

Cite this: *Chem. Sci.*, 2022, 13, 6348

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

Received 1st April 2022
Accepted 5th May 2022

DOI: 10.1039/d2sc01887j

rsc.li/chemical-science

Regioselective synthesis of spirocyclic pyrrolines via a palladium-catalyzed Narasaka–Heck/C–H activation/[4 + 2] annulation cascade reaction†

Wan-Xu Wei,^{‡a} Xiangtao Kong,^{‡b} Rui-Qiang Jiao,^a Xue-Song Li,^a Cui-Tian Wang,^a Yuke Li^c and Yong-Min Liang^{*,a}

A novel palladium-catalyzed spirocyclization through sequential Narasaka–Heck cyclization, C–H activation and [4 + 2] annulation has been developed. In this reaction, cheap and readily available 2-chlorobenzoic acid or ethyl phenylpropiolate was employed as the C2 insertion unit to react with γ,δ -unsaturated oxime ester. The key step in this transformation is the regioselective insertion of the C2 synthon into the spiro-palladacycle intermediate that is formed by the δ -C–H activation process, thereby efficiently assembling a series of spirocyclic pyrrolines with high regiocontrol. Furthermore, density functional theory (DFT) calculations and control experiments were performed to gain some insights into the reaction mechanism.

Introduction

In the past few decades, palladium-catalyzed inert C–H bond activation, as an extremely powerful tool for constructing useful compounds, including industrial materials, pharmaceuticals and natural products, has experienced tremendous developments due to its high atom- and step-economy.^{1–11} Many of the pioneering studies on palladium-catalyzed directing-group-assisted C–H activation have been widely investigated.^{12–18} Moreover, palladium-catalyzed intramolecular Heck-type cyclization/C–H activation cascade reactions, as a complementary strategy for the remote C–H bond activation, were also extensively reported.^{19,20} In 1994, Grigg and co-workers for the first time discovered that the *in situ* generated transient σ -alkyl-Pd(II) intermediate of Heck cyclization could activate the remote C–H bond to construct palladacycle, and its direct reductive elimination forms spiro-heterocycles.^{21,22} This efficient strategy represents an elegant means to complex carbocyclic and heterocyclic molecular frameworks in one step from well-designed starting materials.^{23–30} Afterward, other conversion methods of palladacycle, including [1,4]-Pd shift^{31–35} and

coupling reagent capture,^{36–42} have also been developed to furnish various polycyclic compounds. However, direct reductive elimination and [1,4]-Pd shift conversions of palladacycle rely on the inherent C–H bonds as the terminal functional group, thus leading to poor product diversity. The palladacycle capture strategy has been drawing significant attention because various external reagents could be introduced by trapping palladacycle. Despite great progress, such domino reactions of the capturing strategy are usually initiated by the oxidative addition of palladium to aryl halogens in most cases; in contrast, other triggering modes remain underdeveloped. To the best of our knowledge, the regioselective insertion of unsymmetrical synthons into the palladium center is difficult to control, yielding mainly inseparable isomeric mixtures.^{43–50}

In 1999, Narasaka and co-workers for the first time reported a palladium catalyzed cyclization of γ,δ -unsaturated oxime ester, namely the Narasaka–Heck reaction,^{51–53} which is an efficient method for synthesizing pyrrole. Subsequently, this kind of reaction was widely used to establish structurally diverse N-heterocyclic compounds,^{54–57} such as imidazoles,⁵⁸ pyridines,^{59–61} indoles⁶² and isoquinolines.^{63,64} What is more, Bower,^{65–69} Zhu,⁷⁰ Tong⁷¹ and other groups^{72–75} extensively synthesized functionalized pyrrolines by using nucleophiles to trap the σ -alkyl-Pd(II) intermediate of the Narasaka–Heck cyclization. In addition, our group reported the synthesis of polyfluorophenylated pyrrolines by using the $C_6F_5CO_2^-$ leaving group as the $C_6F_5^-$ source *via* its decarboxylation.⁷⁶ Altogether, previous reports about the Narasaka–Heck reaction mainly focused on σ -alkyl-Pd(II) intermediate nucleophile trapping and β -hydrogen elimination. Recently, our group made a significant breakthrough, synthesizing a series of highly strained spirocyclobutane-pyrrolines through a Narasaka–Heck/C–H

^aState Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000, P. R. China. E-mail: liangym@lzu.edu.cn

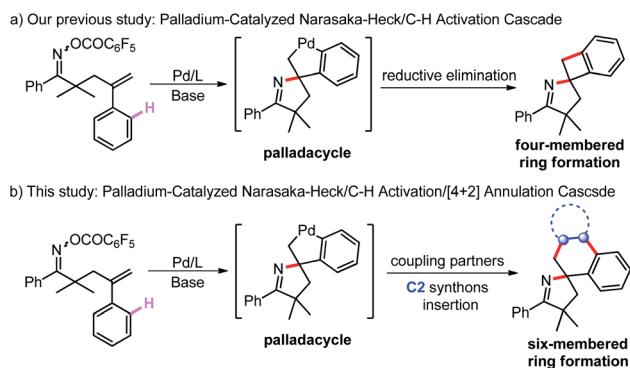
^bHenan Key Laboratory of New Optoelectronic Functional Materials, College of Chemistry and Chemical Engineering, Anyang Normal University, Anyang 455000, P. R. China

^cDepartment of Chemistry, Centre for Scientific Modeling and Computation, Chinese University of Hong Kong, Shatin, Hong Kong, P. R. China

† Electronic supplementary information (ESI) available. CCDC 2124283 and 2124287. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2sc01887j>

‡ These authors contributed equally.





Scheme 1 (a) Our previous study; (b) this study.

activation cascade reaction (Scheme 1a), which is the first case of using the σ -alkyl-Pd(II) intermediate from Narasaka-Heck cyclization for intramolecular C-H activation.⁷⁷ Despite numerous achievements, the ring size of spirocyclic pyrrolines is limited. Consequently, methods to obtain more diverse spirocyclic pyrrolines are highly desirable, which can be accomplished *via* employing external reagents to capture the palladacycle from Narasaka-Heck/C-H activation cascade.

While the efficient synthesis of various spirocyclic pyrrolines through the domino Narasaka-Heck/C-H activation reaction has been reported, the ring size is limited to a four-membered ring. There is an urgent need for methods to access more diverse spirocyclic products, which are regarded as significant scaffolds in drug discovery and development.^{78–82} Inspired by these causes and our interest in tandem reactions involving palladacycles, we envisioned that a spiro-palladacycle formed by the Narasaka-Heck/C-H activation cascade could be trapped by the C2 synthon (Scheme 1b), and its insertion leads to the formation of a six-membered ring.

Results and discussion

For the insertion of an aromatic ring, cheap and readily available 2-chlorobenzoic acid, in sharp contrast to the unselective insertion of aryl or aryl halide, inserts into palladacycle with high regioselectivity because the palladacycle reacts with 2-chlorobenzoic acids through two sequential C-C cross-couplings, and two C-C bonds are formed with excellent chemoselectivity.^{83–90} Consequently, we commenced our initial investigation by employing γ,δ -unsaturated oxime ester **1a** and 2-chlorobenzoic acid **2a** as the model substrates (Table 1). Fortunately, the anticipated domino reaction of **1a** and **2a** was conducted in the presence of Pd(OAc)₂, P(*p*-Tol)₃ and K₂CO₃ in DMF at 140 °C for 12 h under an argon atmosphere, generating the desired product **3aa** in 15% yield (Table 1, entry 1). Given the previous literature reporting that *n*-Bu₄NCl probably activate and stabilize palladium complexes,^{91–94} we added *n*-Bu₄NCl (2.0 equiv.) to the reaction system and found that the extra addition of *n*-Bu₄NCl do have a positive effect on the conversion (Table 1, entry 2). Further examination of the bases, such as Cs₂CO₃, Rb₂CO₃ and K₃PO₄, showed that Rb₂CO₃ was the most

Table 1 Condition optimization for the reaction of γ,δ -unsaturated oxime ester and 2-chlorobenzoic acid^a

Entry	Pd	Ligand	Base	Yield (%)
1 ^b	Pd(OAc) ₂	P(<i>p</i> -Tol) ₃	K ₂ CO ₃	15
2	Pd(OAc) ₂	P(<i>p</i> -Tol) ₃	K ₂ CO ₃	31
3	Pd(OAc) ₂	P(<i>p</i> -Tol) ₃	Cs ₂ CO ₃	34
4	Pd(OAc) ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	40
5	Pd(OAc) ₂	P(<i>p</i> -Tol) ₃	K ₃ PO ₄	7
6	Pd(OAc) ₂	P(<i>o</i> -Tol) ₃	Rb ₂ CO ₃	Trace
7	Pd(OAc) ₂	P(4-OMe-Ph) ₃	Rb ₂ CO ₃	39
8	Pd(OAc) ₂	PPh ₃	Rb ₂ CO ₃	21
9	Pd(OAc) ₂	P(2-furan) ₃	Rb ₂ CO ₃	Trace
10	Pd(PPh ₃) ₂ Cl ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	36
11	Pd(dba) ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	34
12	Pd(MeCN) ₂ Cl ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	52
13	Pd(TFA) ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	31
14 ^c	Pd(MeCN) ₂ Cl ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	64
15 ^{c,d}	Pd(MeCN) ₂ Cl ₂	P(<i>p</i> -Tol) ₃	Rb ₂ CO ₃	65

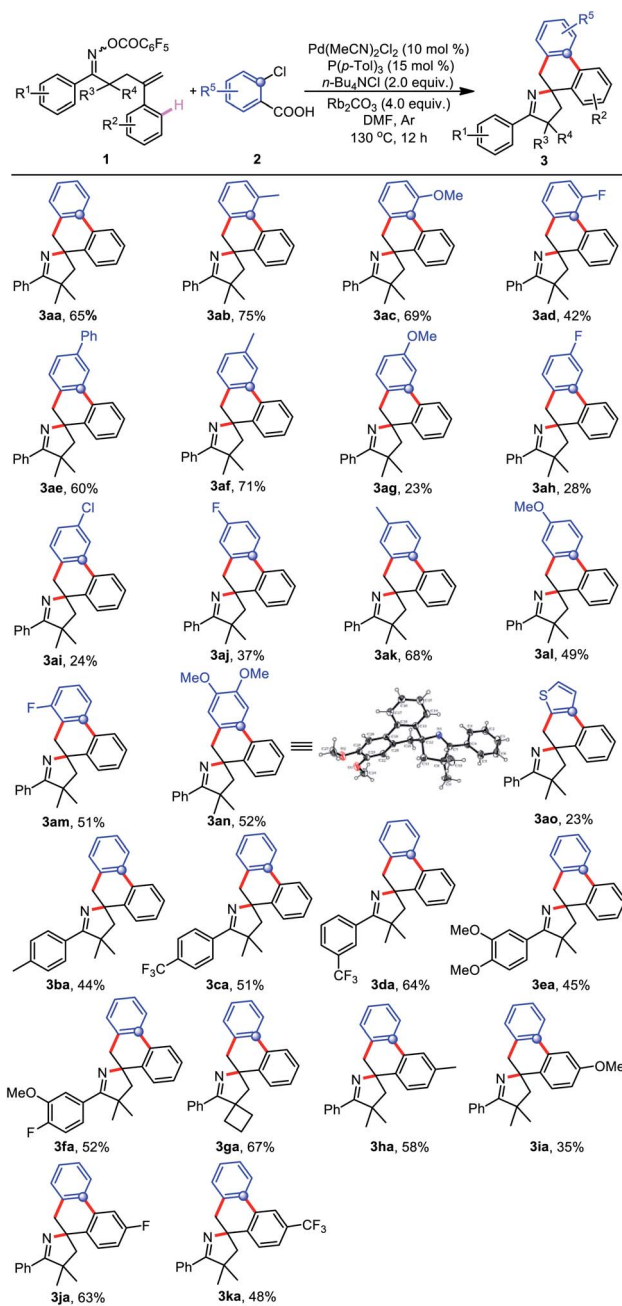
^a Reaction conditions unless otherwise noted: **1a** (0.2 mmol), **2a** (0.3 mmol), Pd (10 mol%), ligand (15 mol%), base (4.0 equiv.), *n*-Bu₄NCl (2.0 equiv.), DMF (2 mL), 140 °C, 12 h, Ar; isolated yields. ^b No *n*-Bu₄NCl. ^c **1a** (0.3 mmol), **2a** (0.2 mmol). ^d 130 °C.

effective in terms of yield (Table 1, entries 3–5). Using other ligands, including P(*o*-Tol)₃, P(4-OMe-Ph)₃, PPh₃, and P(2-furan)₃, did not improve the yield (Table 1, entries 6–9). Next, after careful screening of palladium sources (Table 1, entries 10–13), Pd(MeCN)₂Cl₂ turned out to be the optimal choice. Gratifyingly, the yield was dramatically improved by meticulous fine-tuning of the substrate stoichiometry (Table 1, entry 14). Eventually, reducing the reaction temperature displayed better efficiency, improving the isolated yield of **3aa** to 65% (Table 1, entry 15).

With the optimized reaction conditions in hand (Table 1, entry 15), we examined the generality of this reaction (Table 2). The regioselectivity was initially investigated by testing a variety of 2-chlorobenzoic acid derivatives. As shown in Table 2, the reactions of a series of 2-chlorobenzoic acids **2b–o** with **1a** yielded the desired products **3ab–3ao** with complete regioselectivity. Substrates with a methyl (**2b**), methoxy (**2c**) or fluoro (**2d**) group at the 3-position could efficiently couple with **1a**, despite steric hindrance, yielding the corresponding products (**3ab–3ad**) with perfect regiocontrol. Furthermore, a range of functional groups at the 4-position of 2-chlorobenzoic acid could all survive, furnishing spirocyclic products **3ae–ah**. It is worth noting that the second chloro group of substrate **2i** remained intact during this conversion, albeit with a decreased yield (**3ai**). This protocol was also applicable to 5-substituted 2-chlorobenzoic acids to afford products **3aj–al**. To our delight,



Table 2 Substrate scope for the reaction of γ,δ -unsaturated oxime esters and 2-chlorobenzoic acids^a



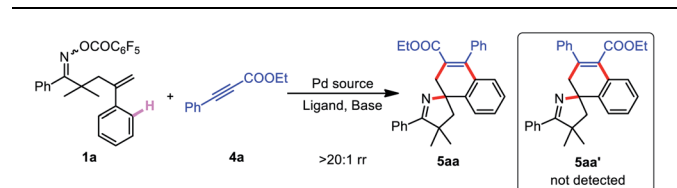
^a Reaction conditions unless otherwise noted: **1** (0.3 mmol), **2** (0.2 mmol), Pd(MeCN)₂Cl₂ (10 mol%), P(*p*-Tol)₃ (15 mol%), Rb₂CO₃ (4.0 equiv.), *n*-Bu₄NCl (2.0 equiv.), DMF (2 mL), 130 °C, 12 h, Ar; isolated yields.

the reaction of the sterically hindered substrates **2m** with **1a** successfully gave **3am** in 51% yield. Pleasingly, di- and thiophen-substituted reactants were converted into **3an** and **3ao** *via* this protocol, respectively; the spirocyclic structure of **3an** was definitively elucidated by X-ray crystal structure analysis (see the ESI[†]). Subsequently, the scope of γ,δ -unsaturated oxime esters **1** was evaluated. The γ,δ -unsaturated oxime esters **1b**–

d substituted with electron-donating methyl or electron-withdrawing trifluoromethyl groups at the *para*- or *meta*-position of the aromatic ring on the oxime ester showed good reactivity in this conversion, and provided the corresponding products (**3ba**–**3da**) in 44–64% yields. As expected, disubstituted substrates **1e** and **1f** could also be subjected to the tandem cyclization with **2a**. In addition, the reactant **1g** bearing a spirocyclobutyl moiety also exhibited high reactivity, and **3ga** was obtained in 67% yield. Similarly, substituting the aryl ring on the alkene with electron-rich or electron-deficient groups, such as methyl (**1h**), methoxy (**1i**), fluoro (**1j**) and trifluoromethyl (**1k**), delivered the desired products **3ha**–**3ka** of the cascade reaction with **2a**.

Inspired by the above results, we next turned our attention to probing the feasibility of employing cheap and readily accessible ethyl phenylpropiolate as the C2 synthon.^{95,96} We began our studies by investigating the reaction of γ,δ -unsaturated oxime ester **1a** and ethyl phenylpropiolate **4a**. It is satisfactory that the target product **5aa** was obtained in 53% yield and more than 20 : 1 ratio of regioisomers (rr) in a catalytic system consisting of Pd(PPh₃)₄ and Cs₂CO₃ in dioxane at 100 °C for 22 h (Table 3, entry 1). Further exploration of the solvent showed that toluene was the optimal choice (Table 3, entries 2–4). Next, various combinations of palladium sources and ligands were carefully screened (Table 3, entries 5–7), and Pd(PPh₃)₄ was identified as the most suitable catalyst. Using other bases, such as K₂CO₃, Na₃PO₄, K₃PO₄, NaOAc and PhCOOK, did not improve the yield (Table 3, entries 8–12). Subsequently, the structure of **5aa** was definitively elucidated by X-ray crystal structure analysis (see the ESI[†]).

Table 3 Condition optimization for the reaction of γ,δ -unsaturated oxime ester and ethyl phenylpropiolate^a



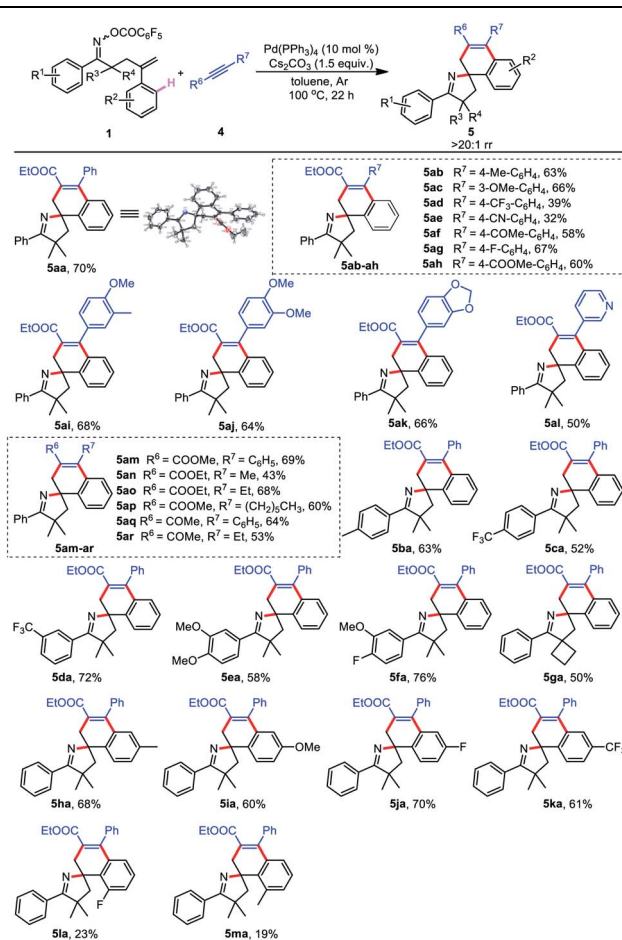
Entry	Pd/ligand	Base	Solvent	Yield (%)
1	Pd(PPh ₃) ₄ /—	Cs ₂ CO ₃	Dioxane	53
2	Pd(PPh ₃) ₄ /—	Cs ₂ CO ₃	MeCN	37
3	Pd(PPh ₃) ₄ /—	Cs ₂ CO ₃	DCE	Trace
4	Pd(PPh ₃) ₄ /—	Cs ₂ CO ₃	Toluene	70
5	Pd(OAc) ₂ /PPh ₃	Cs ₂ CO ₃	Toluene	47
6	Pd(OAc) ₂ /XPhos	Cs ₂ CO ₃	Toluene	33
7	Pd(PPh ₃) ₄ /PCy ₃ ·HBF ₄	Cs ₂ CO ₃	Toluene	68
8	Pd(PPh ₃) ₄ /—	K ₂ CO ₃	Toluene	45
9	Pd(PPh ₃) ₄ /—	Na ₃ PO ₄	Toluene	33
10	Pd(PPh ₃) ₄ /—	K ₃ PO ₄	Toluene	44
11	Pd(PPh ₃) ₄ /—	NaOAc	Toluene	38
12	Pd(PPh ₃) ₄ /—	PhCOOK	Toluene	25

^a Reaction conditions unless otherwise noted: **1a** (0.2 mmol), **4a** (0.4 mmol), Pd (10 mol%), ligand (20 mol%), base (1.5 equiv.), solvent (2 mL), 100 °C, 22 h, Ar; isolated yields; rr values were determined by ¹H NMR.



After identifying the optimal reaction conditions, we set out to investigate the substrate scope of this cascade reaction. As shown in Table 4, both substrates **1** and **4** can be changed, thus constructing a new class of spirocyclic pyrrolines (**5aa–ma**). To assess the influence of **4a** electronic effects on the reaction outcomes, a wide scope of functional groups, including electron-donating methyl (**4b**) and methoxy (**4c**) groups and electron-withdrawing trifluoromethyl (**4d**), cyano (**4e**), acetyl (**4f**), fluoro (**4g**), and ester (**4h**) groups were introduced into the aryl ring of **4a**, and all were well tolerated. In addition, several disubstituted substrates (**4i–k**) also performed well. The pyridine-substituted product **5al** was generated in 50% yield, indicating the compatibility of the heterocycle. Moreover, methyl phenylpropiolate **4m** was also a viable coupling partner of **1a** to provide **5am** in 69% yield. When R^7 was not an aromatic ring but an alkyl group, spirocyclic products **5an–ap** were still successfully synthesized. Gratifyingly, substitution of the ester with ketone did not impede the generation of **5aq** and **5ar**. Satisfactorily, both single and double substituents of the aryl ring on oxime ester were subjected to the optimal conditions,

Table 4 Substrate scope for the reaction of γ,δ -unsaturated oxime esters and alkynes^a



^a Reaction conditions unless otherwise noted: **1** (0.2 mmol), **4** (0.4 mmol), Pd(PPh₃)₄ (10 mol%), Cs₂CO₃ (1.5 equiv.), toluene (2 mL), 100 °C, 22 h, Ar; isolated yields.

delivering the target products **5ba–fa** in 52–76% yield. Remarkably, substrate **1g** with spirocyclobutane as the R^3 and R^4 substituents could also cyclize with **4a**. Furthermore, reactants (**1h–m**) bearing various functional groups of the aryl ring on the alkene could participate in the spirocyclization with **4a**.

A series of mechanistic studies were then conducted. First, to probe the regioselective insertion of ethyl phenylpropiolate **4a** into spirocyclopalladacycle **C** and the potential side reaction of intermediate **C**, DFT calculations were performed (see the ESI† for details).⁹⁷ As shown in Fig. 1, the energy barrier for the direct reductive elimination of spirocyclopalladacycle **C** is much higher than that for the migratory insertion of **4a**, so the direct reductive elimination of **C** would not occur in this reaction. In addition, the calculated energy-difference between the corresponding transition states (**J-TS** and **J-TS'**) for the two insertion patterns of ethyl phenylpropiolate favors the formation of **5aa** other than **5aa'**, which is responsible for the high *rr* value of **5aa**. What is more, a series of control experiments were performed to explore whether the C–H activation process is the rate-determining step in this transformation. The intermolecular competition reaction (Scheme 2a) of equimolar **1a** and **1a-D₅** with **2a** gave an intermolecular KIE value of 4.4, suggesting that the cleavage of the C–H bond during the CDM step of the tandem Narasaka–Heck/C–H activation/decarboxylation reaction is the rate-determining step. Similarly, the intermolecular competition experiment (Scheme 2b) of **1a**, **1a-D₅** and **4a** also revealed that the C–H bond cleavage might be the rate-determining step for the reaction of γ,δ -unsaturated oxime esters and alkynes.

On the basis of our experimental results and previous reports, a plausible catalytic cycle of this cascade reaction is illustrated in Scheme 3. Initially, oxidative addition of the Pd(0) to γ,δ -unsaturated oxime ester **1a** followed by Narasaka–Heck type cyclization forms the σ -alkyl-Pd(II) intermediate **B**, which

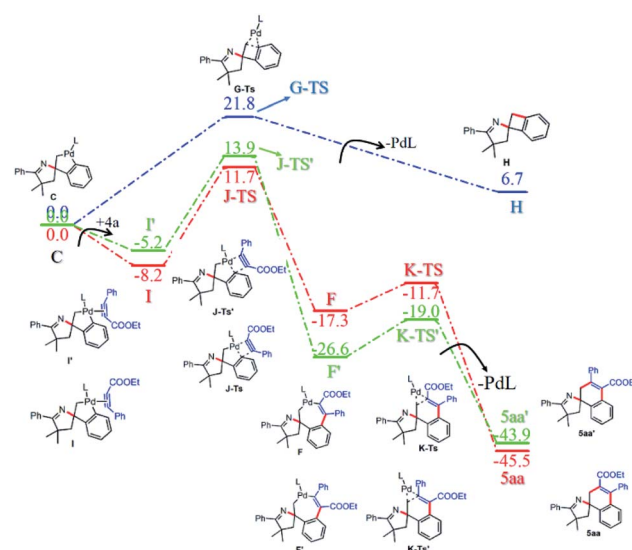
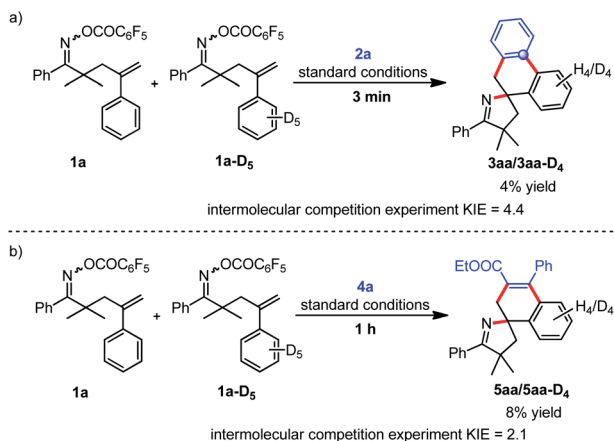
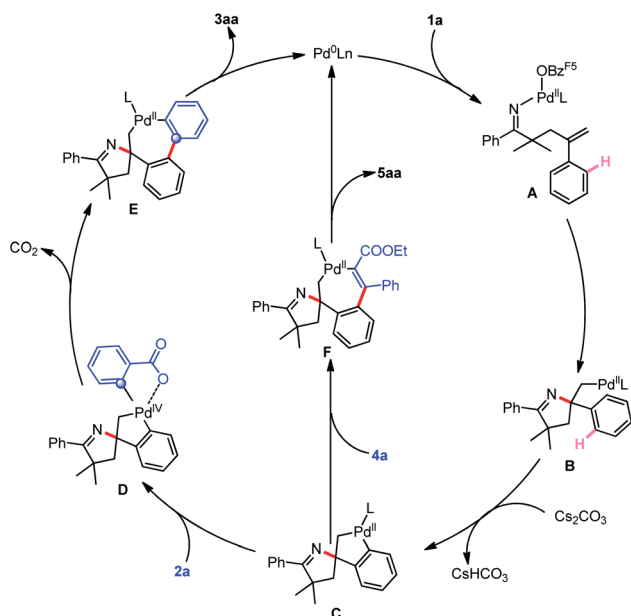


Fig. 1 Free energy profile for the migratory insertion step with ethyl phenylpropiolate **4a** and the direct reductive elimination of spirocyclopalladacycle **C** ($L = \text{PPh}_3$). The relative free energies are presented in kcal mol⁻¹.





Scheme 2 Control experiments, (a) kinetic isotope effect experiment of **1a** and **1a-D₅** with **2a**; (b) kinetic isotope effect experiment of **1a** and **1a-D₅** with **4a**.



Scheme 3 Proposed mechanism.

undergoes intramolecular C–H activation to generate spirocyclic intermediate **C**. Then, when 2-chlorobenzoic acid **2a** is employed as the C2 synthon, spirocyclic intermediate **C** transforms into palladacycle(IV) species **D** by the second oxidative addition to the C–Cl bond of **2a** with the assistance of an *ortho*-chelating carboxyl group, whose sequential reductive elimination and decarboxylation produces intermediate **E**, and the two sequential C–C cross-couplings are the key to the regioselective introduction of an aromatic ring. Eventually, target product **3aa** and Pd(0) species are delivered by the reductive elimination of intermediate **E**. Alternatively, for the reaction with ethyl phenylpropiolate **4a**, the regioselective migratory insertion of **4a** into spirocyclic intermediate **C** forms intermediate **F**, and its reductive elimination generates the final product **5aa** and Pd(0).

Conclusions

In conclusion, we developed a palladium-catalyzed Narasaka–Heck/C–H activation/[4 + 2] annulation cascade reaction, in which cheap and readily available 2-chlorobenzoic acid or ethyl phenylpropiolate is employed as the C2 insertion unit to react with γ,δ -unsaturated oxime ester. Remarkably, the highly regioselective insertion of the C2 synthon into the spirocyclic intermediate that is formed by δ -C–H activation is the key step in this transformation, thus providing a novel means for efficiently assembling a range of spirocyclic pyrrolines with high regiocontrol. What is more, DFT calculations revealed that the energy-difference between the corresponding transition states for the two insertion patterns of ethyl phenylpropiolate is the reason for the high *rr* value of **5aa**. And further control experiments suggested that the cleavage of the C–H bond is the rate-determining step in this reaction.

Data availability

All data associated with this study are available in the article and ESI.†

Author contributions

W.-X. W. performed the methodology, synthesis, characterization, and analysis, and wrote the manuscript. X. K. and Y. L. carried out the calculation studies. R.-Q. J., X.-S. L., and C.-T. W. revised the manuscript. Y.-M. L. designed the project and supervised the whole experiment. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

This work was supported by a grant from the National Natural Science Foundation of China (NSF 22171114 and 21772075).

References

- O. Baudoin, *Chem. Soc. Rev.*, 2011, **40**, 4902–4911.
- O. Baudoin, *Acc. Chem. Res.*, 2017, **50**, 1114–1123.
- X. Chen, K. M. Engle, D.-H. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2009, **48**, 5094–5115.
- S. H. Cho, J. Y. Kim, J. Kwak and S. Chang, *Chem. Soc. Rev.*, 2011, **40**, 5068–5083.
- Á. Gutiérrez-Bonet, F. Juliá-Hernández, B. de Luis and R. Martín, *J. Am. Chem. Soc.*, 2016, **138**, 6384–6387.
- Z. Huang, H. N. Lim, F. Mo, M. C. Young and G. Dong, *Chem. Soc. Rev.*, 2015, **44**, 7764–7786.
- R. Jazzar, J. Hitce, A. Renaudat, J. Sofack-Kreutzer and O. Baudoin, *Chem.–Eur. J.*, 2010, **16**, 2654–2672.
- B.-J. Li and Z.-J. Shi, *Chem. Soc. Rev.*, 2012, **41**, 5588–5598.
- B.-J. Li, S.-D. Yang and Z.-J. Shi, *Synlett*, 2008, **2008**, 949–957.



- 10 T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147–1169.
- 11 S. R. Neufeldt and M. S. Sanford, *Acc. Chem. Res.*, 2012, **45**, 936–946.
- 12 D. Alberico, M. E. Scott and M. Lautens, *Chem. Rev.*, 2007, **107**, 174–238.
- 13 R. G. Bergman, *Nature*, 2007, **446**, 391–393.
- 14 O. Daugulis, H.-Q. Do and D. Shabashov, *Acc. Chem. Res.*, 2009, **42**, 1074–1086.
- 15 K. M. Engle, T.-S. Mei, M. Wasa and J.-Q. Yu, *Acc. Chem. Res.*, 2012, **45**, 788–802.
- 16 C. Jia, T. Kitamura and Y. Fujiwara, *Acc. Chem. Res.*, 2001, **34**, 633–639.
- 17 A. E. Shilov and G. B. Shul'pin, *Chem. Rev.*, 1997, **97**, 2879–2932.
- 18 M. Wasa and J.-Q. Yu, *J. Am. Chem. Soc.*, 2008, **130**, 14058–14059.
- 19 V. P. Mehta and J.-A. García-López, *ChemCatChem*, 2017, **9**, 1149–1156.
- 20 Y. Ping, Y. Li, J. Zhu and W. Kong, *Angew. Chem., Int. Ed.*, 2019, **58**, 1562–1573.
- 21 D. Brown, K. Grigg, V. Sridharan and V. Tambyrajah, *Tetrahedron Lett.*, 1995, **36**, 8137–8140.
- 22 R. Grigg, P. Fretwell, C. Meerholtz and V. Sridharan, *Tetrahedron*, 1994, **50**, 359–370.
- 23 D. S. Chung, J. S. Lee, H. Ryu, J. Park, H. Kim, J. H. Lee, U. B. Kim, W. K. Lee, M.-H. Baik and S.-g. Lee, *Angew. Chem., Int. Ed.*, 2018, **57**, 15460–15464.
- 24 W. Du, Q. Gu, Z. Li and D. Yang, *J. Am. Chem. Soc.*, 2015, **137**, 1130–1135.
- 25 Q. Huang and R. C. Larock, *Tetrahedron Lett.*, 2009, **50**, 7235–7238.
- 26 T. Piou, L. Neuville and J. Zhu, *Angew. Chem., Int. Ed.*, 2012, **51**, 11561–11565.
- 27 R. T. Ruck, M. A. Huffman, M. M. Kim, M. Shevlin, W. V. Kandur and I. W. Davies, *Angew. Chem., Int. Ed.*, 2008, **47**, 4711–4714.
- 28 G. Satyanarayana, C. Maichle-Mössmer and M. E. Maier, *Chem. Commun.*, 2009, 1571–1573, DOI: [10.1039/B820636H](https://doi.org/10.1039/B820636H).
- 29 F. Ye, Y. Ge, A. Spannenberg, H. Neumann and M. Beller, *Nat. Commun.*, 2020, **11**, 5383.
- 30 J. Ye, Z. Shi, T. Sperger, Y. Yasukawa, C. Kingston, F. Schoenebeck and M. Lautens, *Nat. Chem.*, 2017, **9**, 361–368.
- 31 A. Bunescu, T. Piou, Q. Wang and J. Zhu, *Org. Lett.*, 2015, **17**, 334–337.
- 32 T. Čarný, R. Rocaboy, A. Clemenceau and O. Baudoin, *Angew. Chem., Int. Ed.*, 2020, **59**, 18980–18984.
- 33 A. Clemenceau, P. Thesmar, M. Gicquel, A. Le Flohic and O. Baudoin, *J. Am. Chem. Soc.*, 2020, **142**, 15355–15361.
- 34 Q. Huang, A. Fazio, G. Dai, M. A. Campo and R. C. Larock, *J. Am. Chem. Soc.*, 2004, **126**, 7460–7461.
- 35 T. Piou, A. Bunescu, Q. Wang, L. Neuville and J. Zhu, *Angew. Chem., Int. Ed.*, 2013, **52**, 12385–12389.
- 36 A. Lu, X. Ji, B. Zhou, Z. Wu and Y. Zhang, *Angew. Chem., Int. Ed.*, 2018, **57**, 3233–3237.
- 37 M. Pérez-Gómez, S. Hernández-Ponte, D. Bautista and J.-A. García-López, *Chem. Commun.*, 2017, **53**, 2842–2845.
- 38 C. Shao, Z. Wu, X. Ji, B. Zhou and Y. Zhang, *Chem. Commun.*, 2017, **53**, 10429–10432.
- 39 B. Tan, L. Bai, P. Ding, J. Liu, Y. Wang and X. Luan, *Angew. Chem., Int. Ed.*, 2019, **58**, 1474–1478.
- 40 Z. Wu, D. Ma, B. Zhou, X. Ji, X. Ma, X. Wang and Y. Zhang, *Angew. Chem., Int. Ed.*, 2017, **56**, 12288–12291.
- 41 H. Zheng, Y. Zhu and Y. Shi, *Angew. Chem., Int. Ed.*, 2014, **53**, 11280–11284.
- 42 Z. Zuo, J. Wang, J. Liu, Y. Wang and X. Luan, *Angew. Chem., Int. Ed.*, 2020, **59**, 653–657.
- 43 X. Luo, Y. Xu, G. Xiao, W. Liu, C. Qian, G. Deng, J. Song, Y. Liang and C. Yang, *Org. Lett.*, 2018, **20**, 2997–3000.
- 44 M. Pérez-Gómez and J.-A. García-López, *Angew. Chem., Int. Ed.*, 2016, **55**, 14389–14393.
- 45 M. Pérez-Gómez, L. Navarro, I. Saura-Llamas, D. Bautista, M. Lautens and J.-A. García-López, *Organometallics*, 2017, **36**, 4465–4476.
- 46 M. Sickert, H. Weinstabl, B. Peters, X. Hou and M. Lautens, *Angew. Chem., Int. Ed.*, 2014, **53**, 5147–5151.
- 47 D. Wei, M. Y. Li, B. B. Zhu, X. D. Yang, F. Zhang, C. G. Feng and G. Q. Lin, *Angew. Chem., Int. Ed.*, 2019, **58**, 16543–16547.
- 48 T. Yao and D. He, *Org. Lett.*, 2017, **19**, 842–845.
- 49 H. Yoon, A. Lossouarn, F. Landau and M. Lautens, *Org. Lett.*, 2016, **18**, 6324–6327.
- 50 Z. Zuo, H. Wang, Y. Diao, Y. Ge, J. Liu and X. Luan, *ACS Catal.*, 2018, **8**, 11029–11034.
- 51 K. Narasaka and M. Kitamura, *Eur. J. Org. Chem.*, 2005, **2005**, 4505–4519.
- 52 H. Tsutsui, M. Kitamura and K. Narasaka, *Bull. Chem. Soc. Jpn.*, 2002, **75**, 1451–1460.
- 53 H. Tsutsui and K. Narasaka, *Chem. Lett.*, 1999, **28**, 45–46.
- 54 S. Chiba, M. Kitamura, O. Saku and K. Narasaka, *Bull. Chem. Soc. Jpn.*, 2004, **77**, 785–796.
- 55 M. Kitamura, S. Chiba, O. Saku and K. Narasaka, *Chem. Lett.*, 2002, **31**, 606–607.
- 56 M. Kitamura and K. Narasaka, *Chem. Rec.*, 2002, **2**, 268–277.
- 57 K. Okamoto, T. Oda, S. Kohigashi and K. Ohe, *Angew. Chem., Int. Ed.*, 2011, **50**, 11470–11473.
- 58 S. Zaman, K. Mitsuru and A. D. Abell, *Org. Lett.*, 2005, **7**, 609–611.
- 59 S. Liu and L. S. Liebeskind, *J. Am. Chem. Soc.*, 2008, **130**, 6918–6919.
- 60 Z.-H. Ren, Z.-Y. Zhang, B.-Q. Yang, Y.-Y. Wang and Z.-H. Guan, *Org. Lett.*, 2011, **13**, 5394–5397.
- 61 H. Tsutsui and K. Narasaka, *Chem. Lett.*, 2001, **30**, 526–527.
- 62 Y. Tan and J. F. Hartwig, *J. Am. Chem. Soc.*, 2010, **132**, 3676–3677.
- 63 T. Gerfaud, L. Neuville and J. Zhu, *Angew. Chem., Int. Ed.*, 2009, **48**, 572–577.
- 64 P. C. Too, Y.-F. Wang and S. Chiba, *Org. Lett.*, 2010, **12**, 5688–5691.
- 65 A. Faulkner and J. F. Bower, *Angew. Chem., Int. Ed.*, 2012, **51**, 1675–1679.
- 66 A. Faulkner, J. S. Scott and J. F. Bower, *J. Am. Chem. Soc.*, 2015, **137**, 7224–7230.



- 67 I. R. Hazelden, R. C. Carmona, T. Langer, P. G. Pringle and J. F. Bower, *Angew. Chem., Int. Ed.*, 2018, **57**, 5124–5128.
- 68 N. J. Race and J. F. Bower, *Org. Lett.*, 2013, **15**, 4616–4619.
- 69 N. J. Race, A. Faulkner, G. Fumagalli, T. Yamauchi, J. S. Scott, M. Rydén-Landergren, H. A. Sparkes and J. F. Bower, *Chem. Sci.*, 2017, **8**, 1981–1985.
- 70 X. Bao, Q. Wang and J. Zhu, *Angew. Chem., Int. Ed.*, 2017, **56**, 9577–9581.
- 71 C. Chen, L. Hou, M. Cheng, J. Su and X. Tong, *Angew. Chem., Int. Ed.*, 2015, **54**, 3092–3096.
- 72 C. Chen, Y. Bao, J. Zhao and B. Zhu, *Chem. Commun.*, 2019, **55**, 14697–14700.
- 73 L. Feng, L. Guo, C. Yang, J. Zhou and W. Xia, *Org. Lett.*, 2020, **22**, 3964–3968.
- 74 L. Wang and C. Wang, *Org. Chem. Front.*, 2018, **5**, 3476–3482.
- 75 Y. Zhang, H.-J. Ai and X.-F. Wu, *Org. Chem. Front.*, 2020, **7**, 2986–2990.
- 76 W.-X. Wei, S. Chen, Y. Xia, M. Li, X.-S. Li, Y.-P. Han, C.-T. Wang and Y.-M. Liang, *ChemCatChem*, 2019, **11**, 5754–5757.
- 77 W.-X. Wei, Y. Li, Y.-T. Wen, M. Li, X.-S. Li, C.-T. Wang, H.-C. Liu, Y. Xia, B.-S. Zhang, R.-Q. Jiao and Y.-M. Liang, *J. Am. Chem. Soc.*, 2021, **143**, 7868–7875.
- 78 L. Bondada, R. Rondla, U. Pradere, P. Liu, C. Li, D. Bobeck, T. McBrayer, P. Tharnish, J. Courcambeck, P. Halfon, T. Whitaker, F. Amblard, S. J. Coats and R. F. Schinazi, *Bioorg. Med. Chem. Lett.*, 2013, **23**, 6325–6330.
- 79 D. G. Brown, P. R. Bernstein, A. Griffin, S. Wesolowski, D. Labrecque, M. C. Tremblay, M. Sylvester, R. Mauger, P. D. Edwards, S. R. Throner, J. J. Folmer, J. Cacciola, C. Scott, L. A. Lazor, M. Pourashraf, V. Santhakumar, W. M. Potts, S. Sydserff, P. Giguère, C. Lévesque, M. Dasser and T. Groblewski, *J. Med. Chem.*, 2014, **57**, 733–758.
- 80 Y. Deng, Z. Yang, G. W. Shipps, S.-M. Lo, R. West, J. Hwa, S. Zheng, C. Farley, J. Lachowicz, M. van Heek, A. S. Bass, D. P. Sinha, C. R. Mahon and M. E. Cartwright, *Bioorg. Med. Chem. Lett.*, 2013, **23**, 791–796.
- 81 D. A. Griffith, R. L. Dow, K. Huard, D. J. Edmonds, S. W. Bagley, J. Polivkova, D. Zeng, C. N. Garcia-Irizarry, J. A. Southers, W. Esler, P. Amor, K. Loomis, K. McPherson, K. B. Bahnck, C. Préville, T. Banks, D. E. Moore, A. M. Mathiowetz, E. Menhaji-Klotz, A. C. Smith, S. D. Doran, D. A. Beebe and M. F. Dunn, *J. Med. Chem.*, 2013, **56**, 7110–7119.
- 82 J. O. Link, J. G. Taylor, L. Xu, M. Mitchell, H. Guo, H. Liu, D. Kato, T. Kirschberg, J. Sun, N. Squires, J. Parrish, T. Keller, Z.-Y. Yang, C. Yang, M. Matles, Y. Wang, K. Wang, G. Cheng, Y. Tian, E. Mogalian, E. Mondou, M. Cornpropst, J. Perry and M. C. Desai, *J. Med. Chem.*, 2014, **57**, 2033–2046.
- 83 W. C. Fu, Z. Wang, W. T. K. Chan, Z. Lin and F. Y. Kwong, *Angew. Chem., Int. Ed.*, 2017, **56**, 7166–7170.
- 84 Y. Gu, X. Sun, B. Wan, Z. Lu and Y. Zhang, *Chem. Commun.*, 2020, **56**, 10942–10945.
- 85 X. Luo, L. Zhou, H. Lu, G. Deng, Y. Liang, C. Yang and Y. Yang, *Org. Lett.*, 2019, **21**, 9960–9964.
- 86 X. Yang, X. Chen, Y. Xu, M. Zhang, G. Deng, Y. Yang and Y. Liang, *Org. Lett.*, 2021, **23**, 2610–2615.
- 87 Y. Yang, B. Zhou, X. Zhu, G. Deng, Y. Liang and Y. Yang, *Org. Lett.*, 2018, **20**, 5402–5405.
- 88 M. Zhang, W. Deng, M. Sun, L. Zhou, G. Deng, Y. Liang and Y. Yang, *Org. Lett.*, 2021, **23**, 5744–5749.
- 89 Q. Zhao, W. C. Fu and F. Y. Kwong, *Angew. Chem., Int. Ed.*, 2018, **57**, 3381–3385.
- 90 L. Zhou, M. Sun, F. Zhou, G. Deng, Y. Yang and Y. Liang, *Org. Lett.*, 2021, **23**, 7150–7155.
- 91 C. Amatore, M. Azzabi and A. Jutand, *J. Am. Chem. Soc.*, 1991, **113**, 8375–8384.
- 92 C. Amatore and A. Jutand, *Acc. Chem. Res.*, 2000, **33**, 314–321.
- 93 M. Piber, A. E. Jensen, M. Rottländer and P. Knochel, *Org. Lett.*, 1999, **1**, 1323–1326.
- 94 X. Yang, H. Lu, X. Zhu, L. Zhou, G. Deng, Y. Yang and Y. Liang, *Org. Lett.*, 2019, **21**, 7284–7288.
- 95 J. F. Rodríguez, A. D. Marchese and M. Lautens, *Org. Lett.*, 2018, **20**, 4367–4370.
- 96 H. Yoon, M. Röhlz, F. Landau and M. Lautens, *Angew. Chem., Int. Ed.*, 2017, **56**, 10920–10923.
- 97 I. Franzoni, H. Yoon, J.-A. García-López, A. I. Poblador-Bahamonde and M. Lautens, *Chem. Sci.*, 2018, **9**, 1496–1509.

