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Nickel-catalyzed three-component olefin reductive dicarbofunctionalization to access alkylborates†

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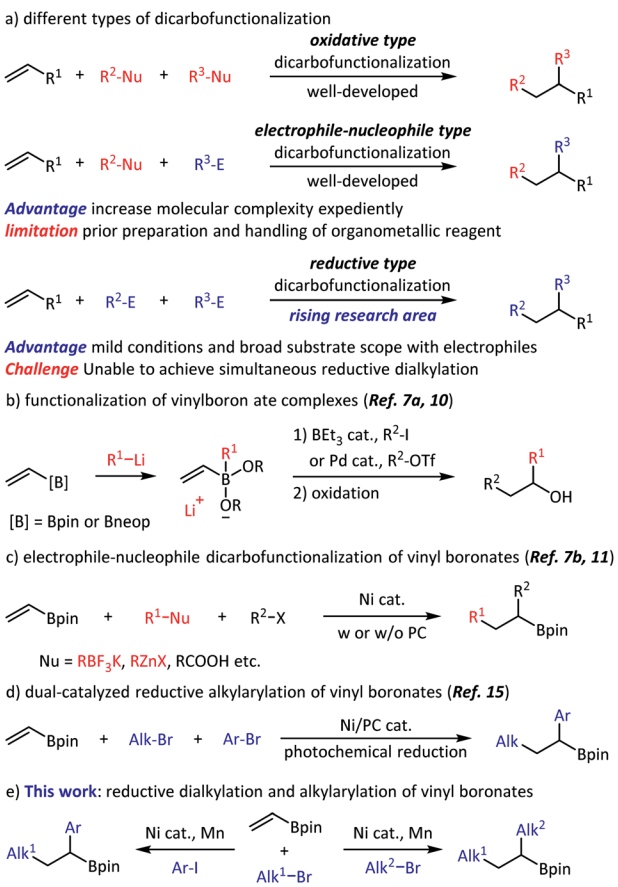
We report a three-component olefin reductive dicarbofunctionalization for constructing alkylborates, specifically, nickel-catalyzed reductive dialkylation and alkylarylation of vinyl boronates with a variety of alkyl bromides and aryl iodides. This reaction exhibits good coupling efficiency and excellent functional group compatibility, providing convenient access to the late-stage modification of complex natural products and drug molecules. Combined with alkylborate transformations, this reaction could also find applications in the modular and convergent synthesis of complex compounds.

Introduction

Olefins are fundamental chemicals in organic synthesis. They frequently occur in natural products, are produced in enormous quantities in the petroleum industry, and are prepared through a variety of synthetic methods in the laboratory. The reactive double bonds make olefins attractive substrates for high-complexity synthesis. Among the well-developed olefin functionalization strategies,[1,2] the rising reductive dicarbofunctionalization has already been proven to be a powerful and straightforward method (Scheme 1a).[3] For example, Nevado and co-workers realized nickel-catalyzed intermolecular olefin reductive alkylarylation, in which one C(sp^3)–C(sp^3) bond and one C(sp^3)–C(sp^2) bond were formed.[4] Chu and co-workers reported an example of intermolecular olefin reductive carboacylation with fluoroalkyl iodides and acyl chlorides.[5] However, the development of important dialkylation processes[6] is relatively limited and still relies on organometallics that are sensitive to many functional groups.[7,8]

Recently, dicarbofunctionalization of commercially available vinyl boronates has been applied to the diversified synthesis of alkylborates.[9] For example, Morken, Studer and Aggarwal independently achieved functionalization of a vinylboron ate complex using an organolithium reagent and another electrophile (Scheme 1b).[7a,10] Most recently, the electrophile-nucleophile dicarbofunctionalization of a vinyl boronate has been achieved with appropriate radical precursor (Scheme 1c).[7b,11] In addition, hydroalkylation and hydroarylation of alkenyl boronic esters has



Scheme 1 Dicarbofunctionalization of vinyl boronates to access alkylborates. B_2pin_2 = bis(pinacolato)diboron. B_2neop_2 = bis(neopentyl glycolato)diboron. Tf = triflyl. Nu = nucleophile. E = electrophile. w = with. w/o = without. PC = photoredox catalysis. Ar = aryl. Alk = alkyl.

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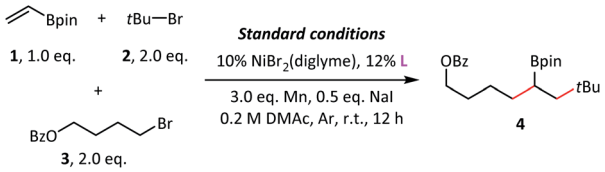
also been realized.[12] Despite these great successes, general and modular methods to access alkylborates without using any organometallic reagents are still desirable. With our focus on olefin reductive coupling[13] and alkylborate synthesis,[14] we set out to realize the regioselective dicarbofunctionalization of vinyl boronates, taking advantage of nickel-catalyzed reductive coupling and classical Giese-type addition. Very recently, Martin and co-workers reported an efficient alkylarylation of vinyl boronates through the nickel/photoredox dual-catalyzed reductive cross-coupling (Scheme 1d).[15] Our work extended the approach towards an alkyl,alkyl-difunctionalization. Intermolecular three-component reductive olefin dialkylation, especially alkyl,alkyl-difunctionalization of vinyl boronates, could find many applications in organic synthesis and medicinal chemistry; however, to the best of our knowledge, is yet to be reported, and is addressed in this work. Herein, we report a three-component olefin reductive dicarbofunctionalization for constructing alkylborates, specifically, nickel-catalyzed reductive dialkylation and alkylarylation of vinyl boronates with a variety of alkyl bromides and aryl iodides (Scheme 1e). This reaction shows good coupling efficiency, excellent functional group compatibility, and a high degree of regioselectivity. From the point of view of alkylborate transformations,[16] this reaction might find a number of applications in modular and convergent synthesis of complex, densely functionalized compounds.

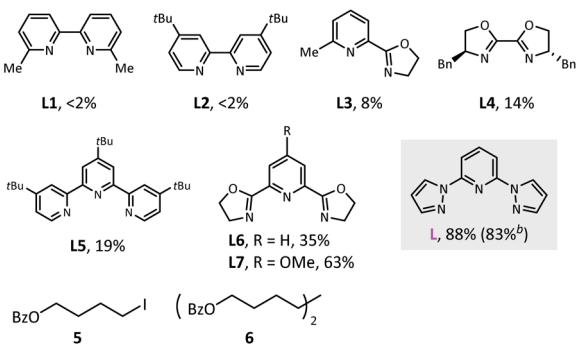
Results and discussion

We began this study with the synthesis of alkylborate **4** through the proposed dialkylation (Table 1). We systematically screened

Table 1 Optimization of the reaction conditions[a]



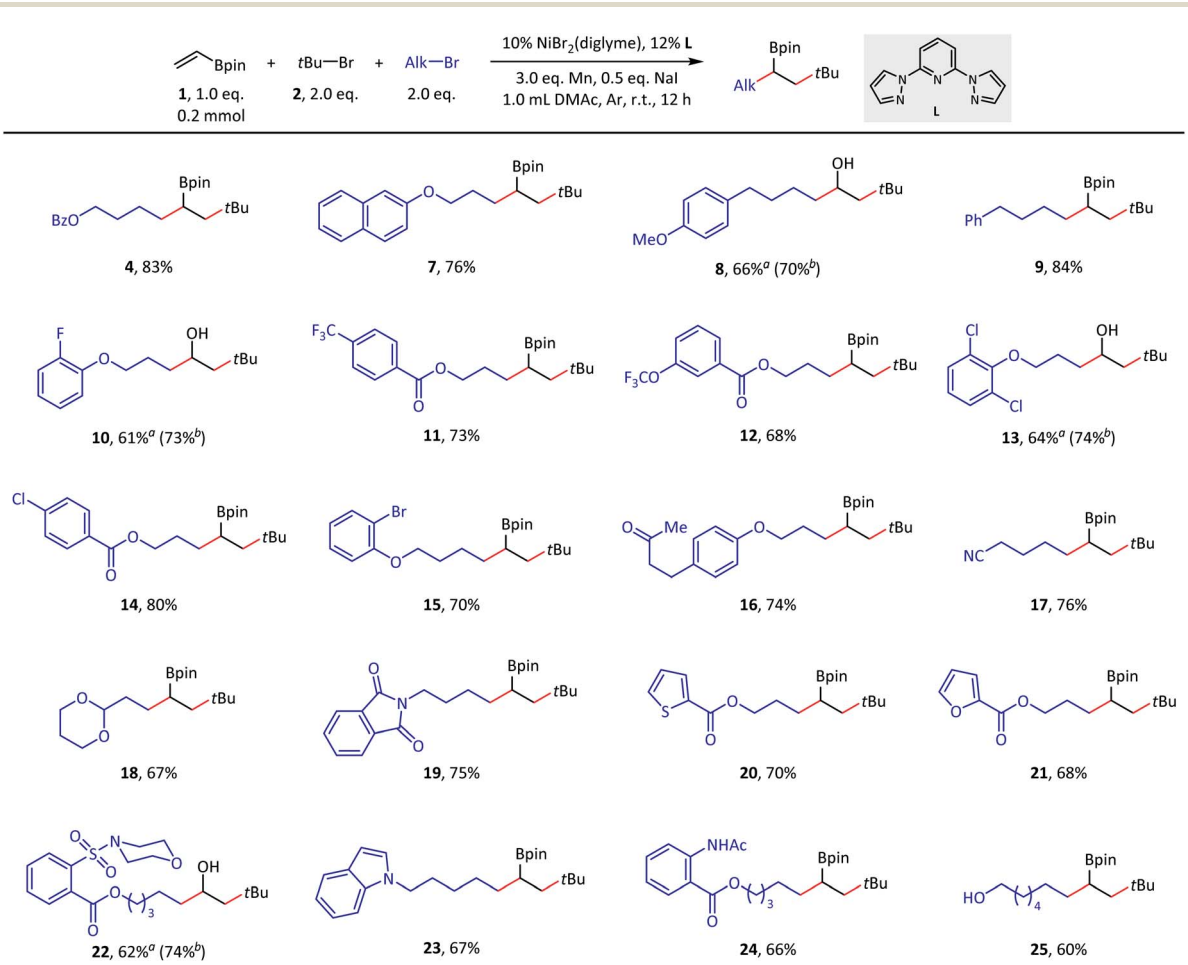
Entry	Deviation from standard conditions	Yield (%)
1	None	88 (83[b])
2	W/o $NiBr_2$(diglyme) or w/o **L**	N.R.
3	$NiCl_2(PPh_3)_2$, NiI_2, or $Ni(COD)_2$ instead of $NiBr_2$(diglyme)	49–83
4	3.0 eq. Zn instead of Mn	76
5	3.0 eq. B_2pin_2 and 3.0 eq. LiOMe instead of Mn	44
6	3.0 eq. B_2pin_2 and 3.0 eq. K_3PO_4 instead of Mn	50
7	3.0 eq. DEMS and 3.0 eq. Na_2CO_3 instead of Mn	11
8	DMF, or NMP instead of DMAc	72–87
9	THF, 1,4-dioxane, CH_3CN, or DMSO instead of DMAc	<2
10	**5** instead of **3**	54
11	*t*BuI or *t*BuCl instead of *t*BuBr	<2
12	*t*BuCl with 20% Cp_2TiCl_2 instead of *t*BuBr	<2
13	30% TBAI instead of 50% NaI	82
14	20% NaI instead of 50% NaI	45
15	Ratio of **1** : **2** : **3** = 1 : 1 : 1 instead of 1 : 2 : 2	52
16	Ratio of **1** : **2** : **3** = 1 : 1.5 : 2 instead of 1 : 2 : 2	76



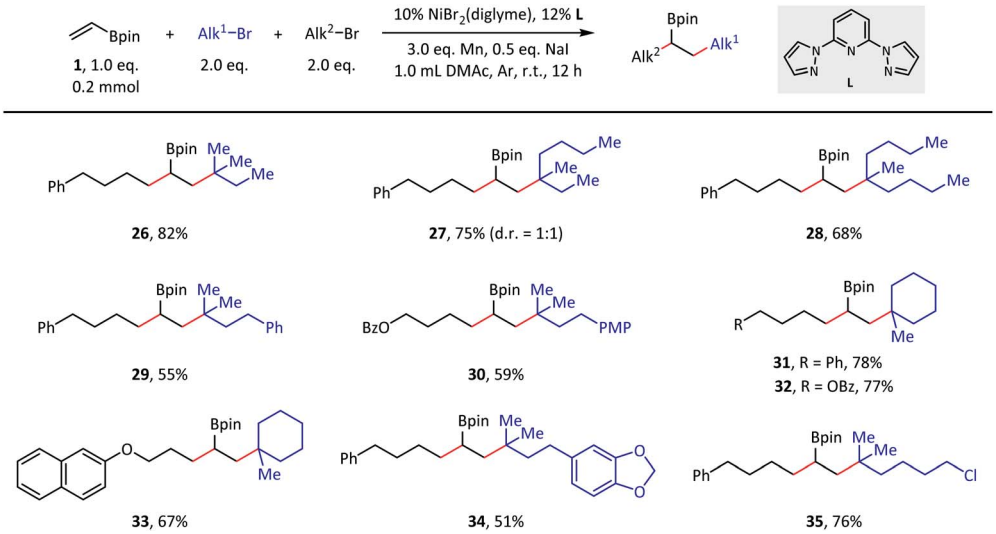
[a] Standard conditions: **1** (0.1 mmol, 1.0 equiv.), **2** (0.2 mmol, 2.0 equiv.), **3** (0.2 mmol, 2.0 equiv.), $NiBr_2$(diglyme) (0.01 mmol, 10 mol%), **L** (0.012 mmol, 12 mol%), Mn (0.3 mmol, 3.0 equiv.), NaI (0.05 mmol, 0.5 equiv.), DMAc (0.5 mL, 0.2 M), argon, room temperature (r.t.), 12 h. GC yield. 4,4′-Dimethoxybenzophenone was used as an internal standard. [b] Isolated yield. Bz = benzoyl. Diglyme = 2-methoxyethyl ether. DMAc = *N*,*N*-dimethylacetamide. COD = *cis*,*cis*-1,5-cyclooctadiene. DEMS = diethoxymethylsilane. DMF = *N*,*N*-dimethylformamide. NMP = 1-methyl-2-pyrrolidinone. THF = tetrahydrofuran. DMSO = dimethyl sulfoxide. Cp_2TiCl_2 = titanocene dichloride. TBAI = tetrabutylammonium iodide.

all the reaction parameters (see the ESI† for more details), and desired product **4** was obtained in 88% gas chromatography (GC) yield and 83% isolated yield in the presence of $NiBr_2$(diglyme), a dipyrazolpyridine ligand (**L**), a Mn(0) reductant, and a NaI additive in DMAc (entry 1). A number of other nitrogen-containing ligands were compared: all bidentate ligands, bipyridine ($\mathbf{L_1}$ and $\mathbf{L_2}$), pyridine-oxazoline ($\mathbf{L_3}$), and bioxazoline ($\mathbf{L_4}$) were inefficient; tridentate tripyridine ($\mathbf{L_5}$) yielded only a small amount of the desired products; and pyridine-oxazoline ligands ($\mathbf{L_6}$ and $\mathbf{L_7}$) produced moderate yields. In the absence of nickel catalysts or ligands, dialkylation could not proceed (entry 2). Other nickel sources, including $NiCl_2(PPh_3)_2$, NiI_2, and $Ni(COD)_2$ could also be used instead of $NiBr_2$(diglyme); however, they led to different decreases in coupling efficiency (entry 3). Metal Zn[13c,17] and diboron[13b,18] were potential reductants for this transformation (entries 4–6),[19] but our previously used nickel-silane reductive system[13a,d] was incompetent (entry 7). Amide solvents were critical: DMF and NMP resulted in comparable yields (entry 8) to that of DMAc (optimal conditions), but the reaction was completely inhibited in THF, 1,4-dioxane, CH_3CN, and DMSO (entry 9). The performance of primary alkyl iodide **5** was barely satisfactory (entry 10), and a significant amount of homocoupling product **6** was observed. Tertiary alkyl bromides were irreplaceable: the corresponding iodides and chlorides provided no dialkylation product (entry 11), even in the presence of activator reagents (entry 12). Finally, the iodide ion additive and ratio of starting material were also carefully selected (entries 13–16).

With suitable conditions in hand, we set out to evaluate the scope of this olefin dialkylation reaction. As shown in Scheme 2, a variety of primary alkyl bromides delivered desired products **7–25** in moderate to good yields (60–84%). Because of mild reductive cross-coupling conditions, this reaction exhibited good compatibility with a wide range of synthetically useful functional groups, such as ester (**4**), ether (**7–8**), aryl fluoride (**10**), trifluoromethyl (**11**), and trifluoromethoxy (**12**) groups. Satisfactory chemoselectivity was observed in compounds **13–15**; in these cases, aryl chlorides and bromides were proven to be less reactive than alkyl bromides. This chemoselectivity provided a profitable platform for further manipulations at the surviving aryl electrophilic sites. Both base-sensitive ketone (**16**) and cyano (**17**) groups and acid-sensitive acetal (**18**) groups posed no problem during this transformation. Several heterocycles such as phthalimide (**19**), thiophene (**20**), furan (**21**),



Scheme 2 Substrate scope of primary alkyl bromides. Standard conditions: as shown in Table 1, entry 1, 0.2 mmol scale. Isolated yield. [a] The product was isolated after the oxidization of the corresponding alkylborate. Isolated yield. [b] Nuclear magnetic resonance (NMR) yield for the corresponding alkylborate. Dibromomethane was used as an internal standard.

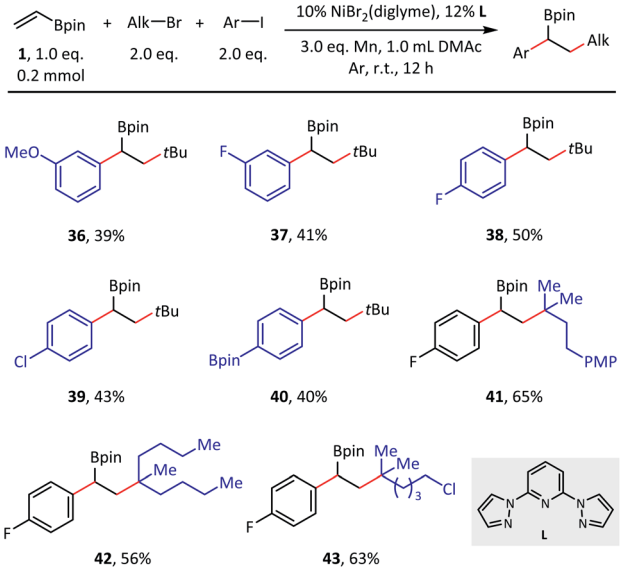


Scheme 3 Substrate scope of tertiary alkyl bromides. Standard conditions: as shown in Table 1, entry 1, 0.2 mmol scale. Isolated yield. PMP = *p*-methoxyphenyl.

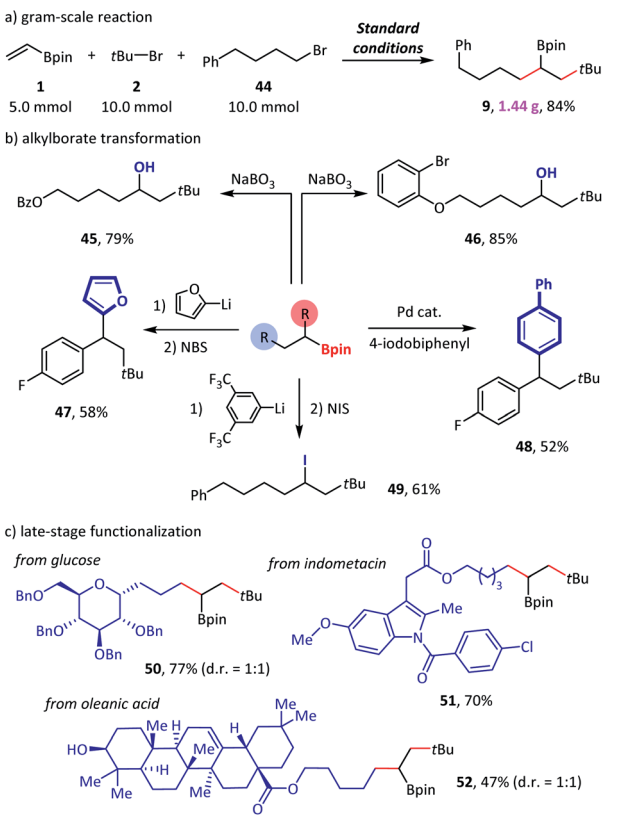
morpholine (**22**), and indole (**23**) moieties, were well tolerated. Finally, this reaction also performed well in the presence of amide-possessing N–H bonds (**24**) and unprotected alcohol (**25**) groups.

The versatility of this reaction was further demonstrated in terms of the tertiary alkyl partners (Scheme 3). Both acyclic (**26–30**) and cyclic (**31–33**) tertiary alkyl bromides were successfully converted to the desired products. With respect to the acyclic substrates, dramatically different steric hindrances only resulted in a slight influence on the coupling efficiencies. Finally, tertiary alkyl bromides containing ester (**32**), ether (**33**), acetal (**34**), and C(sp^3)–Cl (**35**) groups were indeed good substrates during the transformation and afforded the corresponding products with moderate to good isolated yields.

Although the primary focus of this study was olefin reductive dialkylation, the optimized conditions could also be extended to alkylarylation (Scheme 4). Benzylic boronates were obtained



Scheme 4 Substrate scope of olefin reductive alkylarylation. Conditions: as shown in Table 1, entry 1, without NaI, 0.2 mmol scale. Isolated yield.



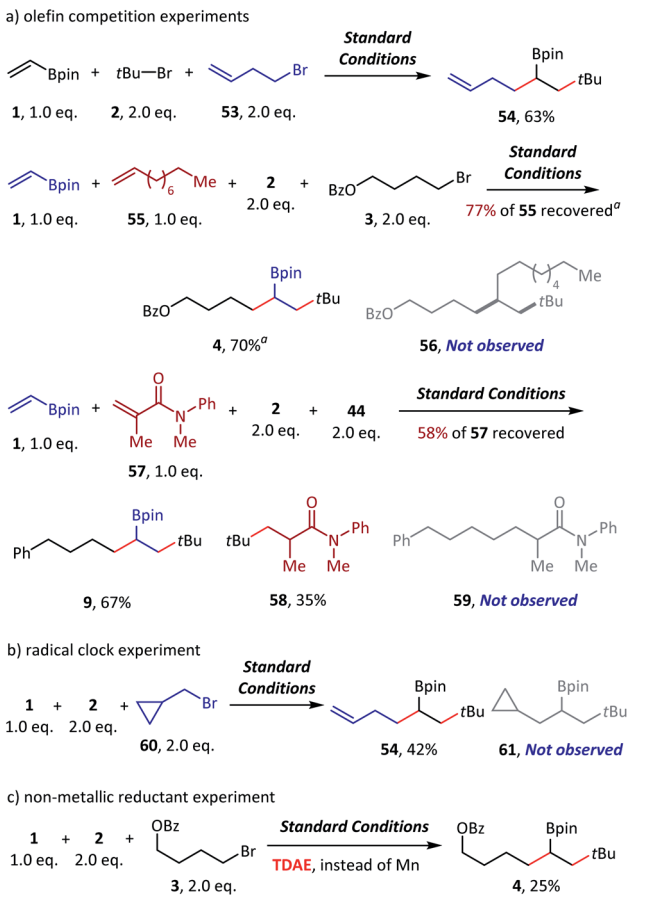
Scheme 5 Synthetic applications. Standard conditions: as shown in Table 1, entry 1. Isolated yield. See the ESI† for more details. NBS = *N*-bromosuccinimide. NIS = *N*-iodosuccinimide.

conveniently with the simultaneous formation of one aryl–alkyl bond and one alkyl–alkyl bond. With respect to aryl coupling partners, both electron-donating (**36**) and electron-withdrawing (**37–39**) substituents were well tolerated in the *meta*- and *para*-positions and afforded the corresponding products in moderate (39–50%) isolated yields. In addition, this transformation is orthogonal to classical Suzuki cross-coupling procedures, as the C(sp^2)–B bond remained intact in substrate **40**. Finally, different tertiary alkyl bromides were also explored (**41–43**), in which the desired alkylarylation products were delivered smoothly.

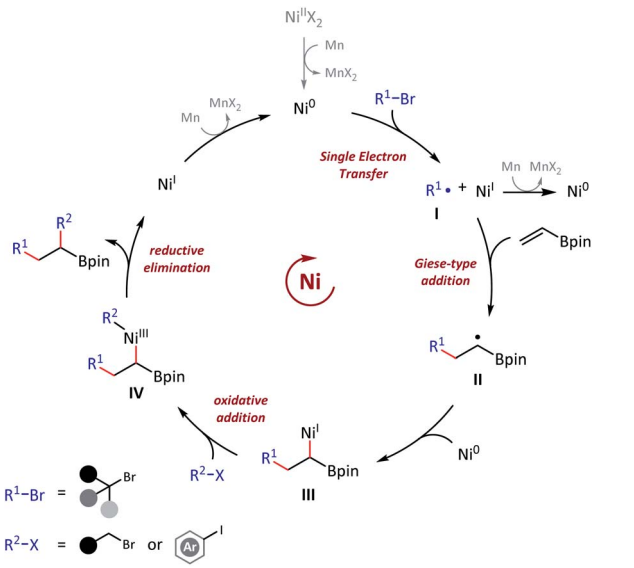
In a scale-up reaction, we successfully obtained reductive dialkylation product **9** with a satisfactory 84% isolated yield (Scheme 5a), which highlights the practicality of this new alkylborate synthetic method. Combined with alkylborate transformations, our method provided a modular strategy for the synthesis of complex compounds (Scheme 5b). For example, structurally complicated alcohols (**45–46**),[11a] diaryl alkanes (**47–48**),[20] and alkyl iodide (**49**)[21] were created *via* such an assembly-line synthetic route. Finally, we used this method for the late-stage functionalization of complex natural products and drug molecules (Scheme 5c). The efficient conversion of glucose (**50**), indomethacin (**51**), and oleanic acid (**52**) derivatives to the desired products demonstrated a high degree of tolerance to diverse functional groups.

To examine the reaction mechanism, we carried out competition experiments (Scheme 6a). 4-Bromobut-1-ene (**53**) was subjected to standard conditions, and desired product **54** was obtained in 63% isolated yield, with the terminal alkene group retained. In the competition reaction between vinyl boronate (**1**) and dec-1-ene (**55**), the vinyl boronate dialkylation product (**4**) was formed in 70% GC yield. However, the dialkylation product (**56**) of dec-1-ene was not observed, with 77% recovery of the starting material dec-1-ne (**55**). The competition reaction between vinyl boronate (**1**) and acrylamide (**57**) was also conducted, and both the vinyl boronate dialkylation product (**9**) and the acrylamide alkylation product (**58**) were observed. Thus, electron-deficient olefins were more reactive in this reaction, and no reaction occurred for the electron-rich olefins. In addition, tertiary alkyl bromides exhibited higher radical addition reactivity than the primary alkyl bromides (see ESI† for more details). The radical clock experiment was tested using (bromomethyl)cyclopropane (**60**), and we obtained only ring opening product **54** in 42% yield, which revealed the radical activation of primary alkyl bromides (Scheme 6b). Finally, the nonmetallic reductant TDAE was used instead of Mn(0) and resulted in a decent 25% GC yield. We deduced that the activation of alkyl bromides was a single-electron-transfer (SET) process, but not the *in situ* formation of alkylmanganese reagents (Scheme 6c).

Based on the aforementioned experimental observations and previous literatures,[4a,11a,22] an envisioned mechanism for this olefin reductive dicarbofunctionalization was proposed (Scheme 7). We had sufficient evidences to prove that this reaction was initiated with the formation of a nucleophilic *tert*-alkyl radical (**I**), and added to the vinyl boronate (**1**). Then the resulting *sec*-alkyl radical (**II**), which was stabilized by



Scheme 6 Mechanistic probes. Standard conditions: as shown in Table 1, entry 1, 0.2 mmol scale. Isolated yield. [a] GC yield. 4,4′-Dimethoxybenzophenone was used as an internal standard. See the ESI† for more details. TDAE = tetrakis(dimethylamino)ethylene.



Scheme 7 Envisioned mechanism. R^1 = *tert*-alkyl. R^2 = *prim*-alkyl or aryl. X = halogen.

contiguous boron atom, might be trapped by a nickel catalyst, and then to finish the cross-coupling. The mechanistic basis of our reaction design, namely the formation of a boron atom stabilized radical, was in consistent with Martin's work.[15] It should also be pointed out that the actual mechanism might be more complicated due to a number of changeable valence states of nickel catalysts under reductive conditions.

Conclusions

We reported a convenient method to access alkylborates through nickel-catalyzed olefin reductive dialkylation and alkylarylation of vinyl boronates. A variety of alkyl bromides and aryl iodides were converted to the corresponding products with both good coupling efficiency and excellent functional group compatibility. This reaction is practical and useful in the late-stage modification of natural products and the modular synthesis of complex compounds. Our next challenge is the improvement of stereochemical control.[23]

Conflicts of interest

There is no conflict of interest to report.

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Notes and references

1 For selected reviews on olefin dicarbofunctionalization, see: (*a*) R. K. Dhungana, S. KC, P. Basnet and R. Giri, *Chem. Rec.*, 2018, **18**, 1314; (*b*) J.-S. Zhang, L. Liu, T. Chen and L.-B. Han, *Chem.–Asian J.*, 2018, **13**, 2277; (*c*) Y. Ping, Y. Li, J. Zhu and W. Kong, *Angew. Chem., Int. Ed.*, 2019, **58**, 1562; (*d*) R. Giri and S. KC, *J. Org. Chem.*, 2018, **83**, 3013.

2 For selected examples on olefin dicarbofunctionalization, see: (*a*) K. B. Urkalan and M. S. Sigman, *Angew. Chem., Int. Ed.*, 2009, **48**, 3146; (*b*) A. Trejos, A. Fardost, S. Yahiaoui and M. Larhed, *Chem. Commun.*, 2009, 7587; (*c*) M. S. McCammant, L. Liao and M. S. Sigman, *J. Am. Chem. Soc.*, 2013, **135**, 4167; (*d*) Z. Liu, T. Zeng, K. S. Yang and K. M. Engle, *J. Am. Chem. Soc.*, 2016, **138**, 15122; (*e*) B. Shrestha, P. Basnet, R. K. Dhungana, S. Kc, S. Thapa, J. M. Sears and R. Giri, *J. Am. Chem. Soc.*, 2017, **139**, 10653; (*f*) W. Li, J. K. Boon and Y. Zhao, *Chem. Sci.*, 2018, **9**, 600; (*g*) J. Derosa, V. T. Tran, M. N. Boulous, J. S. Chen and K. M. Engle, *J. Am. Chem. Soc.*, 2017, **139**, 10657; (*h*) P. Basnet, R. K. Dhungana, S. Thapa, B. Shrestha, S. Kc, J. M. Sears and R. Giri, *J. Am. Chem. Soc.*, 2018, **140**, 7782; (*i*) H. Cong and G. C. Fu, *J. Am. Chem. Soc.*, 2014, **136**, 3788; (*j*) W. You and M. K. Brown, *J. Am. Chem. Soc.*, 2015, **137**, 14578; (*k*) J. A. Walker, K. L. Vickerman, J. N. Humke and L. M. Stanley, *J. Am. Chem. Soc.*, 2017, **139**, 10228; (*l*) T. Qin, J. Cornella, C. Li, L. R. Malins, J. T. Edwards, S. Kawamura, B. D. Maxwell, M. D. Eastgate and P. S. Baran, *Science*, 2016, **352**, 801; (*m*) J.-W. Gu, Q.-Q. Min, L.-C. Yu and X. Zhang, *Angew. Chem., Int. Ed.*, 2016, **55**, 12270; (*n*) L. Wu, F. Wang, X. Wan, D. Wang, P. Chen and G. Liu, *J. Am. Chem. Soc.*, 2017, **139**, 2904; (*o*) M. P. Watson and E. N. Jacobsen, *J. Am. Chem. Soc.*, 2008, **130**, 12594; (*p*) W. You and M. K. Brown, *J. Am. Chem. Soc.*, 2014, **136**, 14730; (*q*) 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; (*r*) D. Huang, D. Olivieri, Y. Sun, P. Zhang and T. R. Newhouse, *J. Am. Chem. Soc.*, 2019, **141**, 16249; (*s*) 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; (*t*) M. Koy, P. Bellotti, F. Katzenburg, C. G. Daniliuc and F. Glorius, *Angew. Chem., Int. Ed.*, 2020, **59**, 2375.

3 For selected examples on olefin reductive dicarbofunctionalization, see: (*a*) D. Anthony, Q. Lin, J. Baudet and T. Diao, *Angew. Chem., Int. Ed.*, 2019, **58**, 3198; (*b*) J. Li, Y. Luo, H. W. Cheo, Y. Lan and J. Wu, *Chem*, 2019, **5**, 192; (*c*) K. Wang, Z. Ding, Z. Zhou and W. Kong, *J. Am. Chem. Soc.*, 2018, **140**, 12364; (*d*) C.-S. Yan, Y. Peng, X.-B. Xu and Y.-W. Wang, *Chem.–Eur. J.*, 2012, **18**, 6039; (*e*) 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.

4 (*a*) W. Shu, A. García-Domínguez, M. T. Quirós, R. Mondal, D. J. Cárdenas and C. Nevado, *J. Am. Chem. Soc.*, 2019, **141**, 13812; (*b*) A. García-Domínguez, Z. Li and C. Nevado, *J. Am. Chem. Soc.*, 2017, **139**, 6835.

5 X. Zhao, H.-Y. Tu, L. Guo, S. Zhu, F.-L. Qing and L. Chu, *Nat. Commun.*, 2018, **9**, 3488.

6 J. Choi and G. C. Fu, *Science*, 2017, **356**, eaaf7230.

7 For selected examples of olefin dialkylation using organometallics, see: (*a*) M. Kischkewitz, K. Okamoto, C. Mück-Lichtenfeld and A. Studer, *Science*, 2017, **355**, 936; (*b*) M. Chierchia, P. Xu, G. J. Lovinger and J. P. Morken, *Angew. Chem., Int. Ed.*, 2019, **58**, 14245; (*c*) J. Terao, K. Saito, S. Nii, N. Kambe and N. Sonoda, *J. Am. Chem. Soc.*, 1998, **120**, 11822; (*d*) K. Wakabayashi, H. Yorimitsu and K. Oshima, *J. Am. Chem. Soc.*, 2001, **123**, 5374; (*e*) J. Derosa, V. A. van der Puyl, V. T. Tran, M. Liu and K. M. Engle, *Chem. Sci.*, 2018, **9**, 5278; (*f*) C. Xu, Z.-F. Yang, L. An and X. Zhang, *ACS Catal.*, 2019, **9**, 8224.

8 For a recent example of two-component olefin reductive dialkylation, see: Q. Lin and T. Diao, *J. Am. Chem. Soc.*, 2019, **141**, 17937.

9 (*a*) A. Noble, R. S. Mega, D. Pflästerer, E. L. Myers and V. K. Aggarwal, *Angew. Chem., Int. Ed.*, 2018, **57**, 2155; (*b*) B. Zhao, Z. Li, Y. Wu, Y. Wang, J. Qian, Y. Yuan and Z. Shi, *Angew. Chem., Int. Ed.*, 2019, **58**, 9448.

10 (*a*) L. Zhang, G. J. Lovinger, E. K. Edelstein, A. A. Szymaniak, M. P. Chierchia and J. P. Morken, *Science*, 2016, **351**, 70; (*b*)

M. Silvi, C. Sandford and V. K. Aggarwal, *J. Am. Chem. Soc.*, 2017, **139**, 5736.

11 (*a*) M. W. Campbell, J. S. Compton, C. B. Kelly and G. A. Molander, *J. Am. Chem. Soc.*, 2019, **141**, 20069; (*b*) R. S. Mega, V. K. Duong, A. Noble and V. K. Aggarwal, *Angew. Chem., Int. Ed.*, 2020, **59**, 4375.

12 (*a*) Y. Zhang, B. Han and S. Zhu, *Angew. Chem., Int. Ed.*, 2019, **58**, 13860; (*b*) S. Bera and X. Hu, *Angew. Chem., Int. Ed.*, 2019, **58**, 13854.

13 (*a*) X. Lu, B. Xiao, Z.-Q. Zhang, T.-J. Gong, W. Su, Y. Fu and L. Liu, *Nat. Commun.*, 2016, **7**, 11129; (*b*) X. Lu, Y. Wang, B. Zhang, J.-J. Pi, X.-X. Wang, T.-J. Gong, B. Xiao and Y. Fu, *J. Am. Chem. Soc.*, 2017, **139**, 12632; (*c*) X. Lu, X.-X. Wang, T.-J. Gong, J.-J. Pi, S.-J. He and Y. Fu, *Chem. Sci.*, 2019, **10**, 809; (*d*) S.-J. He, J.-W. Wang, Y. Li, Z.-Y. Xu, X.-X. Wang, X. Lu and Y. Fu, *J. Am. Chem. Soc.*, 2020, **142**, 214.

14 (*a*) W. Su, T.-J. Gong, X. Lu, M.-Y. Xu, C.-G. Yu, Z.-Y. Xu, H.-Z. Yu, B. Xiao and Y. Fu, *Angew. Chem., Int. Ed.*, 2015, **54**, 12957; (*b*) L. Li, T.-J. Gong, X. Lu, B. Xiao and Y. Fu, *Nat. Commun.*, 2017, **8**, 345; (*c*) X. Lu, Z.-Q. Zhang, L. Yu, B. Zhang, B. Wang, T.-J. Gong, C.-L. Tian, B. Xiao and Y. Fu, *Chin. J. Chem.*, 2019, **37**, 11.

15 S.-Z. Sun, Y. Duan, R. S. Mega, R. J. Somerville and R. Martin, *Angew. Chem., Int. Ed.*, 2020, **59**, 4370.

16 (*a*) B. S. L. Collins, C. M. Wilson, E. L. Myers and V. K. Aggarwal, *Angew. Chem., Int. Ed.*, 2017, **56**, 11700; (*b*) J. Schmidt, J. Choi, A. T. Liu, M. Slusarczyk and G. C. Fu, *Science*, 2016, **354**, 1265; (*c*) C. Sandford and V. K. Aggarwal, *Chem. Commun.*, 2017, **53**, 5481.

17 (*a*) L. K. G. Ackerman, M. M. Lovell and D. J. Weix, *Nature*, 2015, **524**, 454; (*b*) D. A. Everson, B. A. Jones and D. J. Weix, *J. Am. Chem. Soc.*, 2012, **134**, 6146.

18 H. Xu, C. Zhao, Q. Qian, W. Deng and H. Gong, *Chem. Sci.*, 2013, **4**, 4022.

19 (*a*) J. Gu, X. Wang, W. Xue and H. Gong, *Org. Chem. Front.*, 2015, **2**, 1411; (*b*) C. E. I. Knappke, S. Grupe, D. Gärtner, M. Corpet, C. Gosmini and A. Jacobi von Wangelin, *Chem.–Eur. J.*, 2014, **20**, 6828.

20 (*a*) A. Bonet, M. Odachowski, D. Leonori, S. Essafi and V. K. Aggarwal, *Nat. Chem.*, 2014, **6**, 584; (*b*) D. Imao, B. W. Glasspoole, V. S. Laberge and C. M. Crudden, *J. Am. Chem. Soc.*, 2009, **131**, 5024.

21 Y. Xi and J. F. Hartwig, *J. Am. Chem. Soc.*, 2016, **138**, 6703.

22 Y. Jin and C. Wang, *Chem. Sci.*, 2019, **10**, 1780.

23 A moderate 40% enantiomeric excess was obtained using a pyridine-oxazoline ligand (see the ESI† for more details).

