

Cite this: *Chem. Sci.*, 2021, 12, 6712

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

Received 25th February 2021  
Accepted 9th April 2021

DOI: 10.1039/d1sc01115d

rsc.li/chemical-science

# Nickel-catalyzed asymmetric reductive aryl-allylation of unactivated alkenes†

Zhiyang Lin,‡ Youxiang Jin,‡ Weitao Hu and Chuan Wang<sup>§</sup>\*

Herein we report a nickel-catalyzed asymmetric reductive aryl-allylation of aryl iodide-tethered unactivated alkenes, wherein both acyclic allyl carbonates and cyclic vinyl ethylene carbonates can serve as the coupling partners. Furthermore, the direct use of allylic alcohols as the electrophilic allyl source in this reaction is also viable in the presence of BOC anhydride. Remarkably, this reaction proceeds with high linear/branched-, *E/Z*- and enantio-selectivity, allowing the synthesis of various chiral indanes and dihydrobenzofurans (50 examples) containing a homoallyl-substituted quaternary stereocenter with high optical purity (90–98% ee). In this reductive reaction, the use of pregenerated organometallics can be circumvented, giving this process good functionality tolerance and high step-economy.

## Introduction

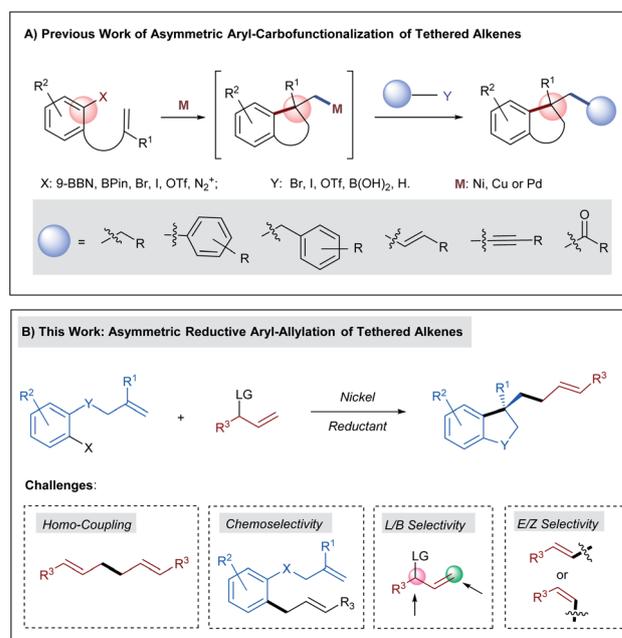
In recent years, the rapid development of transition-metal catalyzed asymmetric aryl-carbofunctionalizations of aryl borane- or aryl (pseudo)halide-tethered alkenes allow the efficient synthesis of chiral benzene-annulated cyclic compounds in a highly enantioselective fashion (Scheme 1A).<sup>1</sup> The enantiodetermining step of these reactions relies on facially selective intramolecular Heck-type aryl-metallation. After ring closure, the generated chiral alkyl metal species can be intercepted by a boronic acid, an organo(pseudo)halide, a terminal alkyne, or carbon monoxide to deliver the cross-coupling products in either a redox-neutral or a reductive pathway. Hitherto, the successfully installed carbo-moieties following this reaction sequence include alkyl,<sup>2–4</sup> aryl,<sup>4–6</sup> benzyl,<sup>7</sup> alkenyl,<sup>4,8</sup> alkynyl,<sup>9</sup> and carbonyl.<sup>10</sup> However, transition-metal catalyzed highly enantioselective olefin carbo-allylation still remains elusive mainly due to the issues in controlling chemo-, regio-, and stereo-selectivity.<sup>11,12</sup>

Herein we anticipated that a two-component enantioselective aryl-allylation of aryl-halide-tethered alkenes would be achieved through a reaction with an appropriate electrophilic allylating agent under reductive nickel catalysis<sup>13</sup> (Scheme 1B). The challenges of the target reaction lie in the following aspects: (1) allylic electrophiles are highly reactive and thus could easily outcompete aryl halides in the interaction with low-valent nickel, leading to undesired homo-coupling; (2) the direct coupling between aryl halides and allylic electrophiles is also a significant complicating factor; (3) difficulty in discriminating

both ends of the generated  $\pi$ -allylic nickel intermediate could result in a mixture of linear and branched products; (4) the newly formed C–C double bond gives rise to a potential issue of controlling *E/Z*-selectivity.

## Results and discussion

For the optimization of the reaction conditions, the aryl-iodide-tethered alkene **1a** and the allylic Boc carbonate **2a** (ref. 14) were



**Scheme 1** (A) Previous work of asymmetric aryl-carbofunctionalizations of tethered alkenes; (B) asymmetric reductive aryl-allylation of tethered alkenes.

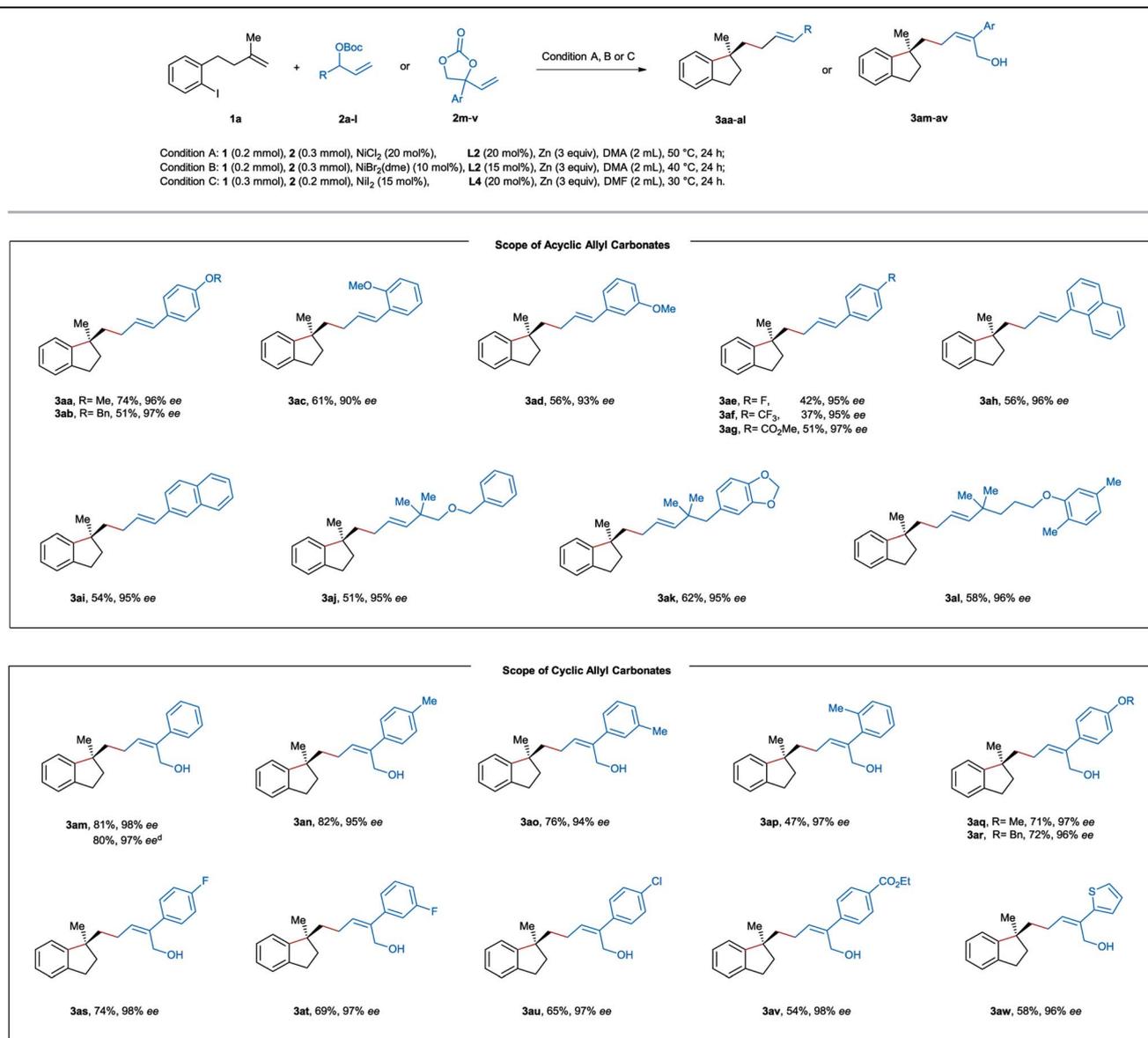
Hefei National Laboratory for Physical Science at the Microscale, Department of Chemistry, Center for Excellence in Molecular Synthesis, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui, 20237, P. R. China. E-mail: chuamw@ustc.edu.cn

† Electronic supplementary information (ESI) available: Experimental procedure, spectra data, NMR data, and HPLC data. See DOI: 10.1039/d1sc01115d

‡ These authors contributed equally.





Table 2 Evaluation of the substrate scope of allylic carbonates<sup>a-c</sup>

<sup>a</sup> Condition A: **3aa–ad**; condition B: **3ae–al**; condition C: **3am–aw**. <sup>b</sup> Yields of the isolated products after column chromatography. <sup>c</sup> Enantiomeric excesses were determined by HPLC analysis on a chiral stationary phase. <sup>d</sup> The reaction was performed on a 5 mmol scale of aryl iodide-tethered alkene **1a**.

complete linear- and *E*-selectivities were achieved for all the isolated products mentioned above.

As a specific class of cyclic allyl carbonates, vinyl ethylene carbonates have been widely applied as a substrate with various coupling partners under the catalysis of Pd, Cu, Ir, or Rh.<sup>16,17</sup> However, the use of vinyl ethylene carbonates in nickel-catalyzed reductive cross-electrophile coupling is still unknown. After screening various reaction parameters, we reoptimized the reaction conditions for vinyl ethylene carbonates as follows: NiI<sub>2</sub> (15 mol%), **L4** (20 mol%), and Zn (3 equiv) in DMF at 30 °C for 24 h. Under these conditions, a series of vinyl-substituted 1,3-dioxolan-2-ones **2m–w** were successfully

utilized as the allyl source in our reductive aryl-allylation, and the corresponding *Z*-configured chiral allylic alcohols **3am–av** and *E*-configured **3aw** were obtained as the only geometry isomer in moderate to good efficiency, complete linear-selectivity and excellent enantioselectivities (Table 2). Notably, the reported reaction could be simply scaled up to 5 mmol in the case of **3am** with a similar yield.

Next, diverse tethered alkenes **1b–l** were subjected to the reaction with different acyclic and cyclic carbonates under the optimal reaction conditions (Table 3). Generally, all the reactions provided the desired products with complete linear- and *E/Z*-selectivities as well as excellent enantioselectivities. Larger

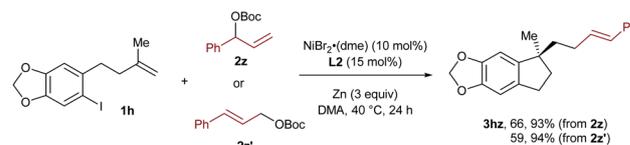


geminal substituents of the olefinic unit (**1b–e**) posed no problem, and moderate to good efficiency could be achieved in these cases. Substituted iodobenzene (**1f–i**) also turned out to be suitable precursors, producing chiral indanes in yields ranging from 41 to 83%. Moreover, our method is also applicable to the efficient construction of a chiral dihydrobenzofuran scaffold starting from the allyl phenyl ethers **1j–l**. In addition, we attempted to construct an indoline and isochroman framework by means of this nickel-catalyzed reaction. Unfortunately, no target cyclization products were formed in these cases.

In the case of **3hz**, we utilized the linear cinnamyl acetate **2z'** as the coupling partner instead of its branched analog **2z**, and found that the same product was afforded with a similar outcome concerning both yields and selectivities (Scheme 2). This result suggests the presence of a  $\pi$ -allylic nickel intermediate in the reaction, and the linear selectivity could be attributed to a regioselective reductive elimination.

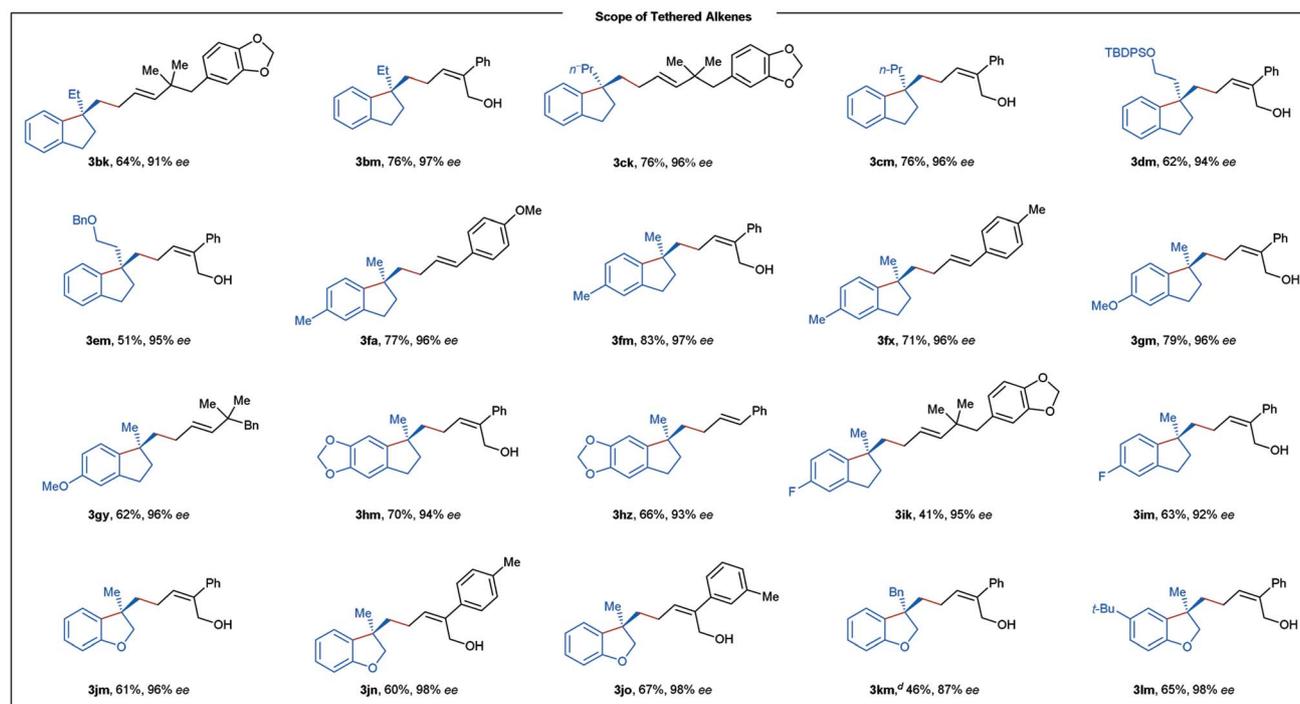
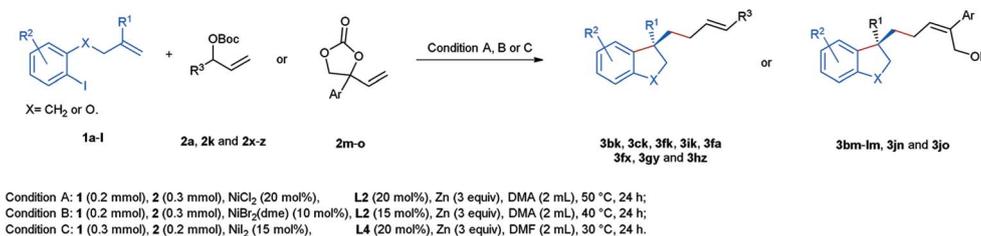
To improve the step economy of our method, we tested the reactions using directly allylic alcohols as the substrates, which

were transformed into the corresponding carbonates *in situ* via a reaction with BOC anhydride (Table 4). Gratifyingly, the target products **3aa** and **3ak** were yielded with excellent enantioselectivities in the selected reactions, although the efficiency was somewhat lower than those obtained using the corresponding carbonates. During the process of scope evaluation of acyclic allyl carbonates, we noticed that some of them, particularly heteroaryl-substituted secondary allylic carbonates, could not be isolated through column chromatography due to rapid decomposition on silica gel. Therefore, this one-pot procedure



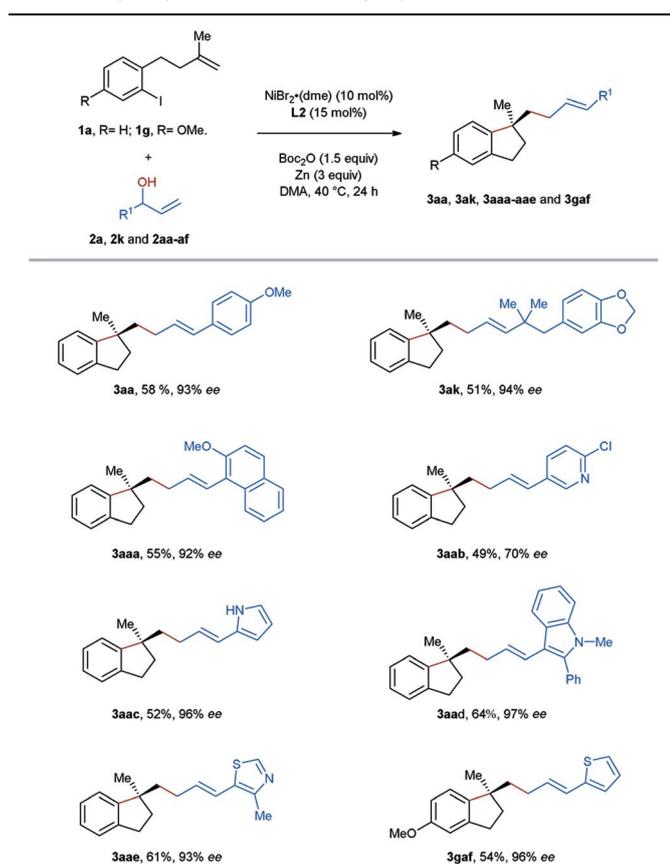
Scheme 2 Comparison of the reactions using linear and branched allyl carbonates.

Table 3 Evaluation of the substrate scope of tethered alkenes<sup>a–c</sup>



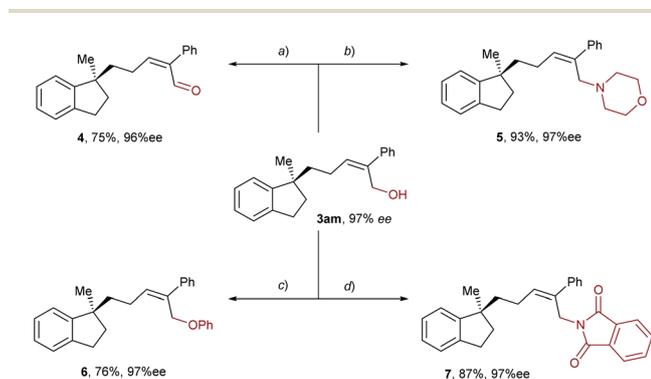
<sup>a</sup> Condition A: **3fa**; condition B: **3ck**, **3fk**, **3ik**, **3fa**, **3fx**, **3gy** and **3hz**; condition C: **3bm–lm**, **3jn** and **3jo**. <sup>b</sup> Yields of the isolated products after column chromatography. <sup>c</sup> Enantiomeric excesses were determined by HPLC analysis on a chiral stationary phase. <sup>d</sup> Reaction time: 48 h.



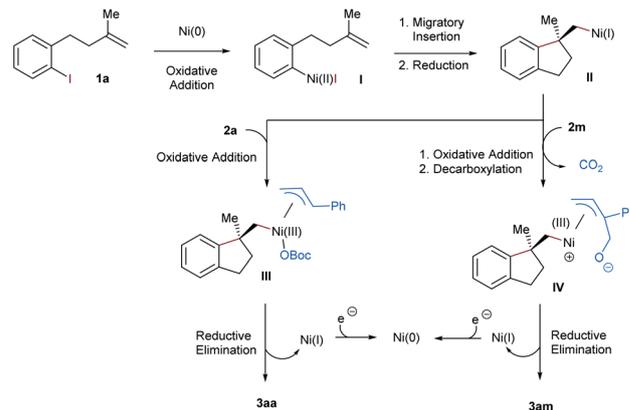
Table 4 Aryl-allylation reaction using allylic alcohols<sup>a-c</sup>

<sup>a</sup> Unless otherwise specified, reactions were performed on a 0.2 mmol scale of the aryl iodide-tethered alkene **1a** or **1g** using 2.0 equiv of allylic alcohols **2a**, **2k** and **2aa-af**, 10 mol%  $\text{NiBr}_2(\text{dme})$ , 15 mol% ligand **L2** and 3 equiv of Zn in 1.0 mL DMA at 40 °C for 24 h. <sup>b</sup> Yields of the isolated product obtained through column chromatography. <sup>c</sup> Enantiomeric Excesses were determined by HPLC analysis on a chiral stationary phase.

provides an entry to prepare aryl-allylation products, which are inaccessible following the reaction employing carbonates. A group of moieties including methoxy-substituted naphthalene (**3aaa**), pyridine (**3aab**), pyrrole (**3aac**), indole (**3aad**), thiazole (**3aae**), and thiophene (**3gaf**) were successfully incorporated into



Scheme 3 Derivatizations of the aryl-allylation product.



Scheme 4 Proposed mechanism.

the framework of the aryl-allylation products according to the protocol of the reactions employing allylic alcohols.

Taking advantage of the attached hydroxyl group as a functional handle, various derivatizations of the aryl-allylation product **3am** were conducted, and the results are demonstrated in Scheme 3. First, compound **3am** was oxidized into an  $\alpha,\beta$ -unsaturated aldehyde **4** in 75% yield by means of Dess-Martin oxidation. Next,  $\text{PBr}_3$ -mediated bromination of **3am** followed by nucleophilic substitution with morpholine furnished an allylic amine **5** in 83% yield over two steps. Moreover, **3am** was subjected to the Mitsunobu reaction using phenol or phthalimide as the nucleophile, delivering an allyl phenyl ether **6** and an allylic imide **7** in 76% and 87% yields, respectively. Notably, the enantioselectivities of all the derivatization products mentioned above remained high.

On the basis of previous reports, we proposed a plausible mechanism for this nickel-catalyzed aryl-allylation reaction in Scheme 4. Initially,  $\text{Ni}(0)$  is formed under reductive conditions and undergoes subsequently oxidative addition with the alkene-tethered aryl iodide **1a**. The resultant  $\text{Ni}(\text{II})$  complex **I** performs a facially selective intramolecular migratory insertion into the pendant olefinic unit, to complete the construction of the chiral benzene-fused ring framework.<sup>6-8</sup> Alternatively, the enantiodiscriminating step could also be facially selective oxidative addition prior to the insertion.<sup>18</sup> The following zinc-mediated single-electron reduction affords the  $\text{Ni}(\text{I})$  intermediate **II**, to which the allylic carbonates **2a** and **2m** are oxidatively added. In the case of the cyclic allyl carbonate **2m**, decarboxylation succeeds the oxidative addition. Next, terminal selective reductive elimination from the generated  $\pi$ -allylic nickel species **III** or **IV** yields the linear aryl-allylation product **3aa** or **3am**, respectively.<sup>14,19</sup> Finally, Zn-mediated reduction of  $\text{Ni}(\text{I})$  regenerates  $\text{Ni}(0)$  for the next catalytic cycle.

## Conclusions

In conclusion, we have developed a highly enantioselective nickel-catalyzed reductive aryl-allylation of aryl iodide-tethered unactivated alkenes with both acyclic and cyclic allyl carbonates as the allylating agent. Moreover, allylic alcohols can be employed directly as the electrophilic allyl source in the



presence of BOC anhydride. The enantiodetermining step of the studied reaction relies on facially selective intramolecular Heck-type arylnickelation, while regioselective reductive elimination from the  $\pi$ -allylic nickel intermediates leads to the linear selectivity of the coupling product. Furthermore, the formation of a new C–C double bond proceeds with high *E/Z*-selectivity. The aforementioned high chemo-, regio- and stereo-control along with mild reductive reaction conditions allow the preparation of diverse highly enantioenriched indanes and dihydrobenzofurans bearing a homoallyl-substituted quaternary stereogenic center with a high tolerance of functionalities.

## Author contributions

C. W. conceived and designed the experiments. Z. L., Y. J. and W. H. performed the experiments and prepared the Supporting Information. C. W. directed the project and wrote the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work is supported by “1000-Youth Talents Plan” start up funding, the National Natural Science Foundation of China (21772183, 22071230), the Fundamental Research Funds for the Central Universities (WK2060190086) and the University of Science and Technology of China.

## Notes and references

- For reviews on transition-metal catalyzed dicarbofunctionalization, see: (a) R. Giri and S. KC, *J. Org. Chem.*, 2018, **83**, 3013; (b) J. Derosa, O. Apolinar, T. Kang, V. T. Tran and K. M. Engle, *Chem. Sci.*, 2020, **11**, 4287; (c) H.-Y. Tu, S. Zhu, F.-L. Qing and L. Chu, *Synthesis*, 2020, **52**, 1346; (d) X. Qi and T. Diao, *ACS Catal.*, 2020, **10**, 8542; (e) Y.-C. Luo, C. Xu and X. Zhang, *Chin. J. Chem.*, 2020, **38**, 1371; (f) Y. Ping and W. Kong, *Synthesis*, 2020, **52**, 979.
- H. Cong and G. C. Fu, *J. Am. Chem. Soc.*, 2014, **136**, 3788.
- Y. Jin and C. Wang, *Angew. Chem., Int. Ed.*, 2019, **58**, 6722.
- Z.-M. Zhang, B. Xu, L. Wu, Y. Wu, Y. Qian, L. Zhou, Y. Liu and J. Zhang, *Angew. Chem., Int. Ed.*, 2019, **58**, 14653.
- W. You and M. K. Brown, *J. Am. Chem. Soc.*, 2015, **137**, 14578.
- K. Wang, Z. Ding, Z. Zhou and W. Kong, *J. Am. Chem. Soc.*, 2018, **140**, 12364.
- Y. Jin, H. Yang and C. Wang, *Org. Lett.*, 2020, **22**, 2720.
- (a) Z.-X. Tian, J.-B. Qiao, G.-L. Xu, X. Pang, L. Qi, W.-Y. Ma, Z.-Z. Zhao, J. Duan, Y. F. Du, P. Su, X.-Y. Liu and X.-Z. Shu, *J. Am. Chem. Soc.*, 2019, **141**, 7637; (b) T. Ma, Y. Chen, Y. Li, Y. Ping and W. Kong, *ACS Catal.*, 2019, **9**, 9127.
- (a) X. Bai, C. Wu, S. Ge and Y. Lu, *Angew. Chem., Int. Ed.*, 2020, **59**, 2764; (b) L. Zhou, S. Li, B. Xu, D. Ji, L. Wu, Y. Liu, Z.-M. Zhang and J. Zhang, *Angew. Chem., Int. Ed.*, 2020, **59**, 2769.
- (a) R. C. Carmona, O. D. Köster and C. R. D. Correia, *Angew. Chem., Int. Ed.*, 2018, **57**, 12067; (b) H. Hu, F. Teng, J. Liu, W. Hu, S. Luo and Q. Zhu, *Angew. Chem., Int. Ed.*, 2019, **58**, 9225; (c) C. Cheng, B. Wan, B. Zhou, Y. Gu and Y. Zhang, *Chem. Sci.*, 2019, **10**, 9853; (d) M. Chen, X. Wang, P. Yang, X. Kou, Z.-H. Ren and Z.-H. Guan, *Angew. Chem., Int. Ed.*, 2020, **59**, 12199; (e) Z. Yuan, Y. Zeng, Z. Feng, Z. Guan, A. Lin and H. Yao, *Nat. Commun.*, 2020, **11**, 2544.
- For examples of the racemic version of transition metal-catalyzed olefin carbo-allylation, see: (a) T. Taniguchi and K. Ogasawara, *Chem. Commun.*, 1998, 1531; (b) K. Semba, N. Ohta, Y. Yano and Y. Nakao, *Chem. Commun.*, 2018, **54**, 11463; (c) K. Semba, N. Ohta and Y. Nakao, *Org. Lett.*, 2019, **21**, 4407; (d) H. Li, M. Zhang, H. Mehfooz, D. Zhu, J. Zhao and Q. Zhang, *Org. Chem. Front.*, 2019, **6**, 3387; (e) V. T. Tran, Z.-Q. Li, T. J. Gallagher, J. Derosa, P. Liu and K. M. Engle, *Angew. Chem., Int. Ed.*, 2020, **59**, 7029.
- During the preparation of our manuscript, Nakao *et al.* reported an enantioselective example of olefin aryl-allylation with moderate enantiocontrol: K. Semba, N. Ohta, F. Paulus, M. Ohata and Y. Nakao, *Chemistry – A European Journal*, 2021, **27**, 5035.
- For general reviews on reductive cross-coupling, see: (a) D. A. Everson and D. J. Weix, *J. Org. Chem.*, 2014, **79**, 4793; (b) T. Moragas, A. Correa and R. Martin, *Chemistry – A European Journal*, 2014, **20**, 8242; (c) J. Gu, X. Wang, W. Xue and H. Gong, *Org. Chem. Front.*, 2015, **2**, 1411; (d) D. J. Weix, *Acc. Chem. Res.*, 2015, **48**, 1767; (e) X. Wang, Y. Dai and H. Gong, *Top. Curr. Chem.*, 2016, **374**, 43; (f) E. Richmond and J. Moran, *Synthesis*, 2018, **50**, 499; (g) K. E. Poremba, S. E. Dibrell and S. E. Reisman, *ACS Catal.*, 2020, **10**, 8237; (h) Y. Jin and C. Wang, *Synlett*, 2020, **31**, 1843.
- For examples of the use of allylic carbonates in nickel-catalyzed cross-electrophile coupling, see: (a) Y. Dai, F. Wu, Z. Zang, H. You and H. Gong, *Chemistry – A European Journal*, 2012, **18**, 808; (b) F. Chen, X. Jia, Y. Yu, Q. Qian and H. Gong, *Angew. Chem., Int. Ed.*, 2017, **56**, 13103; (c) F. Song, F. Wang, L. Guo, X. Feng, Y. Zhang and L. Chu, *Angew. Chem., Int. Ed.*, 2020, **59**, 177.
- F. Yang, Y. Jin and C. Wang, *Org. Lett.*, 2019, **21**, 6989.
- For a review on the use of vinyl ethylene carbonates in transition-metal catalysis, see: W. Guo, J. E. Gómez, À. Cristòfol, J. Xie and A. W. Kleij, *Angew. Chem., Int. Ed.*, 2018, **57**, 13735.
- For examples on the use of vinyl ethylene carbonates in transition-metal catalysis, see: (a) B. M. Trost and G. R. Granja, *Tetrahedron Lett.*, 1991, **32**, 2193; (b) B. M. Trost and A. Aponick, *J. Am. Chem. Soc.*, 2006, **128**, 3931; (c) Y. J. Zhang, J. H. Yang, S. H. Kim and M. J. Krische, *J. Am. Chem. Soc.*, 2010, **132**, 4562; (d) A. Khan, R. Zheng, Y. Kan, J. Ye, J. Xing and Y. J. Zhang, *Angew. Chem., Int. Ed.*, 2014, **53**, 6439; (e) A. Khan, L. Yang, J. Xu, L. Y. Jin and Y. J. Zhang, *Angew. Chem., Int. Ed.*, 2014, **53**, 11257; (f) W. Guo, L. Martínez-Rodríguez, R. Kuniyil, E. Martín, E. C. Escudero-Adán, F. Maseras and A. W. Kleij, *J. Am. Chem. Soc.*, 2016, **138**, 11970; (g) A. Cai, W. Guo, L. Martínez-Rodríguez and A. W. Kleij, *J. Am.*



- Chem. Soc.*, 2016, **138**, 14194; (*h*) W. Guo, L. Martínez-Rodríguez, E. Martín, E. C. Escudero-Adán and A. W. Kleij, *Angew. Chem., Int. Ed.*, 2016, **55**, 11037; (*i*) A. Khan, S. Khan, I. Khan, C. Zhao, Y. Mao, Y. Chen and Y. J. Zhang, *J. Am. Chem. Soc.*, 2017, **139**, 10733; (*j*) L.-C. Yang, Z.-Q. Rong, Y.-N. Wang, Z. Y. Tan, M. Wang and Y. Zhao, *Angew. Chem., Int. Ed.*, 2017, **56**, 2927; (*k*) H. Wang, M. Lorion and L. Ackermann, *Angew. Chem., Int. Ed.*, 2017, **56**, 6339; (*l*) Z.-Q. Rong, L.-C. Yang, S. Liu, Y.-N. Wang, Z. Y. Tan, R.-Z. Huang, Y. Lan and Y. Zhao, *J. Am. Chem. Soc.*, 2017, **139**, 15304; (*m*) N. Miralles, J. E. Gómez, A. W. Kleij and E. Fernández, *Org. Lett.*, 2017, **19**, 6096; (*n*) S. Singha, T. Patra, C. G. Daniliuc and F. Glorius, *J. Am. Chem. Soc.*, 2018, **140**, 3551; (*o*) A. Khan, H. Zhao, M. Zhang, S. Khan and D. Zhao, *Angew. Chem., Int. Ed.*, 2020, **59**, 1340; (*p*) Y. Wang, J. Chai, C. You, J. Zhang, X. Mi, L. Zhang and S. Luo, *J. Am. Chem. Soc.*, 2020, **142**, 3184; (*q*) L. Chen, H. Quan, Z. Xu, H. Wang, Y. Xia, L. Lou and W. Yang, *Nat. Commun.*, 2020, **11**, 2151.
- 18 J.-N. Desrosier, J. Wen, S. Teyrulnikov, S. Biswas, B. Qu, L. Hie, D. Kurouski, L. Wu, N. Grinberg, N. Haddad, C. A. Busacca, N. K. Yee, J. J. Song, N. K. Garg, X. Zhang, M. C. Kozlowski and C. H. Senanayake, *Org. Lett.*, 2017, **19**, 3338.
- 19 L. S. Hegedus and D. H. P. Thompson, *J. Am. Chem. Soc.*, 1985, **107**, 5663.

