 4463; (d) S. Raja, M. Nakajima and M. Rueping, *Angew.*



- Chem., Int. Ed.*, 2015, **54**, 2762; (e) H. Y. Zhang and Z. Lu, *Org. Chem. Front.*, 2018, **5**, 1763; (f) H. Y. Zhang and Z. Lu, *Org. Lett.*, 2018, **20**, 5709; (g) H. Y. Zhang, B. Cheng and Z. Lu, *Org. Lett.*, 2018, **20**, 4028.
- 10 (a) X. H. Liu, L. L. Lin and X. M. Feng, *Acc. Chem. Res.*, 2011, **44**, 574; (b) X. H. Liu, L. L. Lin and X. M. Feng, *Org. Chem. Front.*, 2014, **1**, 298; (c) X. H. Liu, H. F. Zheng, Y. Xia, L. L. Lin and X. M. Feng, *Acc. Chem. Res.*, 2017, **50**, 2621; (d) X. H. Liu, S. X. Dong, L. L. Lin and X. M. Feng, *Chin. J. Chem.*, 2018, **36**, 791; (e) X. M. Feng, Z. Wang and X. H. Liu, *Top. Organomet. Chem.*, 2018, **62**, 147.
- 11 (a) Y. Xia, X. H. Liu, H. F. Zheng, L. L. Lin and X. M. Feng, *Angew. Chem., Int. Ed.*, 2015, **54**, 227; (b) Y. B. Liu, X. H. Liu, H. P. Hu, J. Guo, Y. Xia, L. L. Lin and X. M. Feng, *Angew. Chem., Int. Ed.*, 2016, **55**, 4054; (c) Y. Xia, L. L. Lin, F. Z. Chang, Y. T. Liao, X. H. Liu and X. M. Feng, *Angew. Chem., Int. Ed.*, 2016, **55**, 12228; (d) J. F. Zheng, L. L. Liu, L. Dai, X. Yuan, X. H. Liu and X. M. Feng, *Chem.–Eur. J.*, 2016, **22**, 18254; (e) H. Zhang, Q. Yao, L. L. Lin, C. R. Xu, X. H. Liu and X. M. Feng, *Adv. Synth. Catal.*, 2017, **359**, 3454; (f) L. Dai, L. L. Lin, J. F. Zheng, D. Zhang, X. H. Liu and X. M. Feng, *Org. Lett.*, 2018, **20**, 5314; (g) Y. L. Xu, F. Z. Chang, W. D. Cao, X. H. Liu and X. M. Feng, *ACS Catal.*, 2018, **8**, 10261; (h) J. X. Xu, L. F. Hu, H. P. Hu, S. L. Ge, X. H. Liu and X. M. Feng, *Org. Lett.*, 2019, **21**, 1632.
- 12 (a) Z. L. Zhang, X. H. Liu, Z. Wang, X. H. Zhao, L. L. Lin and X. M. Feng, *Tetrahedron Lett.*, 2014, **55**, 3797; (b) Y. L. Kuang, Y. Lu, Y. Tang, X. H. Liu, L. L. Lin and X. M. Feng, *Org. Lett.*, 2014, **16**, 4244; (c) B. W. Ma, W. W. Luo, L. L. Lin, X. H. Liu and X. M. Feng, *Chem. Commun.*, 2017, **53**, 4077; (d) D. Zhang, C. K. Yin, Y. H. Zhou, Y. L. Xu, L. L. Lin, X. H. Liu and X. M. Feng, *Chem. Commun.*, 2017, **53**, 7925; (e) C. R. Xu, H. F. Zheng, B. W. Hu, X. H. Liu, L. L. Lin and X. M. Feng, *Chem. Commun.*, 2017, **53**, 9741.
- 13 Y. Zhang, F. C. Zhang, L. Chen, J. Xu, X. H. Liu and X. M. Feng, *ACS Catal.*, 2019, **9**, 4834.
- 14 D. Yu, V. T. Thai, L. I. Palmer, G. K. Veits, J. E. Cook, J. R. de Alaniz and J. E. Hein, *J. Org. Chem.*, 2013, **78**, 12784.
- 15 Y. S. Chen, S. X. Dong, X. Xu, X. H. Liu and X. M. Feng, *Angew. Chem., Int. Ed.*, 2018, **57**, 16554.
- 16 CCDC 1971783 (**3m**) contains the ESI.†

