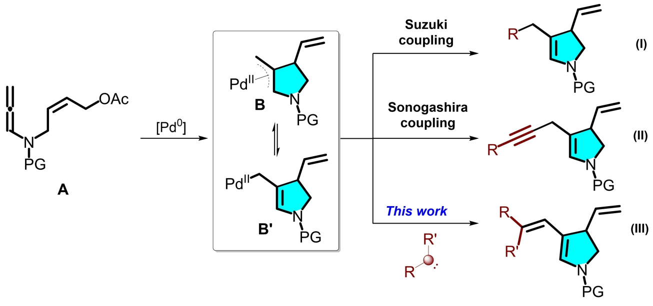
EurJOC
European Journal of Organic Chemistry
Communications
doi.org/10.1002/ejoc.202001625
Chemistry Europe
European Chemical Societies Publishing

Pd-Catalyzed Cascade Metallo-Ene Cyclization/Metallo-Carbene Coupling of Allenamides

Chengqiang Cao,[a] Yi Yang,[a] Xin Li,[a] Yunxia Liu,[a] Hui Liu,*[a] Zengdian Zhao,*[a] and Lei Chen*[a]

A highly efficient palladium-catalyzed cascade metallo-ene/metallo-carbene coupling reaction was developed to produce 2,3-dihydropyrrole derivatives in high yields. In this transformation, two new Csp^3–Csp^2 and Csp^2–Csp^2 bonds were constructed in one-pot. The alkene was one of the most easily functionalized groups, making it possible for these molecules to be transformed into more complex molecules. More importantly, the final product possessed an attractive 1,3,8-trienes scaffold, which was difficult to be synthesized.



Scheme 1. Synthesis of polyfunctionalized 2,3-dihydropyrrole derivates.

Multifunctional pyrrole has attracted much attention due to its widespread presence in natural products, bioactive molecules, material chemistry, and organic chemical intermediates.[1] A lot of drugs and bioactivated compounds bearing pyrrole scaffold have been reported, such as an irreversible pan-ErbB inhibitor pyrotinib,[2] a serotonin reuptake inhibitor from Eli Lilly,[3] farnesyltransferase inhibitors (LB-42708),[4] and drugs with anti-juvenile hormone, antiviral,[5] or antibiotic activity (Figure 1). Therefore, it is important to develop practical and efficient methods for the construction of pyrrole scaffolds.

Until now, numerous efficient methods of constructing pyrrole motifs have been reported.[6–11] The method using transition metal-catalysis has become the most powerful tool,[6] such as Ni,[7] Pd,[8] Pt,[9] Rh,[10] and Ru.[11] Due to the unique reactivity, selectivity, availability, and stability of allenamides, they have been widely used in the synthesis of nitrogen-containing heterocyclic derivatives.[12] In the past few's years, our group has developed a variety of methodologies towards valuable heterocycles using allenamide derivatives.[13] As shown in Scheme 1, in the presence of palladium(0) species, the allenamides **A** could generate two π-allyl palladium intermediates **B** and **B'** with Csp^3–Csp^2 bond formation via Metallo-ene transformation. Based on intermediates **B** and **B'**, we have applied Suzuki coupling and Sonogashira coupling to capture the intermediates to construct 2,3-2H-pyrrole derivates (**I**) and (**II**) bearing aromatic or alkynyl groups.[13b–c] To further explore, novel methodologies to construct functionalized pyrroles, we continued to consider the transformation of intermediate **B** and **B'**. So far, numerous classic methodologies have been developed in the construction of alkenes.[14] Among them, metal-carbene strategy is quite effective in the synthesis of special double bonds in the target position.[15] So we tried to apply metal-carbene strategy to capture the intermediate **B** to furnish the 2,3-dihydropyrrole derivatives bearing triene which is difficult to synthesis via the other method.

Diazo compounds have been well investigated in metal-carbene process.[16–21] The pioneering work of Van Vranken showed that the palladium-catalyzed system promoted diazo compounds to form novel carbon-carbon double bonds.[16] Since Aggarwal's work, the use of tosylhydrazone as diazo compounds precursor promoted palladium-carbene coupling reaction into a new realm with a remarkably wide scope.[17] Various substituted alkenes were synthesized efficiently via palladium-carbene process by Van Vranken,[18] Wang,[19] Barluenga and Valdés,[20] and others.[21]

Considering the pyrrole intermediate **B'**, we assumed that it may form palladium-carbene pyrrole intermediate with diazo compounds to deliver 2,3-2H-pyrroles (**III**) bearing a triene scaffold as shown in Scheme 1. Initially, our study commenced with allenamides (**1**) and *N*-tosyl hydrazones (**2 a**) in the presence of 10 mol% $PdCl_2(PPh_3)_2$, 2.5 equiv. *t*BuOLi at 90 °C in anhydrous dioxane under nitrogen atmosphere. To our delight, the target product **3 a** was obtained in 56 % yield, and excellent E-configuration was obtained which was determined via ^1H NMR spectroscopy (the coupling constant of the proton on $C{=}C$ bond is 16 Hz) (Entry 1, Table 1). However, besides the target product **3 a**, we speculate that the reaction generated the side-product 3a' by GC-MS data. Next, the effect of catalyst, ligand, and solvent was examined in the reaction. When $PdCl_2(PPh_3)_2$ was replaced by $PdCl_2(dppf)$, the yield was increased to 73 %, however, there were still reductive

---

[a] C. Cao, Y. Yang, X. Li, Y. Liu, Prof. H. Liu, Prof. Z. Zhao, Prof. L. Chen
School of Chemistry and Chemical Engineering
Shandong University of Technology
266 West Xincun Road
Zibo 255049, P. R. China
E-mail: chstone@163.com
huiliu1030@163.com
zhaozengdian@sdut.edu.cn

Supporting information for this article is available on the WWW under https://doi.org/10.1002/ejoc.202001625

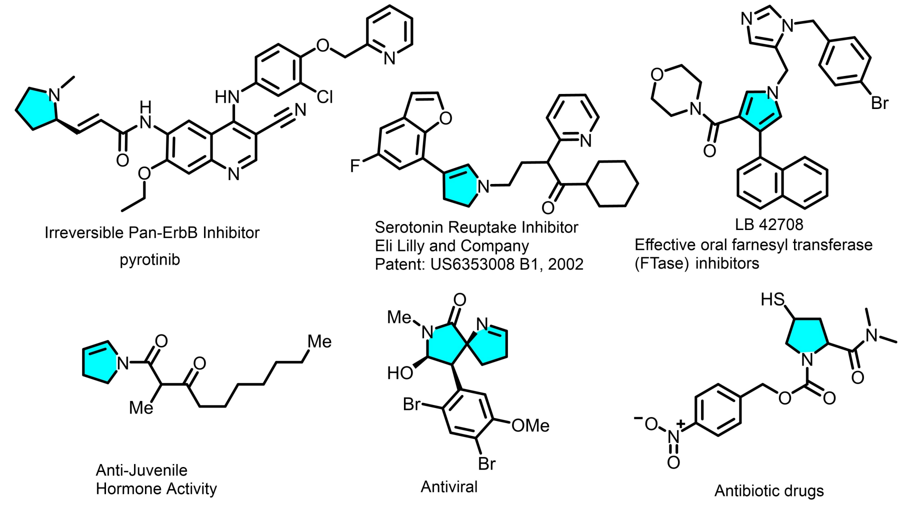
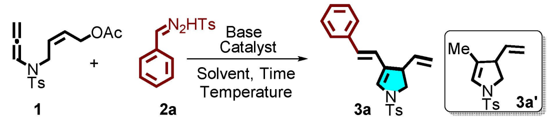
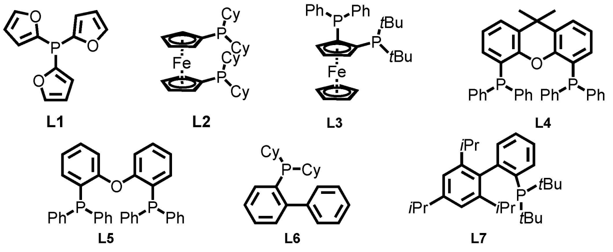


Figure 1. Representative bioactive molecules bearing a 2,3-dihydro-pyrrole scaffolds.

Table 1. Condition optimization screening.[a]



Entry	Catalyst	Base	Solvent	Temperature(°C)	Time(h)	Yield(%)[b]
1	$PdCl_2(PPh_3)_2$	*t*BuOLi	dioxane	90	4	56
2	$PdCl_2$(dppf)	*t*BuOLi	dioxane	90	4	73
3	$PdCl_2$(dppf)	*t*BuOLi	toluene	90	4	71
4	$PdCl_2$(dppf)	*t*BuOLi	*i*PrOH	90	4	26
5	$PdCl_2$(dppf)	*t*BuOLi	MeTHF	90	4	80
6	$Pd_2(dba)_3$/**L1**	*t*BuOLi	MeTHF	90	4	46
7	$Pd(OAc)_2$/**L2**	*t*BuOLi	MeTHF	90	3.5	31
8	$Pd(OAc)_2$/**L3**	*t*BuOLi	MeTHF	90	3	36
9	$Pd(OAc)_2$/**L4**	*t*BuOLi	MeTHF	90	2.5	22
10	$Pd(OAc)_2$/**L5**	*t*BuOLi	MeTHF	90	2.5	46
11	$Pd(OAc)_2$/**L6**	*t*BuOLi	MeTHF	90	3	61
12	$Pd(OAc)_2$/**L7**	*t*BuOLi	MeTHF	90	3	51
13	$Pd(OAc)_2$/dppm	*t*BuOLi	MeTHF	90	3	16
14	$Pd(OAc)_2$/dppe	*t*BuOLi	MeTHF	90	3	44
15	$Pd(OAc)_2$/dppp	*t*BuOLi	MeTHF	90	3.5	69
16	$Pd(OAc)_2$/dppf	*t*BuOLi	MeTHF	90	3	73
17	$Pd(OAc)_2$/dppb	*t*BuOLi	MeTHF	90	3.5	67
18	**$PdCl_2$(dppf)**	**tBuOLi**	**MeTHF**	**90**	**3**	**82**
19	$PdCl_2$(dppf)	*t*BuOLi	MeTHF	110	3	70[c]
20	$PdCl_2$(dppf)	CH_3OLi	MeTHF	90	3	10[d]
21	$PdCl_2$(dppf)	*t*BuOLi	MeTHF	90	3	51[e]



[a] Reation conditions:1 (0.2 mmol), **2 a** (0.4 mmol), [Pd] (0.02 mmol), base (0.5 mmol), solvent (2.0 mL). [b] Isolated. [c] The threaded tube reaction. [d] When other bases were used, the yield was reduced. [e] [Pd] (0.01 mmol).

products present (Entry 2, Table 1). Then toluene, *i*PrOH, and 2-Me–THF were used as a solvent, indicating that 2-Me–THF were used as solvent could provide the corresponding product in 80 % yield (Entry 3–5, Table 1). Surprisingly, the use of MeTHF as solvent could inhibit the formation of byproducts, which was helpful to the purification. Subsequently, we investigated a large number of ligands, including both monodentate and bidentate phosphine ligands might play an important role in the transformation. To further understand the influence of bidentate ligands, the angle size of P–Pd–P in PdLn was investigated. It was found that the yields showed a corresponding relationship with the angle of bidentate ligands such as dppm, dppe, dppp and dppb, and dppf[20c–l] (the P–Pd–P angle bond of dppm is 72.2°, dppe is 85.8°, dppf is 99.1°, dppp is 90.6°, dppb is slightly greater than 99.1°, L4 is 108°, L5 is 113°.) (Figure 2). When P–Pd–P bond angle closed to 99.1° (such as dppf), the yield was closed to reach a high level (Entries 13–17). Furthermore, we investigated the temperature and reaction time, and it indicated that higher temperature and longer reaction time led to the yield decreasing (Entries 18 and 19). In addition, when *t*BuOLi was replaced by CH_3OLi, the yield was sharply decreased to 10 % (Table. 1, Entry 20). Finally, 10 mol% $PdCl_2$(dppf), 2.5 equiv. *t*BuOLi at 90 °C in 2-Me–THF for 3 hours was employed as the standard conditions.

Based on the optimized conditions, the substrate scope of *N*-*p*-tosyl hydrazone was investigated (Table 2). We examined both *N*-*p*-tosyl aldehyde and ketone hydrazones bearing different functional groups under the optimal conditions. When phenyl substitution of aldehyde hydrazone bearing electron-donating group such as –Me, –Et, -*i*Pr, or -*t*Bu, the corresponding products were obtained in good yields (**3 b**, **3 c**, **3 d**, **3 e**). On the other hand, substrates with electron-withdrawing groups such as $-CF_3$, –F, and –Cl could also be effectively transformed to the corresponding products (**3 f**, **3 g**, and **3 h**). In addition, *N*-*p*-tosyl-furfural hydrazone could also produce the corresponding coupling product **3 i** in 77 % yield. Besides *N*-*p*-tosyl-aldehyde hydrazone derivatives, the representative *N*-*p*-tosyl-

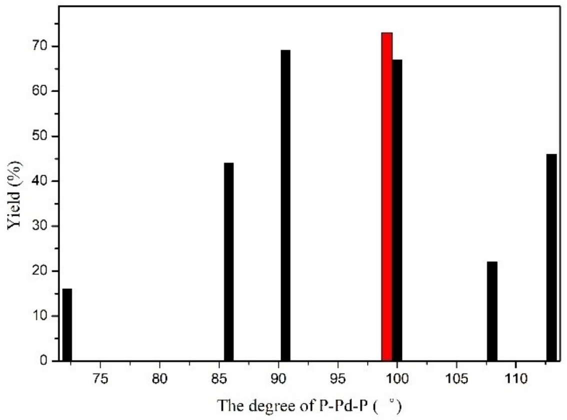
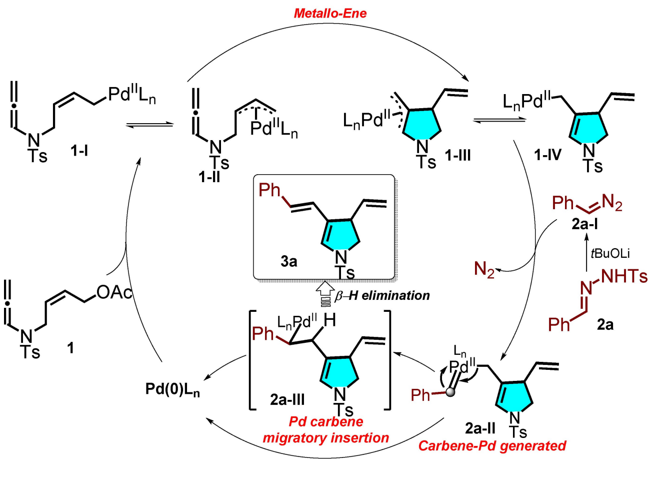


Figure 2. Relationship between bond angle of P–Pd–P and yield.

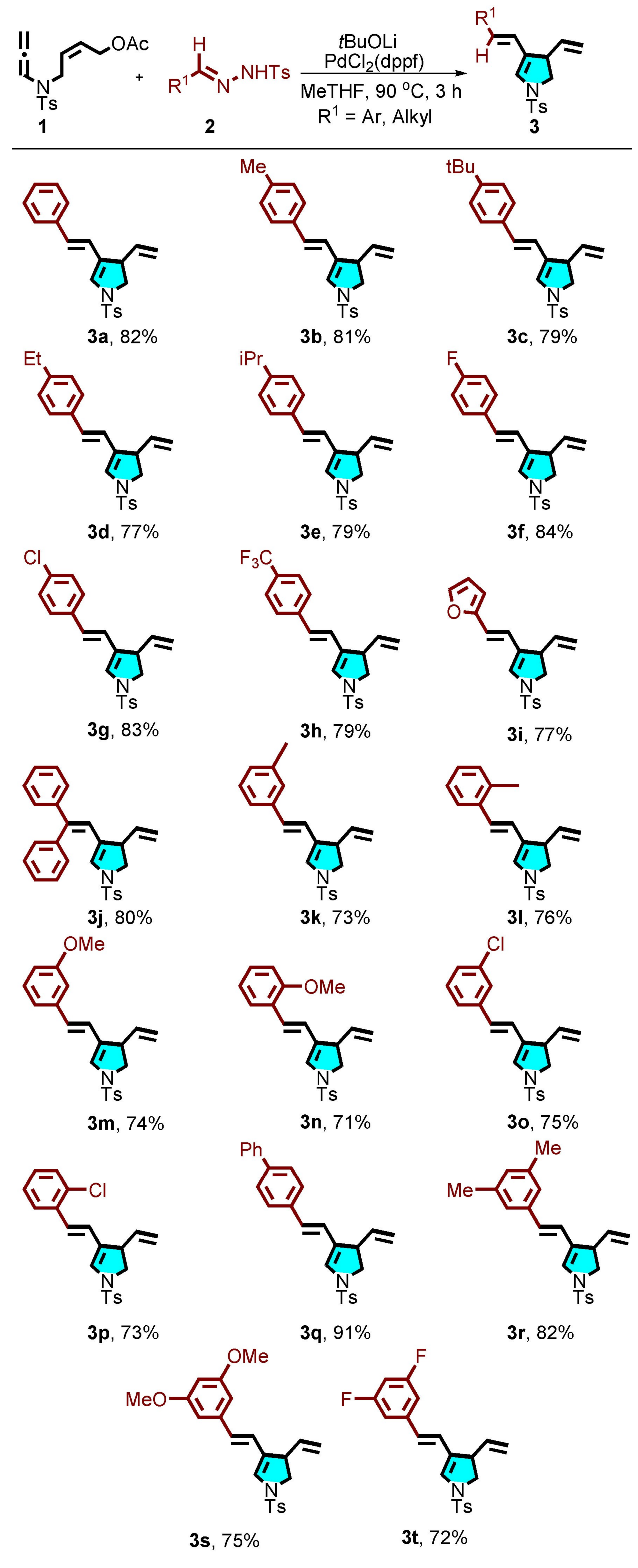
ketone hydrazone derivatives were also investigated. The desired product **3j** from the symmetrical diphenylmethyl ketone derivatives was isolated in 75 %. When the substitutions are in the ortho or meta position of phenyl group of aldehyde hydrazone, both electron-donating groups (*m*-Me, *o*-Me,*m*-OMe, and *o*-OMe) and electron-withdrawing groups (*m*-Cl and *o*-Cl) could give the corresponding products in good yields(**3k**–**3p**). We found the corresponding product **3q** was provided in excellent yield. When phenyl substitution of aldehyde hydrazone bearing two identical substituents such as –Me, –OMe, –F, the corresponding product **3r**–**3t**, could also be obtained in good yields.

A possible pathway for this palladium-catalyzed cascade metallo-ene cyclization/metallo-carbene coupling reaction of allenamides is proposed in Scheme 2. Oxidative addition of Pd(0) with allyl acetate motif generates π-allyl palladium intermediate **1-III** and the intermediate **1-IV**. During this process, Csp^3–Csp^2 bond and alkenyl pyrrole skeleton were constructed. Diazonium substrates **2a-I** is formed in situ from *N*-*p*-tosyl hydrazone derivatives with the assistance of *t*BuOLi, which then reacts with intermediate **1-IV** to form the palladium-carbene complex **2a-II**. Subsequent migratory inser-



Scheme 2. Proposal mechanism for the Pd-carbene reaction system.

Table 2. The scope of substrates.



[a] The condition: 1 (0.2 mmol), 2 (0.4 mmol), $PdCl_2$(dppf) (0.02 mmol), tBuOLi (0.5 mmol), 2-MeTHF (2.0 mL).

tion of palladium carbene afforded the intermediate **2a-III** which produced the target product **3a** via the β-H elimination.

In conclusion, we developed a highly efficient palladium-catalyzed cascade metallo-ene cyclization/ metallo-carbene coupling reaction, and 2,3-dihydropyrrole derivatives were obtained in high yields. During this transformation, two new Csp^3–Csp^2 and Csp^2–Csp^2 bonds were constructed in one-pot. Notably, the final product contained an attractive 1,3,8-trienes scaffold, which is challenging to be synthesized and easily to be transformed into more valuable molecules. Further application of this methodology was will be reported in due course.

Acknowledgements

We gratefully acknowledge the National Natural Science Foundation of China (22078178, 21702126), the Shandong Provincial Natural Science Foundation (ZR2018MB008, ZR2018MB012), Youth Innovative Talents Attracting and Cultivating Plan of Colleges and Universities in Shandong Province, the Shandong Provincal Key Research and Development program of China (2017GGX20131) and the computational resources from Shandong University of Technology. We thank Prof. Di Sun at Shandong University for assistance with the X-ray crystal structure analysis. Technical support from SDU SC&PP research facilities was acknowledged.

Conflict of Interest

The authors declare no conflict of interest.

Keywords: Allenamides · Carbenes · Homogeneous catalysis · Nitrogen heterocycles · Palladium

[1] a) G. Cirrincione, A. M. Almerico, E. Aiello, G. Dattolo, *Recueil des Travaux Chimiques des Pays-Bas* **1993**, *112*, 649–652; b) R. J. Sundberg, in *Comprehensive Heterocyclic Chemistry*, ed. vol. 4 (A. R. Katritzky, C. W. Rees), Pergamon Press, New York, **1984**, *pp.* 269–3157; c) S. Iqbal, H. Rasheed, R. Javed Awan, R. Javed Awan, A. Mukhtar, M. G. Moloney, *Org. Prep. Proced. Int.* **2001**, *33*, 411–454; d) Y. Cheng Z Kang, Y. Ma, J Peng, M. Liu, *Tetrahedron* **2008**, *64*, 7362–7368; e) Q. Sha, H. Arman, M. P. Doyle, *Org. Lett.* **2015**, *17*, 3876–3879; f) D. D. Xuan, *Curr. Org. Chem.* **2020**, *24*, 622–657.

[2] F. Ma, Q. Ouyang, W. Li, Z Jiang, Z. Tong, Y. Liu, H. Li, S. Yu, J. Feng, S. Wang, X. Hu, J. Zou, X. Zhu, B. Xu, *J. Clin. Oncol.* **2019**, *37*, 2610–2619.

[3] L. W. Hertel, Y. C. Xu, *Patent: US6353008 B1*, Eli Lilly and Company (US), **2002**, 14–15.

[4] a) H.-J. Na, S.-J. Lee, Y.-C. Kang, Y.-L. Cho, W.-D. Nam, P. K. M. Kim, K.-S. Ha, H.-T. Chung, H. Lee, Y.-G. Kwon, J. S. Koh, Y.-M. Kim, *J. Immunol.* **2004**, *173*, 1276–1283; b) H.-S. Kim, J. W. Kim, J. Gang, J. Wen, S. S. Koh, J. S. Koh, H.-H. Chung, S. Y. Song, *Toxicol. Appl. Pharmacol.* **2006**, *215*,317–329; c) C.-K. Kim, Y. K. Choi, H. Lee, K.-S. Ha, M.-H. Won, Y.-G. Kwon, Y.-M. Kim, *Mol. Pharmacol.* **2010**, *78*, 142–150.

[5] B. Zhao, H.-W. Liang, J. Yang, Z. Yang, Y. Wei, *ACS Catal.* **2017**, *7*, 5612–5617.

[6] a) B. M. Trost, *Acc. Chem. Res.* **2002**, *35*, 695–705; b) G. C. Lloyd-Jones, *Org. Biomol. Chem.* **2003**, *1*, 215–236; c) H. Y. Jang, M. J. Krische, *Acc. Chem. Res.* **2004**, *37*, 653–661; d) L. Zhang, J. Sun, S. S. Kozmin, *Adv. Synth. Catal.* **2006**, *348*, 2271–2296; e) S. Ma, S. Yu, Z. Gu, *Angew. Chem.* **2006**, *118*, 206–209.

[7] a) B. Radetich, T. V. RajanBabu, *J. Am. Chem. Soc.* **1998**, *120*, 8007–8008; b) T. V. RajanBabu, N. Nomura, J. Jin, B. Radetich, H. Park, M. Nandi, *Chem. Eur. J.* **1999**, *5*, 1963–1968; c) C. Boeing, G. Francio, W. Leitner, *Adv. Synth. Catal.* **2005**, *347*, 1537–1541; d) C. Boeing, J. Hahne, G. Francio, W. Leitner, *Adv. Synth. Catal.* **2008**, *350*, 1073–1080.

[8] a) P. Kisinga, L. A. Goj, R. A. Widenhoefer, *J. Org. Chem.* **2001**, *66*, 635–637; b) A. Heumann, L. Giordano, A. Tenaglia, *Tetrahedron Lett.* **2003**, *44*, 1515–1518; c) I. J. S. Fairlamb, S. Grant, S. Tommasi, J. M. Lynam, M. Bandini, H. Dong, Z. Lin, A. C. Whitwood, *Adv. Synth. Catal.* **2006**, *348*, 2515–2530; d) Y. J. Song, G. Jung, H. Lee, Y. T. Lee, Y. K. Chung, H. Y. Jang, *Tetrahedron Lett.* **2007**, *48*, 6142–6146; e) L. Z. Feng, Z. Y. Gan, X. P. Nie, P. P. Sun, J. C. Bao, *Catal. Commun.* **2010**, *11*, 555–559.

[9] W. D. Kerber, J. H. Koh, M. R. Gagne, *Org. Lett.* **2004**, *6*, 3013–3015.

[10] R. Grigg, J. F. Malone, T. R. B. Mitchell, A. Ramasubbu, R. M. Scott, *J. Chem. Soc. Perkin Trans. 1* **1984**, *0*, 1745–1754.

[11] a) Y. Yamamoto, N. Ohkoshi, M. Kameda, K. Itoh, *J. Org. Chem.* **1999**, *64*, 2178–2179; b) Y. Yamamoto, Y. Nakagai, N. Ohkoshi, K. Itoh, *J. Am. Chem. Soc.* **2001**, *123*, 6372–6380; c) Y. Terada, M. Arisawa, A. Nishida, *Angew. Chem.* **2004**, *116*, 4155–4159; *Angew. Chem. Int. Ed.* **2004**, *43*, 4063–4067; d) I. J. S. Fairlamb, G. P. McGlacken, F. Weissberger, *Chem. Commun.* **2006**, *0*, 988–990.

[12] X. X. Li, Y. C. Liu, N. Ding, X. j Tan, Z. G. Zhao, *RSC Adv.* **2020**, *10*, 36818–36827.

[13] a) F. Yan, H. Liang, J. Song, J. Cui, Q. Liu, S. Liu, P. Wang, Y. Dong, H. Liu, *Org. Lett.* **2017**, *19*, 86; b) H. Liang, F. Yan, X. Dong, Q. Liu, X. Wei, S. Liu, Y. Dong, H. Liu, *Chem. Commun.* **2017**, *53*, 3138–3141; c) H. Liang, L. Meng, X. Chi, S. Yao, H. Chen, L. Jiao, Q. Liu, D. Zhang, Y.i Dong, *Asian J. Org. Chem.* **2018**, *7*, 1793–1796; d) J. Cui, L. Meng, X. Chi, Q. Liu, P. Zhao, D. Zhang, L. Chen, X. Li, Y. Dong, H. Liu, *Chem. Commun.* **2019**, *55*, 4355–4358; e) F. Yan, H. Liang, B. Ai, W. Liang, L. Jiao, S. Yao, P. Zhao, Q. Liu, Y. Dong, H. Liu, *Org. Biomol. Chem.* **2019**, *17*, 2651–2656; f) J. Li, L. Meng, X. Du, Q. Liu, L. Xu, L. Zhang, F. Sun, X. Li, D. Zhang, X. Xiao, H. Liu, *Org. Chem. Front.* **2020**, *7*, 3880–3886.

[14] a) H. Lebel, V. Paquet, *J. Am. Chem. Soc.* **2004**, *126*, 36, 11152–11153; b) S. Enthaler, M. Haberberger, E. Irran, *Chem. Asian J.* **2011**, *6*, 1613–1623; c) Z. Wu, X. Sun, K. Potter, Y. Cao, L. N. Zakharov, P. R. Blakemore, *Angew. Chem. Int. Ed.* **2016**, *55*, 1–6; d) L. Li, J. C. Stimac, L. M. Geary, *Tetrahedron Lett.* **2017**, *58*, 1379–1381; e) K. Bojaryn, S. Fritsch, C. Hirschhäuser, *Org. Lett.* **2019**, *21*, 7, 2218–2222.

[15] a) H. Dong, D. Xu, W. Liu, Y. Zhang, H. Guo, *J. Saudi Chem. Soc.* **2019**, *23*, 1041–1048; b) A. Joshi, R. Semwal, E. Suresh, S. Adimurthy, *Chem. Commun.* **2019**, *55*, 10888; c) H. Peng, Y. Wan, Y. Zhang, G. Deng, *Chem. Commun.* **2020**, *56*, 1417–1420; d) C. A. D. Caiuby, M. P. de Jesus, A. C. B. Burtolos, *J. Org. Chem.* **2020**, *85*, 7433–7445; e) S. Jana, Y. Guo, R. M. Koenigs, *Chem. Eur. J.* **2020**, *26*,1–13.

[16] K. L. Greenman, D. S. Carter, D. L. Van Vranken, *Tetrahedron*, **2001**, *57*, 5219–5225.

[17] V. K. Aggarwal, E. Alonso, I. Bae, G. Hynd, K. M. Lydon, M. J. Palmer, M. Patel, M. Porcelloni, J. Richardson, R. A. Stenson, J. R. Studley, J.-L. Vasse, C. L. Winn, *J. Am. Chem. Soc.* **2003**, *125*, 10926–10940.

[18] a) R. Kudirka, D. L. Van Vranken, *J. Org. Chem.* **2008**, *73*, 3585–3588; b) K. L. Greenman, D. L. Van Vranken, *Tetrahedron*, **2005**, *61*, 6438–6441; c) S. K. Devine, D. L. Van Vranken, *Org. Lett.* **2007**, *9*, 2047–2049; d) S. K. Devine, D. L. Van Vranken, *Org. Lett.* **2008**, *10*, 1909–1911; e) R. Kudirka, S. K. Devine, C. S. Adams, D. L. Van Vranken, *Angew. Chem. Int. Ed.* **2009**, *48*, 3677–3680; f) A. Khanna, C. Maung, K. R. Johnson, T. T. Luong, D. L. Van Vranken, *Org. Lett.* **2012**, *14*, 3233–3235; g) E. S. Gutman, V. Arredondo, D. L. Van Vranken, *Org. Lett.* **2014**, *16*, 5498–5501; h) M. Kitamura, R. Yuasa, D. L. Van Vranken, *Tetrahedron Lett.* **2015**, *56*, 3027–3031; i) I. D. U. A. Premachandra, T. A. Nguyen, C. Shen, E. S. Gutman, D. L. Van Vranken, *Org. Lett.* **2015**, *17*, 5464–5467; j) V. Arredondo, S. C. Hiew, E. S. Gutman, I. D. U. A. Premachandra, D. L. Van Vranken, *Angew. Chem. Int. Ed.* **2017**, *56*, 4156–4159.

[19] a) L. Zhou, F. Ye, Y. Zhang, J. Wang, *J. Am. Chem. Soc.* **2010**, *132*, 13590–13591; b) Q. Xiao, J. Ma, Y. Yang, Y. Zhang, J. Wang, *Org. Lett.* **2009**, *11*, 4732–4735; c) S. Chen, J. Wang, *Chem. Commun.* **2008**, 4198–4200; d) X. Zhao, G. Wu, C. Yan, K. Lu, H. Li, Y. Zhang, J. Wang *Org. Lett.* **2010**, *12*, 5580–5583; e) L. Zhou, F. Ye, J. Ma, Y. Zhang, J. Wang, *Angew. Chem. Int. Ed.* **2011**, *50*, 3510–3514; f) L. Zhou, F. Ye, Y. Zhang, J. Wang, *Org. Lett.* **2012**, *14*, 922–925; g) Q. Xiao, B. Wang, L. Tian, Y. Yang, J. Ma, Y. Zhang, S. Chen, J. Wang, *Angew. Chem. Int. Ed.* **2013**, *52*, 9305–9308; h) X. Wang, Y. Xu, Y. Deng, Y. Zhou, J. Feng, G. Ji, Y. Zhang, J. Wang, *Chem. Eur. J.* **2014**, *20*, 961–965; i) Y. Zhou, F. Ye, X. Wang, S. Xu, Y. Zhang, J. Wang, *J. Org. Chem.* **2015**, *80*, 6109–6118; j) H. Q. Luo, G. J. Wu, S. Xu, K. Wang, C. Q. Wu, Y. Zhang, J. B. Wang, *Chem. Commun.* **2015**, *51*, 13321–13323; k) K. Wang, S. Chen, H. Zhang, S. Xu, F. Ye, Y. Zhang, J. Wang, *Org. Biomol. Chem.* **2016**, *14*, 3809–3820.

[20] a) J. Barluenga, P. Moriel, C. Valdés, F. Aznar, *Angew. Chem. Int. Ed.* **2007**, *46*, 5587–5590; b) J. Barluenga, M. Tomas-Gamasa, P. Moriel, F. Aznar, C. Valdes, *Chem. Eur. J.* **2008**, *14*, 4792–4795; c) J. Barluenga, M. Escribano, P. Moriel, F. Aznar, C. Valdés, *Chem. Eur. J.* **2009**, *15*, 13291–13294; d) J. Barluenga, M. Tomás-Gamasa, F. Aznar, C. Valdés, *Chem. Eur. J.* **2010**, *16*, 12801–12803; e) J. Barluenga, M. Escribano, F. Aznar, C. Valdés, *Angew. Chem. Int. Ed.* **2010**, *49*, 6856–6859; f) J. Barluenga, M. Tomás-Gamasa, F. Aznar, C. Valdés, *Adv. Synth. Catal.* **2010**, *352*, 3235–3240; g) J. Barluenga, L. Florentino, F. Aznar, C. Valdés, *Org. Lett.* **2011**, *13*, 510–513; h) J. Barluenga, N. Quiñones, M.-P. Cabal, F. Aznar, C. Valdés, *Angew. Chem. Int. Ed.* **2011**, *50*, 2350–2353; i) L. Florentino, F. Aznar, C. Valdés, *Org. Lett.* **2012**, *14*, 2323–2325; j) A. Jiménez-Aquino, J. A. Vega, A. A. Trabanco, C. Valdés, *Adv. Synth. Catal.* **2014**, *356*, 1079–1084; k) R. Barroso, M.-P. Cabal, R. Badía-Laiño, C. Valdés, *Chem. Eur. J.* **2015**, *21*, 16463–16473; l) M. Paraja, R. Barroso, M. P. Cabal, C. Valdés, *Adv. Synth. Catal.* **2017**, *359*, 1058–1062.

[21] a) A. C. Albéniz, P. Espinet, R. Manrique, A. Pérez-Mateo, *Angew. Chem. Int. Ed.* **2002**, *41*, 2363–2366; b) M. P. López-Alberca, M. J. Mancheño, I. Fernandez, M. Gomez-Gallego, M. A. Sierra, R. Torres, *Org. Lett.* **2007**, *9*, 1757–1759; c) J. M. Goll, E. Fillion, *Organometallics*, **2008**, *27*, 3622–3625; d) B. Treguier, A. Hamze, O. Provot, J.-D. Brion, M. Alami, *Tetrahedron Lett.* **2009**, *50*, 6549–6552; e) E. Brachet, A. Hamze, J.-F. Peyrat, J.-D. Brion, M. Alami, *Org. Lett.* **2010**, *12*, 4042–4045; f) F. Zhou, K. Ding, Q. Cai, *Chem. Eur. J.* **2011**, *17*, 12268–12271; g) Z.-S. Chen, X.-H. Duan, L.-Y. Wu, S. Ali, K.-G. Ji, P.-X. Zhou, X.-Y. Liu, Y.-M. Liang, *Chem. Eur. J.* **2011**, *17*, 6918–6921; h) I. Meana, A. C. Albeniz, P. Espinet, *Organometallics* **2012**, *31*, 5494–5499; i) I. Meana, A. Toledo, A. C. Albeniz, P. Espinet, *Chem. Eur. J.* **2012**, *18*, 7658–7661; j) H. Chen, L. Huang, W. Fu, X. Liu, H. Jiang, *Chem. Eur. J.* **2012**, *18*, 10497–10500; k) M. Roche, A. Hamze, J.-D. Brion, M. Alami, *Org. Lett.* **2013**, *15*, 148–151; l) M. Roche, A. Hamze, O. Provot, J.-D. Brion, M. Alami, *J. Org. Chem.* **2013**, *78*, 445–454; m) Q. Yang, H. Chai, T. Liu, Z. Yu, *Tetrahedron Lett.* **2013**, *54*, 6485–6489; n) J. Feng, B. Li, Y. He, Z. Gu, *Angew. Chem. Int. Ed.* **2016**, *55*, 2186–2190; o) M.-C. Belhomme, D. Wang, K. J. Szabó, *Org. Lett.* **2016**, *18*, 2503–2506; p) Y. Xie, P. Zhang, L. Zhou, *J. Org. Chem.* **2016**, *81*, 2128–2134.

Manuscript received: December 16, 2020
Revised manuscript received: February 4, 2021
Accepted manuscript online: February 9, 2021