ChemComm

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2019, **55**, 14011

Received 18th September 2019,
Accepted 25th October 2019

DOI: 10.1039/c9cc07346a

rsc.li/chemcomm

Phosphine-catalyzed (3+2)/(2+3) sequential annulation involving a triple nucleophilic addition reaction of γ-vinyl allenoates†‡

Jiaxu Feng and You Huang *

A phosphine-catalyzed (3+2)/(2+3) sequential annulation involving a triple nucleophilic addition reaction of γ-vinyl allenoates was successfully developed. The reaction provided efficient and more practical access to functionalized hydropyrroloimidazolones with good to excellent yields under mild reaction conditions. Notably, γ-vinyl allenoate served as a triple-electrophilic intermediate in this protocol.

Hydropyrroloimidazolones constitute a valuable class of nitrogen heterocycles and are widely prevalent in biologically active products and pharmaceuticals (Fig. 1).[1] While effective methods for their syntheses have been reported with substituted N-heterocycles,[2] these syntheses remain a formidable challenge.

Phosphine-catalyzed nucleophilic addition[3] is one of the most popular tools for the assembly of C–C and C–N bonds in organic synthesis.[4] In this field, activated allenoates have been recognized as one of the most effective starting materials[5] and the seminal work has been vastly expanded upon, leading to great potential for the synthesis of natural products.[6] The formidable breakthrough in phosphine catalysis was reported by Trost, who discovered that the γ-umpolung addition of nucleophiles to activated allenoates and alkynoates leads to the formation of C–C bonds[7] (Scheme 1, (a)). Subsequently, many efforts have been devoted to the γ-umpolung addition of various pro-nucleophiles.[8] Later on, Huang and Lu reported phosphine-catalyzed β-Michael addition[9] under mild reaction conditions (Scheme 1, (b)).

Phosphine-catalyzed nucleophilic addition of allenoates using di-nucleophiles as substrates has emerged as a valuable approach for forming functionalized carbocycles and heterocycles from acyclic reactants (Scheme 1, (c)).[10] In 2002, Lu reported using a tandem reaction involving phosphine-catalyzed umpolung addition and intramolecular conjugate addition to form carbocycles and heterocycles.[11] Later, Lu[12] and Kwon[13] delivered, respectively, the efficient syntheses of carbocycles and heterocycles using allenoates and various dinucleophiles in a tandem reaction. Moreover, Tong[14] and Shi[15] similarly described a phosphine-catalyzed tandem annulation with δ-acetoxy allenoates to 1,3-bisnucleophiles, which could be converted to various heterocycles. Furthermore, the reactions of 1,1- and 1,2-bisnucleophiles with allenoates to form five- and six-membered carbocyclic and heterocyclic products have also been reproted.[16] To the best of our knowledge, there has been no report about reactions between allenoates and nucleophiles involving triple nucleophilic additions, probably because of several challenges that could not be ignored, such as (1) competing reactions at multiple reaction sites in allenoates, (2) difficulty in finding suitable nucleophiles, and (3) difficulty in controlling the regioselectivity. In order to overcome these issues and accomplish this desired reaction, it is critical to carefully design the allenoates and screen multifunctional nucleophiles. On the basis of our group's previous work in the phosphine catalysis of sequential annulation,[17] we designed and synthesized a new kind of γ-vinyl allenoate. Our group provided here the first examples of phosphine-catalyzed (3+2)/(2+3) sequential annulation mediated by a triple nucleophilic addition reaction of γ-vinyl allenoates with urea derivatives (Scheme 1, (d)). This work featured a fine control

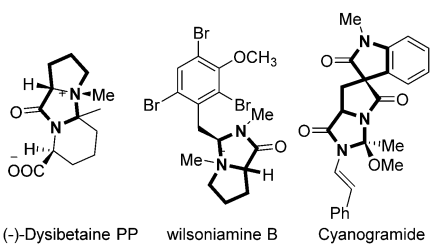
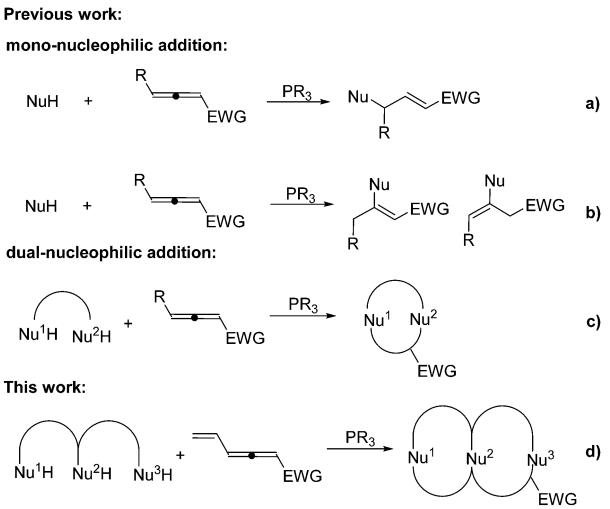


Fig. 1 Selected examples of natural products and bioactive molecules containing the hydropyrroloimidazolone unit.

State Key Laboratory and Institute of Elemento-Organic Chemistry, College of Chemistry, Nankai University, Tianjin 300071, China. E-mail: hyou@nankai.edu.cn

† Dedicated to 100th anniversary of Nankai University and dedicated to the 100th anniversary of the birth of the academician Ruyu Chen.

‡ Electronic supplementary information (ESI) available. CCDC 1938975 (**3aa**), 1938970 (**4aa**) and 1938977 (**5wa**). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c9cc07346a



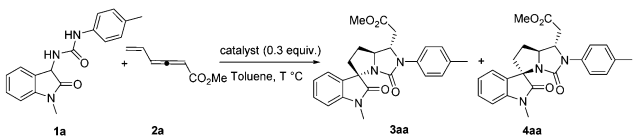
Scheme 1 Nucleophilic addition of the allenoate in the phosphine catalyst.

of the regioselectivity and a wide substrate scope, which provided a new and practical route to the construction of hydropyrroloimidazolone derivatives.

At the outset of our studies, we chose 1-(1-methyl-2-oxoindolin-3-yl)-3-(*p*-tolyl)urea (**1a**) and γ-vinyl allenoates (**2a**) as model starting materials to explore the optimal conditions for this (3+2)/(2+3) nucleophilic addition reaction. As a result of our initial screening of conditions, the use of PPh_3 in toluene at 110 °C led to the corresponding heterocyclic product diastereomer **3aa** in 23% yield (Table 1, entry 1).

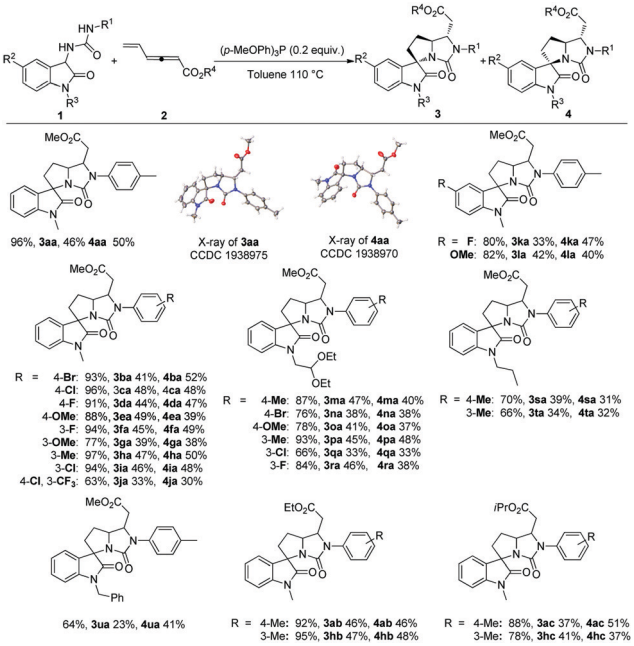
Screening of phosphine catalysts revealed that PBu_3 and $(p\text{-}FC_6H_4)_3P$ were ineffective in this reaction (entries 2 and 3). Gratifyingly, when $(p\text{-}MeOC_6H_4)_3P$ was used, two diastereomers were obtained in 94% total yield. Pleasingly, we were able to completely separate the diastereomers **3aa** and **4aa** using silica-gel

Table 1 Optimization of the reaction conditions[a]



Entry	Cat. (30 mol%)	Temp. (°C)	Yield[b] (%) 3	4
1	PPh_3	110	23	—
2	PBu_3	110	—	—
3	$(p\text{-}FC_6H_4)_3P$	110	—	—
4	$(p\text{-}MeOC_6H_4)_3P$	110	45	49
5	$(p\text{-}MeOC_6H_4)_3P$	50	37	32
6	$(p\text{-}MeOC_6H_4)_3P$	25	32	24
7[c]	$(p\text{-}MeOC_6H_4)_3P$	110	46	50
8[d]	$(p\text{-}MeOC_6H_4)_3P$	110	50	42
9[c,e]	$(p\text{-}MeOC_6H_4)_3P$	110	36	32

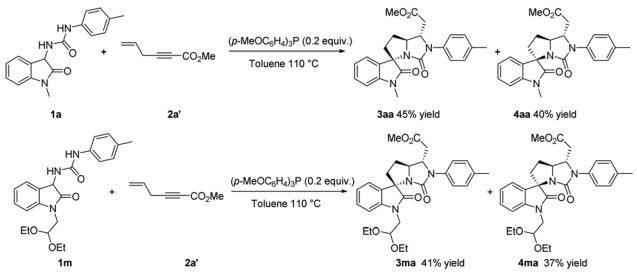
[a] Reaction conditions: 0.20 mmol **1a** (1.0 equiv.), 0.60 mmol **2a** (3.0 equiv.), cat. (30 mol%) in toluene (2.0 mL) at 110 °C. [b] Yield of isolates product. [c] Cat. (20 mol%) was added. [d] Cat. (40 mol%) was added. [e] 0.40 mmol **2a** (2.0 equiv.) was used.



Scheme 2 The scope of this reaction. The reaction was performed under optimum conditions. Isolated yield is shown.

column chromatography and achieved yields of 45% and 49%, respectively (entry 4). Subsequent testing of the effect of temperature confirmed that 110 °C was the best temperature (entries 5 and 6) and in fact showed that the reaction outcome was highly affected by the reaction temperature. Moreover, further evaluation here of reaction conditions showed a higher yield when lowering the catalyst loading to 20% (entry 7), but increasing the $(p\text{-}MeOC_6H_4)_3P$ loading led to a similar result (entry 8). Lowering the amount of **2a** did not result in a satisfactory outcome (entry 9).

With the optimal reaction conditions in hand, we turned our attention to validating the potential and generality of this (3+2)/(2+3) annulation reaction. We first investigated a variety of multifunctional nucleophiles (Scheme 2). A broad range of substituted ureas, including those bearing electron-donating groups (Me or MeO) and electron-withdrawing groups (F, Cl or Br) at the *para*- or *meta*-position of the aryl ring moiety (R^1), were compatible with the reaction conditions and gave the corresponding diastereoisomer products in good to excellent yields (**3aa–3ia**, **4aa–4ia**), respectively, showcasing the excellent functional group tolerance of the reaction. The relative configurations of the diastereoisomers **3aa** and **4aa** were determined by carrying out X-ray crystal analysis and others were assigned by analogy. In addition, urea **1j** with a 3-CF_3, 4-Cl substitution on the aryl group (3-CF_3, 4-Cl bis-substituted urea **1j**) was found to be suitable and afforded desired products with moderate yields. Delightedly, 5-fluorine and the 5-MeO group in the oxindole core also proved to yield good substrates, affording the products (**3ka–3la**, **4ka–4la**) with good yields. Then we explored the effects of the protection of the nitrogen atom in the oxindole core by protecting groups such as $CH_2CH(OEt)_2$ (**1m–1r**), *n*-Pr (**1s–1t**) and Bn (**1u**). It was found that the methyl protecting group was most effective. A gram-scale reaction of urea **1m** and allenoates **2a** was tested, and resulted in



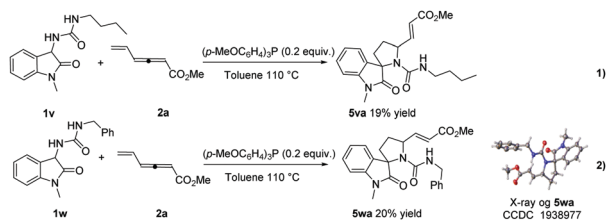
Scheme 3 Further transformations using this method.

an 83% overall yield. Meanwhile, other protecting groups were also well tolerated, which highlighted the broad substrate scope of this reaction. Furthermore, various γ-vinyl allenoates were tested, and produced the target compounds with good yields (**3ab**, **3ac**, **3bb**, **3bc**, **4ab**, **4ac**, **4bb**, **4bc**).

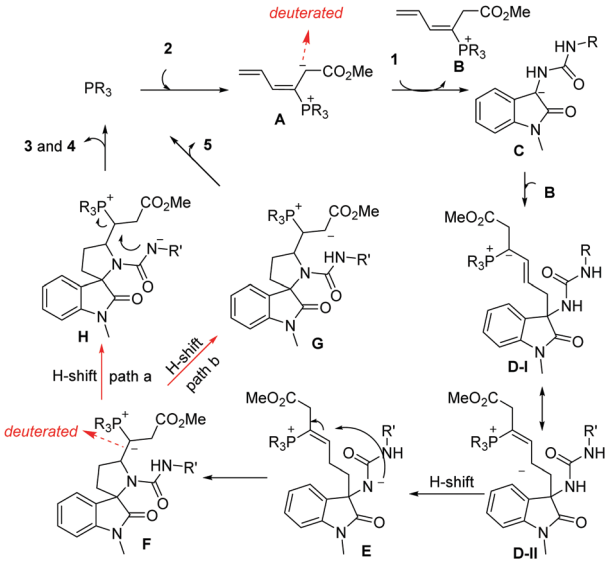
In order to further underscore the synthetic utility of this method, we also explored the reactivities of alkyne compounds. Intriguingly, when methyl hex-5-en-2-ynoate was employed in this annulation, the desired diastereoisomer products **3aa**, **4aa**, **3ma** and **4ma** were also obtained under the same conditions with satisfactory yields (Scheme 3).

To gain further insight into the mechanism of the reaction, control experiments were performed (Scheme 4). Treatment of 1-butyl-3-(1-methyl-2-oxoindolin-3-yl)urea **1v** with γ-vinyl allenoates under the optimal conditions did not yield the corresponding products **3va** and **4va**, but the key intermediate product spirooxindole **5va** was isolated (Scheme 4, (1)). The structure of **5va** was confirmed from NMR and HRMS spectra. Additionally, the reaction of 1-benzyl-3-(1-methyl-2-oxoindolin-3-yl)urea, **1w**, with **2a** was tested, and the intermediate spirooxindole **5wa** was also obtained with 20% yield (Scheme 4, (2)). The structure and relative configuration of intermediate **5wa** was confirmed using X-ray crystallography. Next, two different pro-nucleophiles, **1x** and **1y**, were synthesized and we also examined their reactivities under optimal reaction conditions. However, when the pro-nucleophile **1x** was employed as a substrate, no desired product was afforded under optimal conditions (Scheme S1, (1), see ESI‡ for details), which indicated that the urea nitrogen atom played a crucial role in the annulation. Moreover, substrate **1y** was also inefficient (Scheme S1, (2), ESI‡). These outcomes indicated that the oxindole backbone was indispensable and its structurally unique property may have triggered the formation of the important intermediate **D**.

On the basis of the detailed mechanistic understanding and our previous works,[18] a plausible reaction mechanism was



Scheme 4 Preliminary mechanism study.



Scheme 5 Proposed reaction mechanism.

derived (shown in Scheme 5). This mechanism differs from the phosphine-catalyzed reaction mechanisms of allenoates reported before in which the key intermediates of allenoates were the (1,*n*)-zwitterion or the 1,4-bis-electrophile intermediates.

According to the currently proposed mechanism, first nucleophilic addition to vinyl allenoates **2** by PPh_3 afforded zwitterionic intermediate **A**, which then acted as a base to deprotonate the pro-nucleophile **1** leading to the construction of the intermediates **B** and **C**. Subsequently, according to the mechanism, nucleophilic attack of the vinyl group of intermediate **B** by intermediate **C** produced intermediate **D-I**, which formed an equilibrium with intermediate **D-II**, and then **D-II** deprotonated to generate the corresponding intermediate **E**. Next, according to the proposal, intramolecular Michael addition (the second nucleophilic addition) occurred to give the intermediate **F**, which then underwent a proton shift and the third nucleophilic addition (see path a in Scheme 5), finally producing the desired (3+2)/(2+3) annulation product. Through an alternative path (path b in Scheme 5), byproduct **5** was obtained through an H-shift and subsequent 1,2-elimination of PPh_3.

In summary, we have developed a novel and efficient phosphine-catalyzed (3+2)/(2+3) sequential annulation mediated by triple nucleophilic addition. By using substituted urea compounds as readily accessible precursors of triple-functional nucleophiles, a wide range of hydropyrroloimidazolones were obtained in good to excellent yields under mild conditions, showing the great tolerance of the reaction to a wide variety of functional groups. This step-economical and regionally selective method involved formation of a C–C bond and two C–N bonds and the production of functionalized N-hetero-bicyclic derivatives bearing three stereogenic centers. In this sequence, γ-vinyl allenoates were shown to serve as versatile triple electrophiles and to be able to participate in three nucleophilic additions with pro-nucleophiles. Interestingly, the (3+2)/(2+3) sequential annulation was also compatible with the use of an enyne, and in this case afforded hydropyrroloimidazolone with a satisfactory outcome. This approach provides a potential method

for the preparation of natural products and pharmaceutical molecules. Investigations of further applications of this method are ongoing in our laboratory.

We thank the National Natural Science Foundation of China (21672109, 21871148 and 21472097) for financial support.

Conflicts of interest

There are no conflicts to declare.

Notes and references

1 (*a*) T. Y. Lin, H. H. Wu, J. J. Feng and J. Zhang, *Org. Lett.*, 2018, **20**, 3587–3590; (*b*) F. A. Khan and S. Ahmad, *Tetrahedron Lett.*, 2013, **54**, 2996–2998; (*c*) A. R. Carroll, S. Duffy, M. Sykes and V. M. Avery, *Org. Biomol. Chem.*, 2011, **9**, 604–609.

2 (*a*) L. Zhu, P. Xiong, Z.-Y. Mao, Y.-H. Wang, X. Yan, X. Lu and H.-C. Xu, *Angew. Chem., Int. Ed.*, 2016, **55**, 2226–2229; (*b*) A. E. Nibbs, T. D. Montgomery, Y. Zhu and V. H. Rawal, *J. Org. Chem.*, 2015, **80**, 4928–4941; (*c*) G. J. Choi and R. R. Knowles, *J. Am. Chem. Soc.*, 2015, **137**, 9226–9229; (*d*) H. Zhang, Q. Shen and L. Lu, *Tetrahedron Lett.*, 2011, **52**, 349–351; (*e*) K. C. Nicolaou, P. S. Baran, Y. L. Zhong, S. Barluenga, K. W. Hunt, R. Kranich and J. A. Vega, *J. Am. Chem. Soc.*, 2002, **124**, 2233–2244.

3 (*a*) H. Ni, W. L. Chan and Y. Lu, *Chem. Rev.*, 2018, **118**, 9344–9411; (*b*) H. Guo, Y. C. Fan, Z. Sun, Y. Wu and O. Kwon, *Chem. Rev.*, 2018, **118**, 10049–10293; (*c*) Y. Wei and M. Shi, *Chem. – Asian J.*, 2014, **9**, 2720–2734; (*d*) Y. Lu, S.-X. Wang, X. Han, F. Zhong and Y. Wang, *Synlett*, 2011, 2766–2778; (*e*) B. J. Cowen and S. J. Miller, *Chem. Soc. Rev.*, 2009, **38**, 3102–3116; (*f*) J. L. Methot and W. R. Roush, *Adv. Synth. Catal.*, 2004, **346**, 1035–1050.

4 Selected reports of nucleophilic addition: (*a*) J. Zhang, C. Cheng, D. Wang and Z. Miao, *J. Org. Chem.*, 2017, **82**, 10121–10128; (*b*) A. Marinetti, A. Voituriez and M. Gicquel, *Synlett*, 2014, 142–166; (*c*) F. Lopez and J. L. Mascarenas, *Chem. Soc. Rev.*, 2014, **43**, 2904–2915; (*d*) D. En, G. F. Zou, Y. Guo and W. W. Liao, *J. Org. Chem.*, 2014, **79**, 4456–4462; (*e*) D. Basavaiah, B. S. Reddy and S. S. Badsara, *Chem. Rev.*, 2010, **110**, 5447–5674; (*f*) L. W. Ye, J. Zhou and Y. Tang, *Chem. Soc. Rev.*, 2008, **37**, 1140–1152; (*g*) S. E. Denmark and G. L. Beutner, *Angew. Chem., Int. Ed.*, 2008, **47**, 1560–1638; (*h*) X. Lu, C. Zhang and Z. Xu, *Acc. Chem. Res.*, 2001, **34**, 535–544.

5 (*a*) Z. Wang, X. Xu and O. Kwon, *Chem. Soc. Rev.*, 2014, **43**, 2927–2940; (*b*) Y. C. Fan and O. Kwon, *Chem. Commun.*, 2013, **49**, 11588–11619; (*c*) C. Zhu, B. Yang and J. E. Backvall, *J. Am. Chem. Soc.*, 2015, **137**, 11868–11871; (*d*) C. Zhu, B. Yang, T. Jiang and J. E. Backvall, *Angew. Chem., Int. Ed.*, 2015, **54**, 9066–9069; (*e*) C. Zhu, B. Yang, Y. Qiu and J. E. Backvall, *Angew. Chem., Int. Ed.*, 2016, **55**, 14405–14408.

6 (*a*) Y. Hou, Y. Zhang and X. Tong, *Org. Biomol. Chem.*, 2018, **16**, 5245–5249; (*b*) T. Wang, W. Yao, F. Zhong, G. H. Pang and Y. Lu, *Angew. Chem., Int. Ed.*, 2014, **53**, 2964–2968; (*c*) V. Kumar and S. Mukherjee, *Chem. Commun.*, 2013, **49**, 11203–11205; (*d*) T. J. Martin, V. G. Vakhshori, Y. S. Tran and O. Kwon, *Org. Lett.*, 2011, **13**, 2586–2589; (*e*) X.-Y. Guan, Y. Wei and M. Shi, *Eur. J. Org. Chem.*, 2011, 2673–2677; (*f*) R. Sinisi, J. Sun and G. C. Fu, *Proc. Natl. Acad. Sci. U. S. A.*, 2010, **107**, 20652–20654; (*g*) X.-Y. Guan, Y. Wei and M. Shi, *Org. Lett.*, 2010, **12**, 5024–5027; (*h*) S. Xu, L. Zhou, S. Zeng, R. Ma, Z. Wang and Z. He, *Org. Lett.*, 2009, **11**, 3498–3501.

7 (*a*) B. M. Trost and C.-J. Li, *J. Am. Chem. Soc.*, 1994, **116**, 3167–3168; (*b*) B. M. Trost and C.-J. Li, *J. Am. Chem. Soc.*, 1994, **116**, 10819–10820.

8 Selected reports of γ-umpolung addition: (*a*) T.-C. Kang, L.-P. Wu, F. Sha and X.-Y. Wu, *Tetrahedron*, 2018, **74**, 1017–1023; (*b*) Y.-N. Gao and M. Shi, *Eur. J. Org. Chem.*, 2017, 1552–1560; (*c*) P. Chen and J. Zhang, *Org. Lett.*, 2017, **19**, 6550–6553; (*d*) Q. F. Zhou, K. Zhang and O. Kwon, *Tetrahedron Lett.*, 2015, **56**, 3273–3276; (*e*) T. Wang, Z. Yu, D. L. Hoon, K. W. Huang, Y. Lan and Y. Lu, *Chem. Sci.*, 2015, **6**, 4912–4922; (*f*) T. Wang, D. L. Hoon and Y. Lu, *Chem. Commun.*, 2015, **51**, 10186–10189; (*g*) M. Kalek and G. C. Fu, *J. Am. Chem. Soc.*, 2015, **137**, 9438–9442; (*h*) R. J. Lundgren, A. Wilsily, N. Marion, C. Ma, Y. K. Chung and G. C. Fu, *Angew. Chem., Int. Ed.*, 2013, **52**, 2525–2528; (*i*) I. P. Andrews, B. R. Blank and O. Kwon, *Chem. Commun.*, 2012, **48**, 5373–5375; (*j*) Y. Fujiwara, J. Sun and G. C. Fu, *Chem. Sci.*, 2011, **2**, 2196–2198; (*k*) J. Sun and G. C. Fu, *J. Am. Chem. Soc.*, 2010, **132**, 4568–4569; (*l*) A. L. Cardoso, A. M. Beja, M. R. Silva, J. M. de los Santos, F. Palacios, P. E. Abreu, A. A. C. C. Pais and T. M. V. D. Pinho e Melo, *Tetrahedron*, 2010, **66**, 7720–7725; (*m*) S. W. Smith and G. C. Fu, *J. Am. Chem. Soc.*, 2009, **131**, 14231–14233; (*n*) Y. K. Chung and G. C. Fu, *Angew. Chem., Int. Ed.*, 2009, **48**, 2225–2227; (*o*) D. Virieux, A.-F. Guillouzic and H.-J. Cristau, *Tetrahedron*, 2006, **62**, 3710–3720; (*p*) X. Lu, Z. Lu and X. Zhang, *Tetrahedron*, 2006, **62**, 457–460; (*q*) C. Alvarez-Ibarra, A. G. Csákÿ and C. Gómez de la Oliva, *J. Org. Chem.*, 2000, **65**, 3544–3547; (*r*) Z. Chen, G. Zhu, Q. Jiang, D. Xiao, P. Cao and X. Zhang, *J. Org. Chem.*, 1998, **63**, 5631–5635; (*s*) C. Zhang and X. Lu, *Synlett*, 1995, 645–646.

9 (*a*) V. R. Gandi and Y. Lu, *Chem. Commun.*, 2015, **51**, 16188–16190; (*b*) E. Li, P. Xie, L. Yang, L. Liang and Y. Huang, *Chem. – Asian J.*, 2013, **8**, 603–610.

10 (*a*) Z. Huang, X. Yang, F. Yang, T. Lu and Q. Zhou, *Org. Lett.*, 2017, **19**, 3524–3527; (*b*) P. Xie, W. Lai, Z. Geng, Y. Huang and R. Chen, *Chem. – Asian J.*, 2012, **7**, 1533–1537; (*c*) B. Liu, R. Davis, B. Joshi and D. W. Reynolds, *J. Org. Chem.*, 2002, **67**, 4595–4598.

11 C. Lu and X. Lu, *Org. Lett.*, 2002, **4**, 4677–4679.

12 Z. Lu, S. Zheng, X. Zhang and X. Lu, *Org. Lett.*, 2008, **10**, 3267–3270.

13 J. Szeto, V. Sriramurthy and O. Kwon, *Org. Lett.*, 2011, **13**, 5420–5423.

14 (*a*) D. Wang, W. Liu, Y. Hong and X. Tong, *Org. Lett.*, 2018, **20**, 5002–5005; (*b*) D. Wang and X. Tong, *Org. Lett.*, 2017, **19**, 6392–6395; (*c*) C. Ni, J. Chen, Y. Zhang, Y. Hou, D. Wang, X. Tong, S. F. Zhu and Q. L. Zhou, *Org. Lett.*, 2017, **19**, 3668–3671; (*d*) J. Hu, W. Dong, X.-Y. Wu and X. Tong, *Org. Lett.*, 2012, **14**, 5530–5533.

15 J. Xing, Y. Lei, Y. N. Gao and M. Shi, *Org. Lett.*, 2017, **19**, 2382–2385.

16 (*a*) D. Wang, W. Liu, Y. Hong and X. Tong, *Org. Lett.*, 2018, **20**, 5002–5005; (*b*) S. Kramer and G. C. Fu, *J. Am. Chem. Soc.*, 2015, **137**, 3803–3806; (*c*) D. T. Ziegler, L. Riesgo, T. Ikeda, Y. Fujiwara and G. C. Fu, *Angew. Chem., Int. Ed.*, 2014, **53**, 13183–13187; (*d*) X. Han, W. Yao, T. Wang, Y. R. Tan, Z. Yan, J. Kwiatkowski and Y. Lu, *Angew. Chem., Int. Ed.*, 2014, **53**, 5643–5647; (*e*) Q. Zhang, L. Yang and X. Tong, *J. Am. Chem. Soc.*, 2010, **132**, 2550–2551; (*f*) B. Liu, R. Davis, B. Joshi and D. W. Reynolds, *J. Org. Chem.*, 2002, **67**, 4595–4598.

17 (*a*) E. Li, H. Jin and Y. Huang, *ChemistrySelect*, 2018, **3**, 12007–12010; (*b*) E. Li, M. Chang, L. Liang and Y. Huang, *Eur. J. Org. Chem.*, 2015, 710–714; (*c*) E. Li, P. Jia, L. Liang and Y. Huang, *ACS Catal.*, 2014, **4**, 600–603; (*d*) E. Li and Y. Huang, *Chem. – Eur. J.*, 2014, **20**, 3520–3527; (*e*) E. Li and Y. Huang, *Chem. Commun.*, 2014, **50**, 948–950; (*f*) J. Zheng, Y. Huang and Z. Li, *Org. Lett.*, 2013, **15**, 5758–5761; (*g*) N. Li, P. Jia and Y. Huang, *Chem. Commun.*, 2019, **55**, 10976–10979.

18 (*a*) E. Li, H. Jin, P. Jia, X. Dong and Y. Huang, *Angew. Chem., Int. Ed.*, 2016, **55**, 11591–11594; (*b*) Y. Gu, P. Hu, C. Ni and X. Tong, *J. Am. Chem. Soc.*, 2015, **137**, 6400–6406.

