

Cite this: *Chem. Sci.*, 2022, 13, 7790

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

Received 30th March 2022
Accepted 19th May 2022

DOI: 10.1039/d2sc01840c

rsc.li/chemical-science

Synthesis of oxaboranes *via* nickel-catalyzed dearylyative cyclocondensation†

Mason T. Koeritz,‡ Haley K. Banovetz,‡ Sean A. Prell and Levi M. Stanley *

We report Ni-catalyzed dearylyative cyclocondensation of aldehydes, alkynes, and triphenylborane. The reaction is initiated by oxidative cyclization of the aldehyde and alkyne coupling partners to generate an oxanickelacyclopentene which reacts with triphenylborane to form oxaboranes. This formal dearylyative cyclocondensation reaction generates oxaboranes in moderate-to-high yields (47–99%) with high regioselectivities under mild reaction conditions. This approach represents a direct and modular synthesis of oxaboranes which are difficult to access using current methods. These oxaboranes are readily transformed into valuable building blocks for organic synthesis and an additional class of boron heterocycles. Selective homocoupling forms oxaboroles, oxidation generates aldol products, and reduction and arylation form substituted allylic alcohols.

Introduction

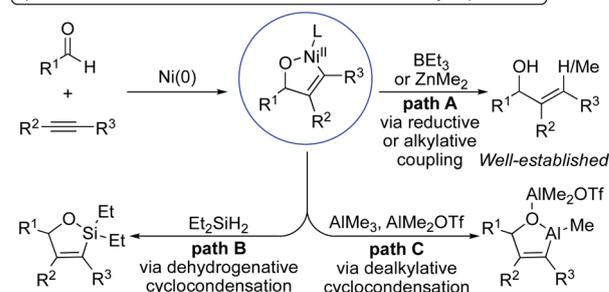
Nickel-catalyzed oxidative cyclization reactions of two π -components enable facile generation of nickelacycles with formation of a new C–C bond.^{1–6} These reactions encompass a broad array of suitable π -components that provide access to a range of substituted nickelacycles. Among these π -components, nickel-catalyzed oxidative cyclizations of aldehydes and alkynes are established methods to generate an array of oxanickelacyclopentenes.² These oxanickelacyclopentenes are versatile intermediates that can be transformed into a variety of synthetically valuable building blocks. Early studies in this area focus on reductive and alkylyative coupling reactions to form substituted allylic alcohols (Scheme 1a, path A).^{2a,b} Subsequently, Montgomery and coworkers discovered that oxanickelacyclopentenes react with diethylsilane to form stable oxasilacyclopentenes *via* dehydrogenative cyclocondensation reactions (Scheme 1a, path B).⁷ Ogoshi and coworkers reported related dealkylative cyclocondensation reactions of oxanickelacyclopentenes with trimethylaluminum to form oxaaluminumacyclopentenes (Scheme 1a, path C).⁸

Oxaboranes⁹ (X = Ar), oxaboroles¹⁰ (X = OH), and related boron heterocycles¹¹ have garnered increased interest in recent years due to their biological activities,¹² optical properties,¹³ and utility as synthetic building blocks. The ability to leverage the reactivity of oxaboracyclopentenes would enable rapid and tailorable syntheses of these boron heterocycles. However,

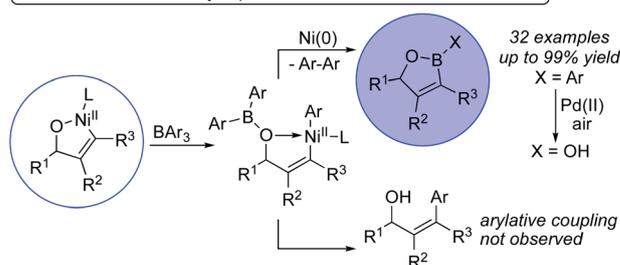
dehydrogenative cyclocondensation reactions analogous to the synthesis of oxasilacyclopentenes would be challenging with dihydridoborane or trihydridoborane reagents due to competing hydroboration of the alkyne component.¹⁴ Analogous reactions with a trialkylborane lead to reductive coupling instead of dealkylative cyclocondensation.^{2b}

We envisioned dearylyative cyclocondensation reactions of aldehydes, alkynes, and a triarylborane as direct, catalytic syntheses of oxaboracyclopentenes (Scheme 1b, top). The use of

a) Previous Studies: Transformations of oxanickelacyclopentenes



b) This Work: Dearylyative cyclocondensation reactions to generate oxaboracyclopentenes



Scheme 1 Reactivity of oxanickelacycles.

Department of Chemistry, Iowa State University, Ames, Iowa 50011, USA. E-mail: lstanley@iastate.edu

† Electronic supplementary information (ESI) available: Experimental details and characterization of all new compounds. See <https://doi.org/10.1039/d2sc01840c>

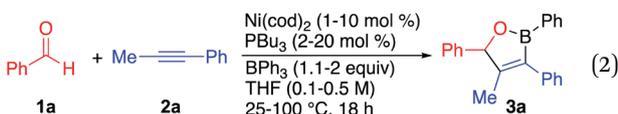
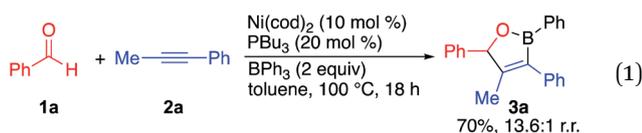
‡ These authors contributed equally to this work.



a triarylborane reagent eliminates the potential for reductive coupling to form allylic alcohols as shown in Scheme 1a. This approach also eliminates the need for complex starting materials,^{10g} strongly basic reaction conditions,^{10d} and multi-step synthetic procedures.^{10ef} The development of dearylyative cyclocondensation reactions to form oxaboracyclopentenes would provide a straightforward and modular entry into these boron heterocycles that addresses the limitations of current synthetic methods. Key to the development of these dearylyative cyclocondensation reactions is the identification of a nickel catalyst that mitigates the potential for arylyative coupling to form substituted allylic alcohols (Scheme 1b, bottom).^{3c} Herein, we report the first nickel-catalyzed couplings of aldehydes, alkynes, and triphenylborane to form oxaboracyclopentenes in high yields with excellent regio- and chemoselectivities.

Results and discussion

In our initial studies, we found that the reaction of benzaldehyde **1a**, 1-phenyl-1-propyne **2a**, and triphenylborane in the presence of a catalyst generated from Ni(cod)₂ and PBu₃ produced oxaborane **3a** in 70% yield and a 13.6 : 1 regioisomeric ratio (eqn (1)). Additionally, we observed the formation of equal amounts of biphenyl in the reaction with no observable arylyative coupling product. This result is consistent with a reaction that proceeds *via* the dearylyative cyclocondensation pathway shown in Scheme 1b.



We next chose to leverage design of experiment (DoE) to increase the yield of the reaction and lower the catalyst loading.¹⁵ We first evaluated categorical factors (ligand and solvent) in the reaction (Table S1†) and found that a catalyst generated from Ni(cod)₂ and PBu₃ produced oxaborane product **3a** in quantitative yields when THF was used as the solvent. However, we recognized the potential to use DoE to further optimize the reaction by lowering the loadings of catalyst and the organoboron reagent (eqn (2)). We evaluated the level of significance of four continuous factors (catalyst loading, reaction concentration, temperature, and loading of the organoboron reagent, Scheme S1 and Table S2†) in 14 reactions using a linear model DoE. The results of this DoE showed that temperature and catalyst loading did not have a significant impact on the yield of the reaction, but the yield of the reaction is positively correlated with increased loadings of triphenylborane. We then performed a quadratic model DoE

consisting of 15 reactions to further optimize our dearylyative cyclocondensation reaction (Scheme S2 and Table S3†). This set of reactions showed that the loading of catalyst could be reduced if the loading of triphenylborane is increased (Fig. 1a). In addition, higher reaction temperatures generally lead to lower yields of the oxaborane product across a range of catalyst loadings (Fig. 1b). Based on the response surfaces in Fig. 1, we chose 5 mol% catalyst and 1.5 equivalents BPh₃ at 50 °C as reaction conditions to evaluate the scope of the dearylyative cyclocondensation reaction.

We initially evaluated the scope of the dearylyative cyclocondensation reaction with respect to the alkyne coupling partner (Scheme 2). The reaction of benzaldehyde with 1-aryl-1-hexyne derivatives **2b–2i** bearing electron-neutral, electron-donating, and electron-withdrawing *para*-substituents generated oxaborane products **3b–3i** in 73–98% yield with up to 11.4 : 1 regioisomeric ratios. A phenolic hydroxyl group was also tolerated in the reaction, with the reaction of alkyne **2i** producing oxaborane **3i** in 85% yield and 9.1 : 1 r.r. The reactions of alkynes containing *meta*-substituted aryl groups lead to oxaborane products **3j** and **3k** in 89% and 72% yield, respectively. The reaction of 1-(2-methylphenyl)-1-hexyne **2l** formed oxaborane **3l** in 80% yield and >20 : 1 regioselectivity as a 1.1 : 1 ratio of diastereomers when the reaction temperature was increased to 70 °C. The reaction of 2-(hex-1-yn-1-yl)naphthalene **2m** generated oxaborane **3m** in 99% yield and 11.1 : 1 r.r. A heteroaromatic ring was also tolerated in the reaction with benzofuran-derived alkyne **2n** leading to oxaborane **3n** in 90% yield. The reaction of enyne **2o** formed oxaborane **3o** in 40% isolated yield with 3.1 : 1 regioselectivity. The lower regioselectivity is presumably due to competing coordinating effects of the alkene.¹⁶ The reaction of benzaldehyde with diphenylacetylene produced oxaborane product **3p** in 84% isolated yield. Aliphatic alkynes are also tolerated in the reaction, with reactions of 3-hexyne and 4-octyne leading to oxaboranes **3q** and **3r** in 80% and 94% yield, respectively. Limitations of the dearylyative cyclocondensation reactions include: (1) aromatic aldehydes bearing strongly electron-withdrawing substituents, such as nitro groups; (2) alkynes containing bulky substituents, such as trimethylsilyl groups, and (3) terminal alkynes due to competing cyclotrimerization processes.^{2b,d,3b,17}

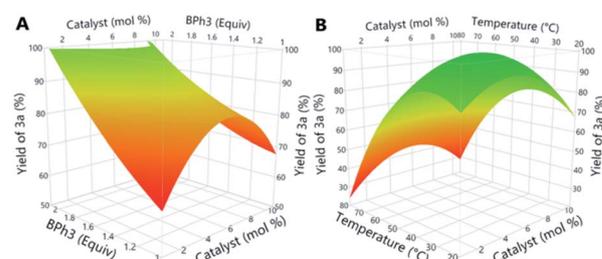
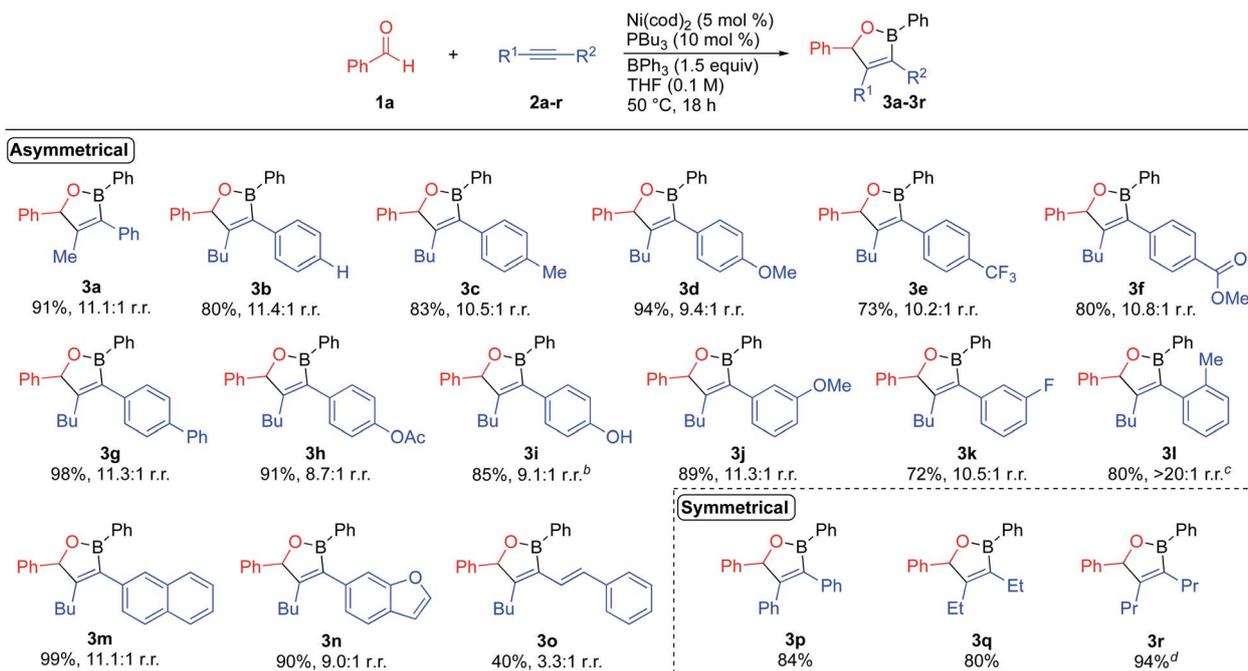


Fig. 1 Response surface analysis of quadratic design of experiment. (A) Yield of **3a** versus catalyst loading and equivalents of triphenylborane at 50 °C. (B) Yield of **3a** versus catalyst loading and temperature with 1.5 equivalents of triphenylborane.

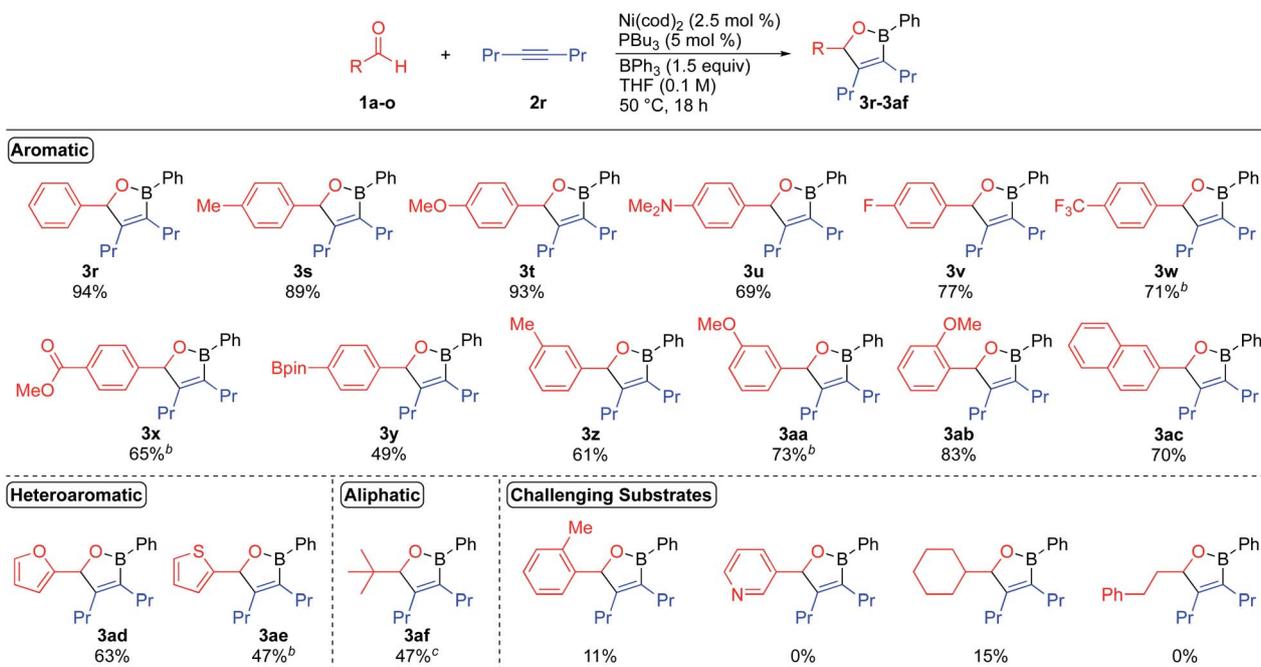




Scheme 2 Alkyne substrate scope for the nickel-catalyzed dearylyative cyclocondensations. ^aReaction conditions: **1a** (0.200 mmol), **2** (0.220 mmol), BPh₃ (0.300 mmol), Ni(cod)₂ (0.010 mmol), PBu₃ (0.020 mmol), THF (2.0 mL, 0.10 M), 50 °C, 18 h. ^bReaction run with 10 mol% Ni(cod)₂, 20 mol% PBu₃, 1.5 equiv. alkyne, and 2 equiv. BPh₃. ^cReaction run at 70 °C. ^dReaction run with 2.5 mol% catalyst.

We next turned our attention to establishing the scope of aldehyde coupling partners (Scheme 3). While investigating the scope of aldehydes with 4-octyne as the alkyne coupling partner, we found that only 2.5 mol% of the catalyst was required to

form oxaboranes derived from aromatic aldehydes containing electron-donating and electron-withdrawing substituents. These reactions lead to the formation of oxaboranes **3s–3ab** in good to excellent yields. In general, reactions of benzaldehyde



Scheme 3 Aldehyde substrate scope for the nickel-catalyzed dearylyative cyclocondensations. ^aReaction conditions: **1** (0.200 mmol), **2r** (0.220 mmol), BPh₃ (0.300 mmol), Ni(cod)₂ (0.005 mmol), PBu₃ (0.010 mmol), THF (2.0 mL, 0.10 M), 50 °C, 18 h. ^bReaction run at 70 °C. ^cReaction run with 10 mol% catalyst.



derivatives bearing electron-donating substituents occur at lower temperatures and form oxaboranes in higher yields, while reactions of benzaldehyde derivatives bearing electron-withdrawing substituents require higher temperatures to generate the corresponding oxaboranes, such as **3w**, **3x**, and **3aa**, in good yields. 2-Naphthaldehyde was also well tolerated, and this reaction formed oxaborane **3ac** in 70% yield. The dearylyative cyclocondensation reaction also tolerates hetero-aromatic aldehydes, such as furfural and 2-thiophenecarboxaldehyde, generating oxaboranes **3ad** and **3ae** in 63% and 47% yield, respectively. Pivaldehyde also proved to be a viable substrate, and this reaction generated oxaborane **3af** in 47% yield. However, aliphatic aldehydes containing alpha-hydrogens, such as cyclohexanecarboxaldehyde and 3-phenylpropanal, proved to be challenging substrates due to competing aldehyde oligomerization.^{2a,18} Reactions of these aldehydes typically formed the corresponding oxaborane products in <15% yield.

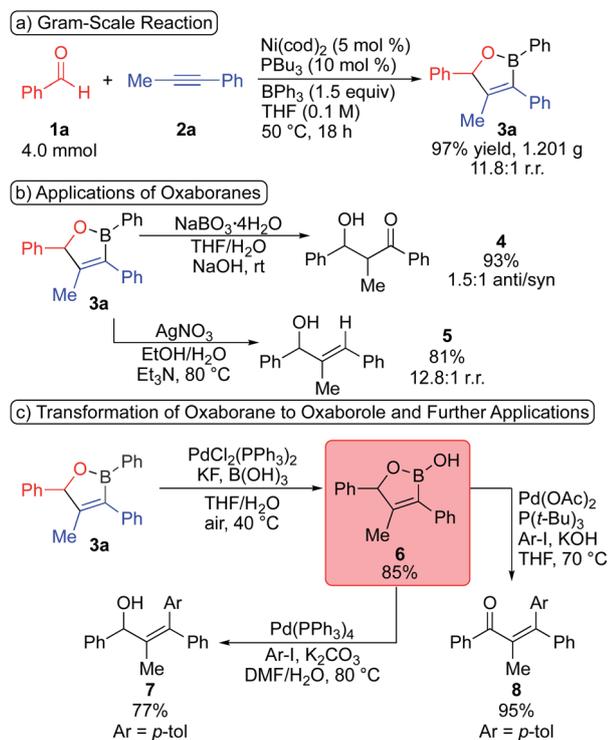
The dearylyative cyclocondensation reaction is currently limited to triphenylborane as the organoboron component. Reactions of other triarylboranes led to significantly lower yields of the corresponding oxaborane products. For example, the reaction of benzaldehyde, 1-phenyl-1-propyne, and tris(4-methoxyphenyl)borane formed the corresponding oxaborane in <20% yield.

The utility of the dearylyative cyclocondensation reaction to generate oxaboranes is shown in Scheme 4. The gram-scale reaction of benzaldehyde (4.0 mmol) and 1-phenyl-1-propyne (4.4 mmol) occurs to form oxaborane **3a** in 97% yield with an 11.8 : 1 regioisomeric ratio (Scheme 4a). We then conducted

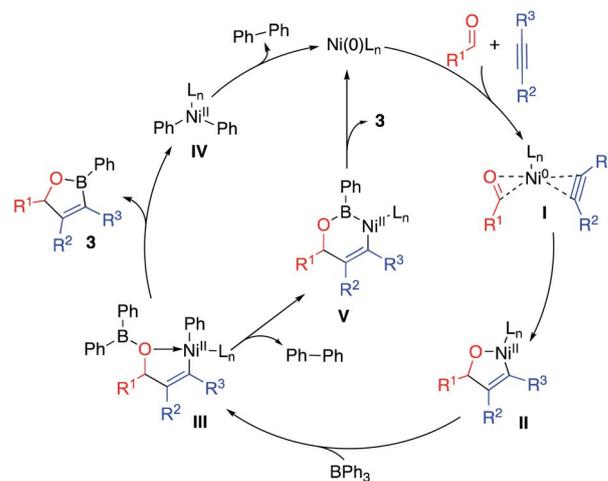
a series of transformations of oxaborane **3a** to demonstrate oxaboranes as versatile synthetic intermediates (Scheme 4b).^{10c} Oxidation of oxaborane **3a** with sodium perborate produced β -hydroxy ketone **4** in 93% yield and 1.5 : 1 d.r.¹⁹ The sequence of dearylyative cyclocondensation and oxidation provides an alternative pathway to cross-aldol addition reactions. Protodeboronation of oxaborane **3a** leads to allylic alcohol **5** in 81% yield.²⁰

We then attempted to transform our oxaborane product to an oxaborole. Dong and coworkers previously reported transformation of oxaborinanes to cyclic hydroxyl boronates *via* hydrolysis in the presence of H₂O/MeOH.^{11d} However, oxaborane **3a** is unreactive under analogous hydrolysis conditions. We were pleased to observe that oxaborole **6** can be generated in 85% yield by selective homocoupling of oxaborane **3a** in the presence of PdCl₂(PPh₃)₂ (Scheme 4c).²¹ The modularity of our oxaborane synthesis and ability to transform oxaboranes to oxaboroles provide access to the biologically active oxaborole motif with high levels of customizability. Additionally, these oxaboroles can also be utilized as versatile synthetic intermediates. Oxaborole **6** undergoes Suzuki–Miyaura coupling with 4-iodotoluene to form highly substituted allylic alcohol **7** in 77% yield when Pd(PPh₃)₄ is used as a precatalyst.²² α,β -Unsaturated ketone **8** is formed in 95% yield through a sequence of Suzuki–Miyaura coupling and oxidation when the catalyst is generated from Pd(OAc)₂ and P(*t*-Bu)₃.²³

Based on mechanisms proposed by Montgomery and Ogoshi for nickel-catalyzed dehydrogenative⁷ and dealkylative^{8,24} cyclocondensation reactions, we propose the following plausible catalytic cycles for this dearylyative cyclocondensation reaction (Scheme 5). Coordination of the Ni(0) catalyst to the alkyne and aldehyde substrates forms intermediate **I**. Oxidative cyclization generates oxanickelacyclopentene intermediate **II**. Transmetalation with triphenylborane forms vinyl-Ni(II)-aryl intermediate **III**. We envision two potential pathways to generate oxaborane **3** from intermediate **III**. One potential pathway involves a second intramolecular transmetalation to form diaryl-Ni(II) intermediate **IV** with release of the oxaborane



Scheme 4 Synthetic transformations of oxaboranes.



Scheme 5 Proposed catalytic cycle.



product **3**. Subsequent reductive elimination from **IV** generates biphenyl and reforms the Ni(0) catalyst. Alternatively, sigma-bond metathesis of the Ni-Ph and B-Ph bonds would lead to direct extrusion of biphenyl from intermediate **III** to form six-membered nickelacycle **V**. Reductive elimination of the vinyl and boryl ligands generates oxaborane product **3** and regenerates the Ni(0) catalyst.

Conclusions

In summary, we have developed a Ni-catalyzed dearylyative cyclocondensation of aldehydes, alkynes, and triphenylborane. This reaction forms C-C and C-B bonds to generate a variety of oxaborane products in up to 99% yield under mild reaction conditions. These oxaborane products are readily transformed into oxaboroles, β -hydroxy ketones, a variety of substituted allylic alcohols, and highly substituted α,β -unsaturated ketones. Further studies to determine the mechanism and expand the scope of dearylyative cyclocondensation reactions are ongoing in our laboratory.

Data availability

The data for this work, including optimization tables, experimental procedures, and characterization data for all compounds are provided in the ESI.†

Author contributions

M. T. K. and H. K. B. contributed equally to this work. M. T. K. and L. M. S. conceived the project. M. T. K. optimized the reaction conditions and performed design of experiment studies. M. T. K., H. K. B., and S. A. P. synthesized starting materials, evaluated the scope of the reaction, and completed synthetic applications. M. T. K., H. K. B., and L. M. S. wrote the manuscript with input from S. A. P.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank the National Science Foundation-CHE (grant no. 1955529) for supporting this work. We gratefully acknowledge Prof. Junqi Li (Iowa State University) for her expertise and advice regarding organoboron compounds.

Notes and references

1 For review of nickel-catalyzed oxidative cyclization reactions, see: (a) J. Montgomery, *Angew. Chem., Int. Ed.*, 2004, **43**, 3890–3908; (b) Y. Hoshimoto, M. Ohashi and S. Ogoshi, *Acc. Chem. Res.*, 2015, **48**, 1746–1755; (c) S. Ogoshi, *Bull. Chem. Soc. Jpn.*, 2017, **90**, 1401–1406; (d) M. Holmes, L. A. Schwartz and M. J. Krische, *Chem. Rev.*, 2018, **118**, 6026–6052.

- 2 For select examples of nickel-catalyzed oxidative cyclization reactions involving aldehydes and alkynes, see: (a) E. Oblinger and J. Montgomery, *J. Am. Chem. Soc.*, 1997, **119**, 9065–9066; (b) W.-S. Huang, J. Chan and T. F. Jamison, *Org. Lett.*, 2000, **2**, 4221–4223; (c) E. A. Colby and T. F. Jamison, *J. Org. Chem.*, 2003, **68**, 156–166; (d) K. M. Miller, W.-S. Huang and T. F. Jamison, *J. Am. Chem. Soc.*, 2003, **125**, 3442–3443; (e) G. M. Mahandru, G. Liu and J. Montgomery, *J. Am. Chem. Soc.*, 2004, **126**, 3698–3699; (f) S. Ogoshi, T. Arai, M. Ohashi and H. Kurosawa, *Chem. Commun.*, 2008, 1347–1349, DOI: [10.1039/B717261C](https://doi.org/10.1039/B717261C); (g) P. R. McCarren, P. Liu, P. H.-Y. Cheong, T. F. Jamison and K. N. Houk, *J. Am. Chem. Soc.*, 2009, **131**, 6654–6655; (h) H. Wang, G. Lu, G. J. Sormunen, H. A. Malik, P. Liu and J. Montgomery, *J. Am. Chem. Soc.*, 2017, **139**, 9317–9324.
- 3 For select examples of nickel-catalyzed oxidative cyclization reactions involving alkynes and other π -components, see: (a) J. Montgomery and A. V. Savchenko, *J. Am. Chem. Soc.*, 1996, **118**, 2099–2100; (b) C. Molinaro and T. F. Jamison, *J. Am. Chem. Soc.*, 2003, **125**, 8076–8077; (c) S. J. Patel and T. F. Jamison, *Angew. Chem., Int. Ed.*, 2003, **42**, 1364–1367; (d) S. Ogoshi, H. Ikeda and H. Kurosawa, *Angew. Chem., Int. Ed.*, 2007, **46**, 4930–4932; (e) X. You, X. Xie, G. Wang, M. Xiong, R. Sun, H. Chen and Y. Liu, *Chem.-Eur. J.*, 2016, **22**, 16765–16769.
- 4 For select examples of nickel-catalyzed oxidative cyclization reactions involving alkenes, see: (a) S. Ogoshi, M. Ueta, T. Arai and H. Kurosawa, *J. Am. Chem. Soc.*, 2005, **127**, 12810–12811; (b) M. Ohashi, M. Ikawa and S. Ogoshi, *Organometallics*, 2011, **30**, 2765–2774; (c) Y. Hoshimoto, Y. Hayashi, H. Suzuki, M. Ohashi and S. Ogoshi, *Angew. Chem., Int. Ed.*, 2012, **51**, 10812–10815; (d) Y. Hayashi, Y. Hoshimoto, R. Kumar, M. Ohashi and S. Ogoshi, *Chem. Commun.*, 2016, **52**, 6237–6240; (e) H. Shirataki, M. Ohashi and S. Ogoshi, *Eur. J. Org. Chem.*, 2019, **2019**, 1883–1887; (f) W.-M. Feng, T.-Y. Li, L.-J. Xiao and Q.-L. Zhou, *Org. Lett.*, 2021, **23**, 7900–7904.
- 5 For select examples of nickel-catalyzed oxidative cyclization reactions involving dienes, see: (a) S. Ogoshi, K.-i. Tonomori, M.-a. Oka and H. Kurosawa, *J. Am. Chem. Soc.*, 2006, **128**, 7077–7086; (b) M. Morimoto, Y. Nishida, T. Miura and M. Murakami, *Chem. Lett.*, 2013, **42**, 550–552; (c) Y.-Q. Li, G. Chen and S.-L. Shi, *Org. Lett.*, 2021, **23**, 2571–2577.
- 6 For an example of nickel-catalyzed oxidative cyclization reaction involving allenes, see: W. Li, N. Chen and J. Montgomery, *Angew. Chem., Int. Ed.*, 2010, **49**, 8712–8716.
- 7 R. D. Baxter and J. Montgomery, *J. Am. Chem. Soc.*, 2008, **130**, 9662–9663.
- 8 M. Ohashi, H. Saijo, T. Arai and S. Ogoshi, *Organometallics*, 2010, **29**, 6534–6540.
- 9 J. Chen, X. Fang, Z. Bajko, J. W. Kampf and A. J. Ashe, *Organometallics*, 2004, **23**, 5088–5091.
- 10 (a) G.-H. Fang, Z.-J. Yan, J. Yang and M.-Z. Deng, *Synthesis*, 2006, **2006**, 1148–1154; (b) Y. Nagashima, K. Hirano, R. Takita and M. Uchiyama, *J. Am. Chem. Soc.*, 2014, **136**, 8532–8535; (c) G. Lafitte, K. Kunihiro, C. Bonneaud,



- B. Dréan, F. Gaigne, V. Parnet, R. Pierre, C. Raffin, R. Vatinel, J.-F. Fournier, B. Musicki, G. Ouvry, C. Bouix-Peter, L. Tomas and C. S. Harris, *Tetrahedron Lett.*, 2017, **58**, 3757–3759; (d) M. Nogami, K. Hirano, M. Kanai, C. Wang, T. Saito, K. Miyamoto, A. Muranaka and M. Uchiyama, *J. Am. Chem. Soc.*, 2017, **139**, 12358–12361; (e) L.-J. Cheng and N. P. Mankad, *Angew. Chem., Int. Ed.*, 2018, **57**, 10328–10332; (f) R. Fritzemeier, A. Gates, X. Guo, Z. Lin and W. L. Santos, *J. Org. Chem.*, 2018, **83**, 10436–10444; (g) M.-B. Li, D. Posevins, A. Geoffroy, C. Zhu and J.-E. Bäckvall, *Angew. Chem., Int. Ed.*, 2020, **59**, 1992–1996.
- 11 (a) H. Saito, S. Otsuka, K. Nogi and H. Yorimitsu, *J. Am. Chem. Soc.*, 2016, **138**, 15315–15318; (b) F. Yang, M. Zhu, J. Zhang and H. Zhou, *Med. Chem. Commun.*, 2018, **9**, 201–211; (c) S. Tsuchiya, H. Saito, K. Nogi and H. Yorimitsu, *Org. Lett.*, 2019, **21**, 3855–3860; (d) H. Lyu, I. Kevlishvili, X. Yu, P. Liu and G. Dong, *Science*, 2021, **372**, 175–182; (e) H. E. Hackney and D. G. Hall, *ChemPhotoChem*, 2022, e202100219, DOI: [10.1002/cptc.202100219](https://doi.org/10.1002/cptc.202100219).
- 12 (a) F. L. Rock, W. Mao, A. Yaremchuk, M. Tukalo, T. Crépin, H. Zhou, Y.-K. Zhang, V. Hernandez, T. Akama, S. J. Baker, J. J. Plattner, L. Shapiro, S. A. Martinis, S. J. Benkovic, S. Cusack and M. R. K. Alley, *Science*, 2007, **316**, 1759–1761; (b) S. J. Baker, C. Z. Ding, T. Akama, Y.-K. Zhang, V. Hernandez and Y. Xia, *Future Med. Chem.*, 2009, **1**, 1275–1288; (c) S. J. Baker, J. W. Tomsho and S. J. Benkovic, *Chem. Soc. Rev.*, 2011, **40**, 4279–4285; (d) D. D. Dixon, J. W. Lockner, Q. Zhou and P. S. Baran, *J. Am. Chem. Soc.*, 2012, **134**, 8432–8435; (e) X. Li, Y.-K. Zhang, J. J. Plattner, W. Mao, M. R. K. Alley, Y. Xia, V. Hernandez, Y. Zhou, C. Z. Ding, J. Li, Z. Shao, H. Zhang and M. Xu, *Bioorg. Med. Chem. Lett.*, 2013, **23**, 963–966.
- 13 (a) M. Nogami, K. Hirano, K. Morimoto, M. Tanioka, K. Miyamoto, A. Muranaka and M. Uchiyama, *Org. Lett.*, 2019, **21**, 3392–3395; (b) M. Nakano, R. Nakamura, Y. Sumida, K. Nagao, T. Furuyama, F. Inagaki and H. Ohmiya, *Chem. Pharm. Bull.*, 2021, **69**, 526–528.
- 14 (a) G. Zweifel, G. M. Clark and N. L. Polston, *J. Am. Chem. Soc.*, 1971, **93**, 3395–3399; (b) N. W. J. Ang, C. S. Buettner, S. Docherty, A. Bismuto, J. R. Carney, J. H. Docherty, M. J. Cowley and S. P. Thomas, *Synthesis*, 2018, **50**, 803–808.
- 15 For select examples of design of experiment in organic synthesis, see: (a) *Design and Optimization in Organic Synthesis*, ed. R. Carlson and J. E. Carlson, Elsevier B. V., Amsterdam, Netherlands, 2005; (b) S. E. Denmark and C. R. Butler, *J. Am. Chem. Soc.*, 2008, **130**, 3690–3704; (c) S. Stone, T. Wang, J. Liang, J. Cochran, J. Green and W. Gu, *Org. Biomol. Chem.*, 2015, **13**, 10471–10476; (d) S. A. Weissman and N. G. Anderson, *Org. Process Res. Dev.*, 2015, **19**, 1605–1633; (e) P. M. Murray, F. Bellany, L. Benhamou, D.-K. Bučar, A. B. Tabor and T. D. Sheppard, *Org. Biomol. Chem.*, 2016, **14**, 2373–2384; (f) G. D. Bowden, B. J. Pichler and A. Maurer, *Sci. Rep.*, 2019, **9**, 11370; (g) M. T. Koeritz, R. W. Burgett, A. A. Kadam and L. M. Stanley, *Org. Lett.*, 2020, **22**, 5731–5736.
- 16 (a) K. M. Miller, T. Luanphaisarnnont, C. Molinaro and T. F. Jamison, *J. Am. Chem. Soc.*, 2004, **126**, 4130–4131; (b) P. Liu, P. McCarren, P. H.-Y. Cheong, T. F. Jamison and K. N. Houk, *J. Am. Chem. Soc.*, 2010, **132**, 2050–2057.
- 17 (a) S. Saito and Y. Yamamoto, *Chem. Rev.*, 2000, **100**, 2901–2916; (b) A. F. Orsino, M. Gutiérrez del Campo, M. Lutz and M.-E. Moret, *ACS Catal.*, 2019, **9**, 2458–2481; (c) A. F. Orsino and M.-E. Moret, *Organometallics*, 2020, **39**, 1998–2010.
- 18 (a) O. Vogl, *J. Macromol. Sci., Part A: Pure Appl. Chem.*, 1967, **1**, 243–266; (b) O. Vogl, *Makromol. Chem.*, 1974, **175**, 1281–1308.
- 19 Y. S. Zhao, X. Q. Tang, J. C. Tao, P. Tian and G. Q. Lin, *Org. Biomol. Chem.*, 2016, **14**, 4400–4404.
- 20 C. Liu, X. Li and Y. Wu, *RSC Adv.*, 2015, **5**, 15354–15358.
- 21 E. R. Darzi, B. M. White, L. K. Loventhal, L. N. Zakharov and R. Jasti, *J. Am. Chem. Soc.*, 2017, **139**, 3106–3114.
- 22 S. Roscales and A. G. Csáký, *Org. Lett.*, 2015, **17**, 1605–1608.
- 23 N. Rodríguez, M. Medio-Simón and G. Asensio, *Adv. Synth. Catal.*, 2007, **349**, 987–991.
- 24 M. Ohashi, O. Kishizaki, H. Ikeda and S. Ogoshi, *J. Am. Chem. Soc.*, 2009, **131**, 9160–9161.

