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Palladium catalyzed regioselective B–C(sp) coupling *via* direct cage B–H activation: synthesis of B(4)-alkynylated *o*-carboranes†

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Pd-catalyzed carboxylic acid guided regioselective alkynylation of cage B(4)–H bonds in *o*-carboranes has been achieved for the first time using two different catalytic systems. In the presence of 5 mol% Pd(OAc)₂ and 3 equiv. of AgOAc, the reaction of 1-COOH-2-R¹-C₂B₁₀H₁₀ with R₃SiC≡CBr in ClCH₂CH₂Cl gives 4-(R₃SiC≡C)-2-R¹-*o*-C₂B₁₀H₁₀ in moderate to high yields. This reaction is compatible with alkynes possessing sterically bulky silyl groups such as ⁱPr₃Si or ^tBuMe₂Si. Meanwhile, another catalytic system of Pd(OAc)₂/AgOAc/K₂HPO₄ can catalyze the direct B(4)-alkynylation of 1-COOH-2-R¹-C₂B₁₀H₁₀ with terminal alkynes R²C≡CH in moderate to high yields. The latter has a broader substrate scope from bulky silyl to aromatic to carboranyl substituents. Desilylation of the resultant products affords carboranyl acetylene 4-(HC≡C)-2-R¹-*o*-C₂B₁₀H₁₀ which can undergo further transformations such as Sonogashira coupling, dimerization and click reactions. It is suggested that the above two catalytic systems may proceed *via* Pd(II)–Pd(IV)–Pd(II) and Pd(II)–Pd(0)–Pd(II) catalytic cycles, respectively. In addition, the silver salt is found to promote the decarboxylation reaction and thereby controls the mono-selectivity.

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Introduction

The development of efficient synthetic methodologies to incorporate alkyne motifs has received broad interest, as they are not only important building blocks in natural products, pharmaceuticals and materials¹ but also essential functional groups in cross-coupling, metathesis and cycloaddition reactions.² Meanwhile, carboranyl acetylenes have proved to be useful basic units in molecular rods,³ nonlinear optical materials,⁴ supramolecular design,⁵ nanovehicles⁶ and metal-organic frameworks.⁷ As there is a lack of direct and efficient methodologies for the synthesis of B-alkynylated carboranes, the alkyne moieties in the aforementioned materials are generally connected to cage carbon atoms,^{3–8} which limits the application scope of the carborane derivatives.

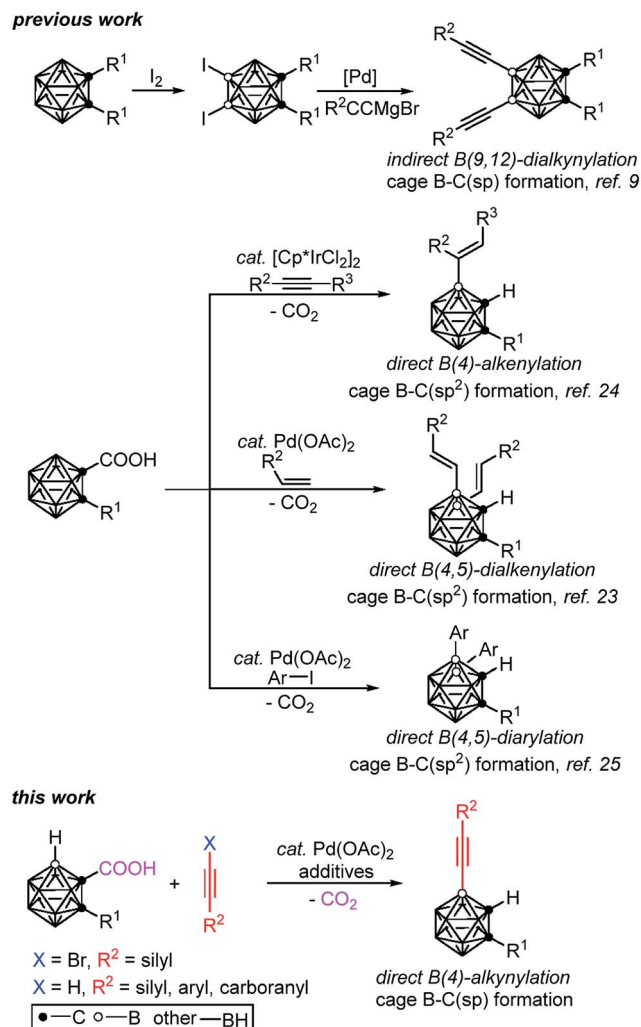
Though cage boron alkynylated carboranes can be prepared by two-step reactions, such as the selective iodination of an *o*-carborane, followed by Pd(0)-catalyzed cross-coupling with alkynyl Grignard reagents,⁹ the installation of iodo groups to specific positions on the carboranes is necessary (Scheme 1). However, the selective iodination of cage B(4,5,7,11)–H is rather challenging, if not impossible.⁸ Thus, we aim to develop new

methodologies for the selective and direct alkynylation of carboranes *via* cage B–H activation.

Directing groups are essential in transition metal catalyzed C–H activation due to their ability to chelate the metal catalyst, position it for selective C–H cleavage, and reduce activation energy by stabilizing the metallacycle intermediates.¹⁰ Nevertheless, strategies using directing groups suffer from limitations when the directing groups are not present in the target molecules. To overcome this problem, the use of traceless directing groups is obviously an ideal method. Recently, the use of –COOH as a weak coordinating yet efficient directing group for transition metal catalyzed phenyl C–H activation has been documented, and has been found to be easily removed by decarboxylation after the reaction.^{10h} Subsequently, carboxylic acid directed phenyl C–H olefination,¹¹ arylation,¹² alkylation,¹³ acylation,¹⁴ carboxylation,¹⁵ amination,¹⁶ hydroxylation¹⁷ and halogenation¹⁸ have been successfully developed. However, to the best of our knowledge, the direct alkynylation of C–H bonds guided by –COOH is still elusive, although nitrogen-based directing-group-guided transition-metal catalyzed phenyl C–H alkynylation has been recently documented using alkynyl halides,¹⁹ hypervalent iodine-alkyne reagents²⁰ and terminal alkynes²¹ as the alkynylating reagents. Meanwhile, oxidative coupling of two C–H bonds for the formation of a C–C bond has received growing interest due to its benefits which include atom-economy, step-economy and less waste.²² Compared with the achievements of phenyl C–H bond oxidative coupling, the regioselective and direct oxidative coupling of an organic C–H bond with a cage B–H bond in *o*-carboranes is very rare.²³

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Scheme 1 Selected examples of transition metal catalyzed formation of cage B–C(sp) and B–C(sp²) bonds in *o*-carboranes.

Very recently, our group has developed a transition metal catalyzed –COOH guided cage B–H alkenylation^{23,24} and arylation²⁵ of *o*-carboranes, in which the carboxyl group is removed in a one-pot fashion. Inspired by these results and other cage B–H activation reactions,^{26–29} we have extended our research to investigate direct cage B–H alkylation by alkynyl halides through a Pd(II)–Pd(IV)–Pd(II) catalytic cycle and by terminal alkynes *via* a Pd(II)–Pd(0)–Pd(II) catalytic cycle. These new findings are reported in this article (Scheme 1).

Results and discussion

Alkynylation using alkynyl halides

The initial reaction of 1-COOH-2-CH₃-*o*-C₂B₁₀H₁₀ (**1a**) with ⁱPr₃SiC≡CBr in the presence of 10 mol% Pd(OAc)₂ and 1 equiv. of AgOAc in toluene at 90 °C for 6 h did not give any of the desired product (entry 1, Table 1). Replacement of toluene with 1,2-dichloroethane (DCE) afforded the desired coupling product 4-(ⁱPr₃SiC≡C)-2-CH₃-*o*-C₂B₁₀H₁₀ in 40% GC yield (entry 2, Table 1). Increasing the amount of AgOAc to 3 equiv. resulted in 90%

GC yield of **3a** (entry 4, Table 1). Higher or lower reaction temperatures led to decreased yields of **3a** (entries 5 and 6, Table 1). Lowering the catalyst loading to 5 mol% did not change the reaction efficiency (entry 7, Table 1). In view of the yields of **3a**, entry 7 in Table 1 was chosen as the optimal reaction conditions.

A variety of carborane monocarboxylic acids (**1**) were examined under the chosen optimal reaction conditions, and the results are compiled in Table 2. All alkyl, alkenyl and aryl substituents on cage C(2), regardless of electronic properties, afforded the coupling products **3** in high isolated yields (entries 1–10 and 13, Table 2). For the heteroatom containing substrate **1j**, the product **3j** was isolated in 78% yield (entry 10, Table 2), whereas that bearing a thiophenyl group (**1l**) afforded the product **3l** in 54% yield (entry 12, Table 2) probably due to the interaction of Pd with the S atom. Meanwhile, substrate **1k** with a naphthyl substituent on cage C(2) gave **3k** in only 40% isolated yield (entry 11, Table 2). For R¹ = H, an inseparable mixture was produced (entry 14, Table 2). When R¹ = Me₃Si, the desilylation species **3n** was isolated in 41% yield after work up (entry 15, Table 2).

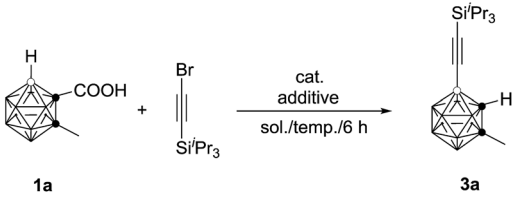
In contrast to R¹ at cage C(2), the scope of R² is highly limited in such a coupling reaction. ^tBuMe₂SiC≡CBr worked well to give **3p** in 70% isolated yield (entry 16, Table 2). However, less hindered Me₃SiC≡CBr was not reactive, probably due to its propensity to coordinate with a Pd center *via* the π bond (entry 17, Table 2). Such a phenomenon was also observed in phenyl C–H alkynylations using R₃SiC≡CBr as reagents.³⁰ It was noted that other alkynyl bromides such as PhC≡CBr and ^tBuC≡CBr were not compatible with this reaction.

Alkynylation using terminal alkynes

As the previous method has a limited substrate scope, we wanted to develop a more atom- and step-economic method for cage B–H alkylation using terminal alkynes as reagents. We commenced our studies by screening for a suitable base for the oxidative coupling of cage B–H in 1-COOH-2-CH₃-*o*-C₂B₁₀H₁₀ (**1a**) with ⁱPr₃SiC≡CH under the aforementioned optimal reaction conditions. No reaction was observed in the absence of a base (entry 1, Table 3). The addition of 2 equiv. of K₂HPO₄ afforded the target product **3a** in 30% GC yield with ⁱPr₃SiC≡C–C≡CⁱPr₃Si as the side product (entry 2, Table 3). To inhibit the formation of a homocoupling side product, ⁱPr₃SiC≡CH was added slowly *via* a syringe pump, leading to a significantly increased yield of **3a** to 56% GC yield (entry 3, Table 3). The yield was further improved to 75% if 2 equiv. of the terminal alkyne was used (entry 4, Table 3). Replacement of 1,2-dichloroethane (DCE) with toluene resulted in a slightly higher yield of **3a** (entry 5, Table 3). Decreasing the reaction temperature to 80 °C afforded **3a** in 86% GC yield (entry 6, Table 3). In view of the yields of **3a**, entry 6 in Table 3 was chosen as the optimal reaction conditions.

This reaction has a much broader substrate scope (R² = silyl, phenyl and carboranyl). The results are compiled in Table 4. For R¹ = alkyl groups, the isolated yields of **3** are comparable to those observed in Table 2. However, if R¹ = aryl unit such as **1g**,

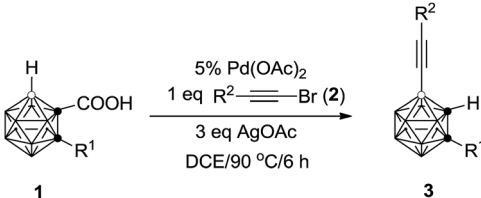


Table 1 Optimization of reaction conditions using alkynyl bromide^a


Entry	Cat (mol%)	Additive (equiv.)	Solvent	Temp (°C)	Yield ^b (%)
1	Pd(OAc) ₂ (10)	AgOAc (1)	Toluene	90	N.R.
2	Pd(OAc) ₂ (10)	AgOAc (1)	DCE	90	40
3	Pd(OAc) ₂ (10)	AgOAc (2)	DCE	90	67
4	Pd(OAc) ₂ (10)	AgOAc (3)	DCE	90	90
5	Pd(OAc) ₂ (10)	AgOAc (3)	DCE	80	70
6	Pd(OAc) ₂ (10)	AgOAc (3)	DCE	100	75
7	Pd(OAc) ₂ (5)	AgOAc (3)	DCE	90	89
8	Pd(OAc) ₂ (2.5)	AgOAc (3)	DCE	90	78
9	Pd(TFA) ₂ (5)	AgOAc (3)	DCE	90	82
10	Pd(OAc) ₂ (5)	Ag ₂ CO ₃ (2)	DCE	90	75
11	Pd(OAc) ₂ (5)	Ag ₂ O (2)	DCE	90	63
12	Pd(OAc) ₂ (5)	AgNO ₃ (3)	DCE	90	30

^a Reactions were conducted on a 0.05 mmol scale in 0.5 mL of solvent in a closed flask for 6 h; DCE = 1,2-dichloroethane; TFA = trifluoroacetate.

^b GC yields.

Table 2 Synthesis of cage B(4)-alkynylated *o*-carboranes using alkynyl bromide^a


Entry	R ¹	R ² (2)	Isolated yield (%)
1	Me (1a)	ⁱ Pr ₃ Si	81 (3a)
2	Et (1b)	ⁱ Pr ₃ Si	76 (3b)
3	ⁱ Pr (1c)	ⁱ Pr ₃ Si	75 (3c)
4	Bn (1d)	ⁱ Pr ₃ Si	73 (3d)
5	Ph (1e)	ⁱ Pr ₃ Si	77 (3e)
6	4-MeC ₆ H ₄ (1f)	ⁱ Pr ₃ Si	82 (3f)
7	3,5-(CH ₃) ₂ C ₆ H ₃ (1g)	ⁱ Pr ₃ Si	70 (3g)
8	4-CF ₃ C ₆ H ₄ (1h)	ⁱ Pr ₃ Si	81 (3h)
9	4-ClC ₆ H ₄ (1i)	ⁱ Pr ₃ Si	72 (3i)
10	4-MeOC ₆ H ₄ (1j)	ⁱ Pr ₃ Si	78 (3j)
11	1-Naphenyl (1k)	ⁱ Pr ₃ Si	40 (3k)
12	2-Thiophenyl (1l)	ⁱ Pr ₃ Si	54 (3l)
13	EtCH=C(Et) (1m)	ⁱ Pr ₃ Si	80 (3m)
14	H (1n)	ⁱ Pr ₃ Si	Messy
15	Me ₃ Si (1o)	ⁱ Pr ₃ Si	41 ^b (3n)
16	Me (1a)	^t BuMe ₂ Si	70 (3p)
17	Me (1a)	Me ₃ Si	N.R. ^c

^a Reactions were conducted on a 0.2 mmol scale of **1** in a closed flask.

^b Me₃Si was removed after work up. ^c N.R. = no reaction.

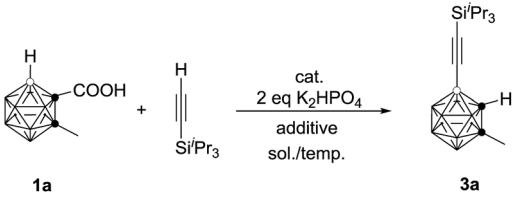
the isolated yield of **3g** is 30% (entry 4, Table 4), which is significantly lower than that of 70% shown in entry 7, Table 2. On the other hand, compounds **1n** (R¹ = H) and **1o** (R¹ = Me₃Si) give **3n** in 35% and 74% yields, respectively (entries 5 and 6, Table 4). These yields are much higher than those found in the previous reaction (entries 14 and 15, Table 2). The reasons for this phenomenon are not clear at this stage.

More importantly, this catalytic system is compatible with phenyl acetylene, producing the corresponding product **3r** in 52% isolated yield (entry 8, Table 4). The coupling efficiency was largely enhanced from R² = Ph, 2-MeC₆H₄, 2,6-(Me)₂C₆H₃, 2-ⁱPrC₆H₄ to 1-ⁿC₆H₁₃-*o*-C₂B₁₀H₁₀, affording the corresponding products, **3s**, **3t**, **3u** and **3v**, in 65%, 73%, 80% and 82% isolated yields, respectively (entries 9–12, Table 4). It should be noted that *o*-carboranyl is a strong electron-withdrawing unit.^{4c} In view of the isolated yields of **3w** and **3x** (entries 13 and 14, Table 4), the electronic effects on the reactions are not obvious as –CH₃ and –CF₃ have significantly different electronic properties. The above data (entries 8–14, Table 4) indicate strongly that bulkier substituents favor the formation of coupling products.

Transformation of **3a**

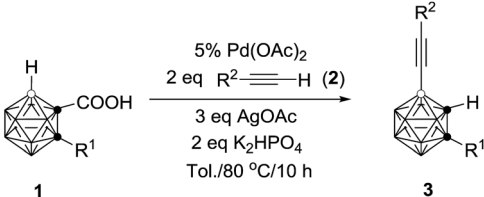
To demonstrate the applications of the resultant compounds **3** as building blocks, further transformation of **3a** was carried out. The ⁱPr₃Si group in **3a** was readily removed by treatment with TBAF (TBAF = tetra-*n*-butylammonium fluoride) to afford quantitatively the terminal alkyne **4a** (Scheme 2). Like other terminal alkynes, compound **4a** can undergo various transformations to give different kinds of carborane-incorporated functional molecules. Sonogashira coupling of **4a** with iodo-benzene or 2-bromothiophene generated **3r** or **5a** in 92% and




Table 3 Optimization of reaction conditions using terminal alkynes^a


Entry	Cat (mol%)	Additive (equiv.)	Solvent	Temp (°C)	Yield ^b (%)
1 ^c	Pd(OAc) ₂ (5)	AgOAc (3)	DCE	90	N.R.
2	Pd(OAc) ₂ (5)	AgOAc (3)	DCE	90	30
3	Pd(OAc) ₂ (5)	AgOAc (3)	DCE	90	56 ^d
4	Pd(OAc) ₂ (5)	AgOAc (3)	DCE	90	75 ^{d,e}
5	Pd(OAc) ₂ (5)	AgOAc (3)	Toluene	90	78 ^{d,e}
6	Pd(OAc) ₂ (5)	AgOAc (3)	Toluene	80	86 ^{d,e}
7	Pd(OAc) ₂ (5)	AgOAc (3)	Toluene	70	Trace
8	Pd(OAc) ₂ (3)	AgOAc (3)	DCE	90	18
9	Pd(TFA) ₂ (5)	AgOAc (3)	DCE	90	26
10	Pd ₂ (dba) ₃ (5)	AgOAc (3)	DCE	90	21
11	Pd(OAc) ₂ (5)	Ag ₂ CO ₃ (2)	DCE	90	15
12	Pd(OAc) ₂ (5)	Ag ₂ O (2)	DCE	90	12
13	Pd(OAc) ₂ (5)	AgNO ₃ (3)	DCE	90	Trace

^a Reactions were conducted on a 0.05 mmol scale of **1a** in 0.5 mL of solvent in the presence of 2 equiv. of K₂HPO₄ in a closed flask for 10 h; DCE = 1,2-dichloroethane; TFA = trifluoroacetate; dba = dibenzylideneacetone. ^b GC yields. ^c Without K₂HPO₄. ^d Terminal alkyne was added dropwise by a syringe pump over a period of 10 h. ^e Two equiv. of terminal alkyne was added.

Table 4 Synthesis of cage B(4)-alkynylated *o*-carboranes using terminal alkynes^a


Entry	R ¹	R ² (2)	Isolated yield (%)
1	Me (1a)	ⁱ Pr ₃ Si	79 (3a)
2	ⁱ Pr (1c)	ⁱ Pr ₃ Si	86 (3c)
3	Bn (1d)	ⁱ Pr ₃ Si	70 (3d)
4	3,5-(CH ₃) ₂ C ₆ H ₃ (1g)	ⁱ Pr ₃ Si	30 (3g)
5	H (1n)	ⁱ Pr ₃ Si	35 (3n)
6	Me ₃ Si (1o)	ⁱ Pr ₃ Si	74 ^b (3n)
7	Me (1a)	^t BuMe ₂ Si	72 (3p)
8	Me (1a)	Ph	52 ^c (3r)
9	Me (1a)	2-CH ₃ C ₆ H ₄	65 ^c (3s)
10	Me (1a)	2,6-(CH ₃) ₂ C ₆ H ₃	73 ^c (3t)
11	Me (1a)	2- ⁱ PrC ₆ H ₄	80 ^c (3u)
12	Me (1a)	 ⁿ C ₆ H ₁₃	82 ^c (3v)
13	Me (1a)	4-CH ₃ C ₆ H ₄	48 ^c (3w)
14	Me (1a)	4-CF ₃ C ₆ H ₄	44 ^c (3x)

^a Reactions were conducted on a 0.2 mmol scale of **1** in a closed flask.
^b Me₃Si was removed after work up. ^c 3 equiv. of terminal alkyne was used.

90% isolated yields, respectively. Glaser–Hay homocoupling of **4a** gave 1,4-dicarboranyldiacetylene (**6a**) in 84% isolated yield. A click reaction of **4a** with phenyl azide afforded carborane-functionalized 1,2,3-triazole (**7a**) in 95% isolated yield.

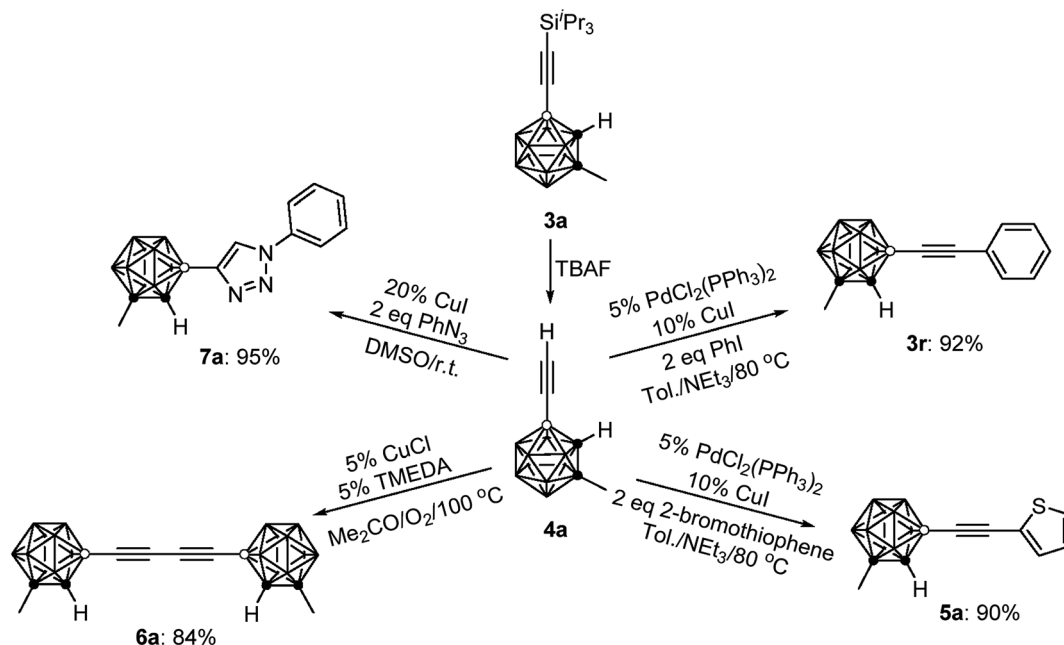
All new compounds **3** and **4a–7a** were fully characterized by ¹H, ¹³C, and ¹¹B NMR spectroscopy as well as high-resolution mass spectrometry (HRMS).³¹ Molecular structures of **4a** and **6a** were further confirmed by single-crystal X-ray analyses and are shown in Fig. 1. Experimental details are included in the ESI.†

Reaction mechanism

To gain some insight into the reaction mechanism, the following control experiments were carried out. No reaction was observed if **1a** was treated with 1 equiv. of ⁱPr₃SiC≡CBr in the presence of 20 mol% Pd(dba)₂ (dba = dibenzylideneacetone) in DCE at 90 °C for 6 h in the absence of AgOAc. On the other hand, under the same reaction conditions, replacement of Pd(dba)₂ with Pd(OAc)₂ gave the alkylation product **3a** in 30% GC yield (Scheme 3a). Similarly, in the presence of 20 mol% Pd(OAc)₂, the reaction of **1a** with 2 equiv. of ⁱPr₃SiC≡CH afforded **3a** in 16% GC yield without AgOAc as the oxidant. While, no **3a** was observed when 20 mol% Pd(dba)₂ was used instead of Pd(OAc)₂ (Scheme 3b). These results suggest that both cross-coupling reactions are initiated by Pd(II) not Pd(0).

Decarboxylation of carboranyl carboxylic acids (**1b** and **3b**–COOH) was also examined (Scheme 3c). Compound **1b** was stable after heating at 90 °C for 12 h in DCE, whereas **3b**–COOH underwent complete decarboxylation within one hour under the same reaction conditions. Notably, it only took ten minutes to

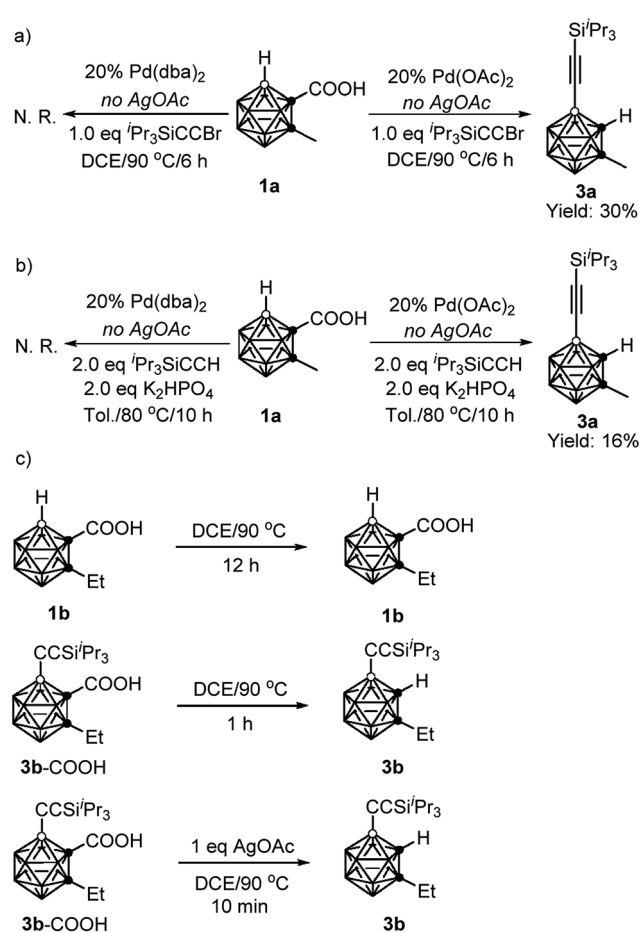




Scheme 2 Transformations of 3a.

convert **3b**-COOH to **3b** in the presence of 1 equiv. of AgOAc. These results clearly indicate that the introduction of an alkynyl group at the cage B(4) site can induce the decarboxylation, and the addition of a silver salt can accelerate such decarboxylation, which is crucial for controlling the mono-selectivity.

On the basis of the aforementioned experimental data, two plausible reaction mechanisms are proposed in Scheme 4. For the Pd(II)-Pd(IV)-Pd(II) catalytic cycle: an exchange reaction of **1** with Pd(OAc)₂, followed by regioselective electrophilic attack at



Scheme 3 Control experiments.

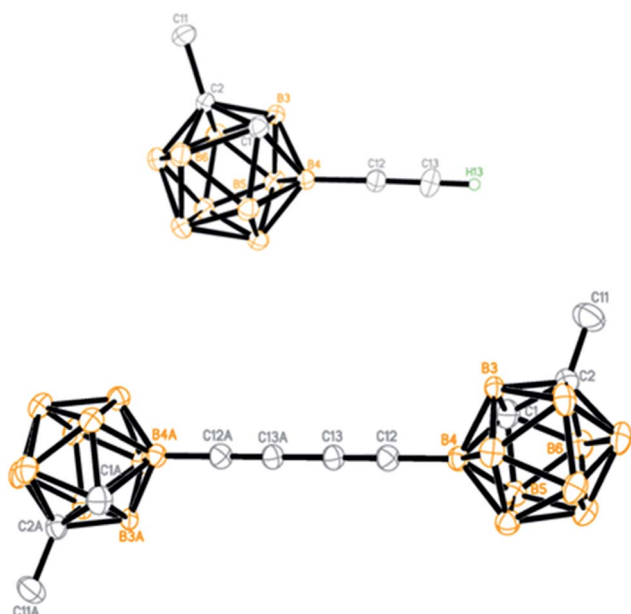
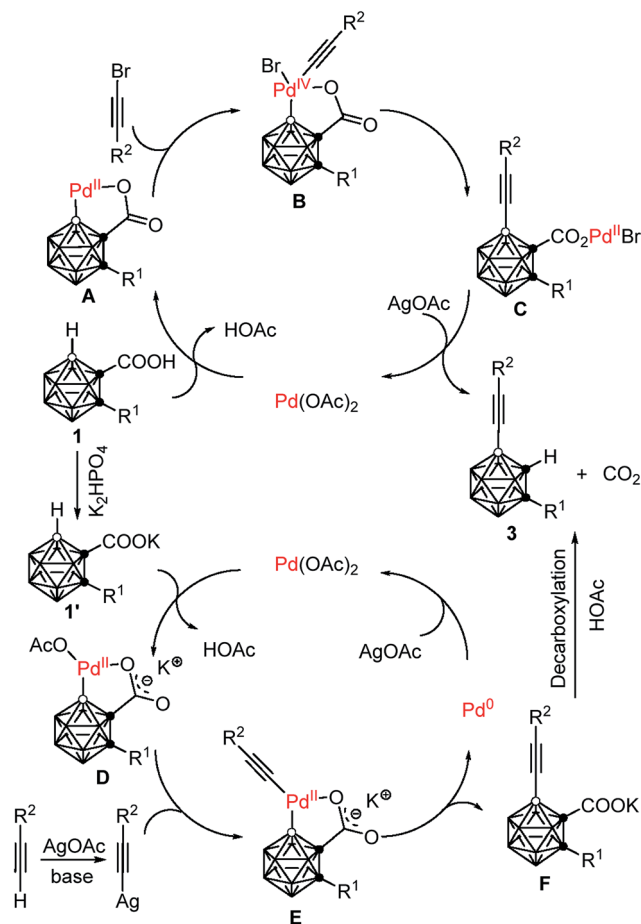


Fig. 1 Molecular structures of **4a** (top) and **6a** (bottom) (only the terminal alkyne H atom is shown for clarity).



Scheme 4 Proposed reaction mechanism.

the more electron-rich cage B(4) site yields the intermediate **A** as the charge distribution on the cage follows the trend B(9,12) > B(8,10) > B(4,5,7,11) > B(3,6).³² Oxidative addition of $R^2C\equiv CBr$ affords a Pd(IV) intermediate **B**.^{25,33} Reductive elimination produces the intermediate **C**, which undergoes a salt metathesis reaction, protonation and decarboxylation to give the final product **3** and regenerates the catalyst Pd(OAc)₂. Meanwhile, another catalytic system involves a Pd(II)–Pd(0)–Pd(II) cycle. An acid–base reaction between K₂HPO₄ and carboranyl carboxylic acid **1** gives the potassium salt **1'**.³⁴ Coordination of the oxygen atom of **1'** to the Pd(II) center, followed by subsequent regioselective electrophilic attack at the more electron-rich cage B(4) site generates the intermediate **D**. Ligand exchange by acetylide gives a carboranyl-palladium acetylide intermediate **E**.^{21b,35} Reductive elimination affords the cage B(4)-alkynylated intermediate **F** and Pd(0). Decarboxylation of **F** results in the formation of the final product **3**, meanwhile Pd(0) is oxidized by AgOAc to regenerate Pd(OAc)₂. It is noted that AgOAc acts as a bromide captor in the Pd(II)–Pd(IV)–Pd(II) catalytic cycle, but as an oxidant to regenerate Pd(II) from Pd(0) in the Pd(II)–Pd(0)–Pd(II) catalytic cycle. However, in both cross-coupling reactions, AgOAc plays a crucial role in promoting decarboxylation and thereby controlling the mono-selectivity.

Conclusion

We have developed two catalytic systems for regioselective and efficient alkyne coupling of cage B(4)–H bonds in *o*-carboranes using alkynyl bromides or terminal alkynes as alkynylating agents, where –COOH acts as a traceless directing group. A series of new cage B(4)-alkynylated *o*-carborane derivatives has been prepared for the first time, which could find many applications in the synthesis of carborane-based materials.^{3–7} This opens up a new window for the functionalization of carboranes by direct oxidative coupling of the cage B–H and organic C–H bonds. This work also offers a useful reference for selective C–H alkyne coupling using carboxylic acid as a traceless directing group in other aromatic systems.

On the basis of control experiments and literature work, two catalytic cycles are proposed for the above two reactions: a Pd(II)–Pd(IV)–Pd(II) cycle for using alkynyl bromides as coupling agents and a Pd(II)–Pd(0)–Pd(II) cycle for employing terminal alkynes as coupling partners. The latter has a broader substrate scope than the former. This work also gives some hints for the development of new catalytic systems for the functionalization of carboranes.

Acknowledgements

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Notes and references

- 1 *Acetylene Chemistry: Chemistry, Biology and Material Science*, ed F. Diederich, P. J. Stang and R. R. Tykwinski, Wiley-VCH, Weinheim, Germany, 2005.
- 2 (a) A. Fürstner and P. W. Davies, *Chem. Commun.*, 2005, 2307–2320; (b) H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2001, **40**, 2004–2021; (c) M. G. Finn and V. V. Fokin, *Chem. Soc. Rev.*, 2010, **39**, 1231–1232; (d) J. P. Brand and J. Waser, *Chem. Soc. Rev.*, 2012, **41**, 4165–4179; (e) R. Chinchilla and C. Nájera, *Chem. Rev.*, 2014, **114**, 1783–1826.
- 3 (a) J. Müller, K. Base, T. F. Magnera and J. Michl, *J. Am. Chem. Soc.*, 1992, **114**, 9721–9722; (b) P. F. H. Schwab, M. D. Levin and J. Michl, *Chem. Rev.*, 1999, **99**, 1863–1933.
- 4 (a) M. F. Hawthorne and A. Moderna, *Chem. Rev.*, 1999, **99**, 3421–3434; (b) J. F. Valliant, K. J. Guenther, A. S. King, P. Morel, P. Schaffer, O. O. Sogbein and K. A. Stephenson, *Coord. Chem. Rev.*, 2002, **232**, 173–230; (c) J. Guo, D. Liu, J. Zhang, Q. Maio and Z. Xie, *Chem. Commun.*, 2015, **51**, 12004–12007.
- 5 (a) H. Jude, H. Disteldorf, S. Fischer, T. Wedge, A. M. Hawkrige, A. M. Arif, M. F. Hawthorne, D. C. Muddiman and P. J. Stang, *J. Am. Chem. Soc.*, 2005, **127**, 12131–12139; (b) B. H. Northrop, H.-B. Yang and P. J. Stang, *Chem. Commun.*, 2008, 5896–5908; (c)



- J. M. Ludlow III, M. Tominaga, Y. Chujo, A. Schultz, X. Lu, T. Xie, K. Guo, C. N. Moorefield, C. Wesdemiotis and G. R. Newkome, *Dalton Trans.*, 2014, **43**, 9604–9611.
- 6 (a) C. J. Villagómez, T. Sasaki, J. M. Tour and L. Grill, *J. Am. Chem. Soc.*, 2010, **132**, 16848–16854; (b) S. Khatua, J. M. Guerrero, K. Claytor, G. Vives, A. B. Kolomeisky, J. M. Tour and S. Link, *ACS Nano*, 2009, **3**, 351–356; (c) P.-T. Chiang, J. Mielke, J. Godoy, J. M. Guerrero, I. Alemany, C. J. Villagomez, A. Saywell, L. Grill and J. M. Tour, *ACS Nano*, 2012, **6**, 592–597; (d) M. Koshino, T. Tanaka, N. Solin, K. Suenaga, H. Isobe and E. Nakamura, *Science*, 2007, **316**, 853.
- 7 (a) A. K. Singh, A. Sadrzadeh and B. I. Yakobson, *J. Am. Chem. Soc.*, 2010, **132**, 14126–14129; (b) O. K. Farha, A. M. Spokoyny, K. L. Mulfort, M. F. Hawthorne, C. A. Mirkin and J. T. Hupp, *J. Am. Chem. Soc.*, 2007, **129**, 12680–12681.
- 8 For selected reviews, see: (a) R. N. Grimes, *Carboranes*, 2nd edn, Elsevier, Oxford, 2011; (b) N. S. Hosmane, *Boron Science: New Technologies and Applications*, Taylor & Francis Books/CRC, Boca Raton, FL, 2011; (c) D. Olid, R. Núñez, C. Viñas and F. Teixidor, *Chem. Soc. Rev.*, 2013, **42**, 3318–3336; (d) Z. Qiu, *Tetrahedron Lett.*, 2015, **56**, 963–971; (e) Z. Xie, *Sci. China: Chem.*, 2014, **57**, 1061–1063.
- 9 (a) A. Himmelsbach and M. Finze, *Eur. J. Inorg. Chem.*, 2010, 2012–2024 and references therein; (b) M. Tominaga, Y. Morisaki and Y. Chujo, *Macromol. Rapid Commun.*, 2013, **34**, 1357–1362; (c) W. Jiang, D. E. Harwell, M. D. Mortimer, C. B. Knobler and M. F. Hawthorne, *Inorg. Chem.*, 1996, **35**, 4355–4359; (d) W. Jiang, C. B. Knobler, C. E. Curtis, M. D. Mortimer and M. F. Hawthorne, *Inorg. Chem.*, 1995, **34**, 3491–3498.
- 10 For selected reviews, see: (a) I. A. I. Mkhaliid, J. H. Barnard, T. B. Marder, J. M. Murphy and J. F. Hartwig, *Chem. Rev.*, 2010, **110**, 890–931; (b) R. Martin and S. L. Buchwald, *Acc. Chem. Res.*, 2008, **41**, 1461–1473; (c) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Rev.*, 2011, **111**, 1293–1314; (d) D.-G. Yu, B.-J. Li and Z.-J. Shi, *Acc. Chem. Res.*, 2010, **43**, 1486–1495; (e) S. R. Neufeldt and M. S. Sanford, *Acc. Chem. Res.*, 2012, **43**, 936–946; (f) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147–1169; (g) X. Chen, K. M. Engle, D.-H. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2009, **48**, 5094–5115; (h) K. M. Engle, T.-S. Mei, M. Wasa and J.-Q. Yu, *Acc. Chem. Res.*, 2012, **45**, 788–802; (i) J.-Q. Yu and Z. Shi, *C–H Activation*, Springer, Berlin, 2010.
- 11 (a) M. Miura, T. Tsuda, T. Satoh, S. Pivsa-Art and M. Nomura, *J. Org. Chem.*, 1998, **63**, 5211–5215; (b) L. Achermann and J. Pospech, *Org. Lett.*, 2011, **13**, 4153–4155; (c) S. Mochida, K. Hirano, T. Satoh and M. Miura, *Org. Lett.*, 2010, **12**, 5776–5779; (d) K. Ueura, T. Satoh and M. Miura, *Org. Lett.*, 2007, **9**, 1407–1409; (e) R. K. Chinnagolla and M. Jeganmohan, *Chem. Commun.*, 2012, **48**, 2030–2032.
- 12 (a) R. Giri, N. Maugel, J.-J. Li, D.-H. Wang, S. P. Breazzano, L. B. Saunders and J.-Q. Yu, *J. Am. Chem. Soc.*, 2007, **129**, 3510–3511; (b) D.-H. Wang, T.-S. Mei and J.-Q. Yu, *J. Am. Chem. Soc.*, 2008, **130**, 17676–17677; (c) H. A. Chiong, Q.-N. Pham and O. Daugulis, *J. Am. Chem. Soc.*, 2007, **129**, 9879–9884; (d) J. Cornella, M. Righi and I. Larrosa, *Angew. Chem., Int. Ed.*, 2011, **50**, 9429–9432; (e) J. Luo, S. Preciado and I. Larrosa, *J. Am. Chem. Soc.*, 2014, **136**, 4109–4112; (f) Y. Zhang, H. Zhao, M. Zhang and W. Su, *Angew. Chem., Int. Ed.*, 2015, **127**, 3888–3892.
- 13 (a) R. Giri, N. Maugel, J.-J. Li, D.-H. Wang, S. P. Breazzano, L. B. Saunders and J.-Q. Yu, *J. Am. Chem. Soc.*, 2007, **129**, 3510–3511; (b) Y.-H. Zhang, B.-F. Shi and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2009, **48**, 6097–6100.
- 14 (a) P. Mamone, G. Danoun and L. J. Gooßen, *Angew. Chem., Int. Ed.*, 2013, **52**, 6704–6708; (b) J. Miao and H. Ge, *Org. Lett.*, 2013, **15**, 2930–2933.
- 15 R. Giri and J.-Q. Yu, *J. Am. Chem. Soc.*, 2008, **130**, 14082–14083.
- 16 (a) Y.-H. Zhang and J.-Q. Yu, *J. Am. Chem. Soc.*, 2009, **131**, 14654–14655; (b) S. Bhadra, W. I. Dzik and L. J. Gooßen, *Angew. Chem., Int. Ed.*, 2013, **52**, 2959–2962.
- 17 (a) K.-H. Ng, F.-N. Ng and W.-Y. Yu, *Chem. Commun.*, 2012, **48**, 11680–11682; (b) F.-N. Ng, Z. Zhou and W.-Y. Yu, *Chem. – Eur. J.*, 2014, **20**, 4474–4480.
- 18 T.-S. Mei, R. Giri, N. Maugel and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2008, **47**, 5215–5297.
- 19 (a) Y. Ano, M. Tobisu and N. Chatani, *Org. Lett.*, 2012, **14**, 354–357; (b) Y. Ano, M. Tobisu and N. Chatani, *Synlett*, 2012, **23**, 2763–2767.
- 20 (a) F. Xie, Z. Qi, S. Yu and X. Li, *J. Am. Chem. Soc.*, 2014, **136**, 4780–4787; (b) C. Feng and T.-P. Loh, *Angew. Chem., Int. Ed.*, 2014, **53**, 2722–2726.
- 21 (a) M. Shang, H.-L. Wang, S.-Z. Sun, H.-X. Dai and J.-Q. Yu, *J. Am. Chem. Soc.*, 2014, **136**, 11590–11593; (b) S. H. Kim, S. H. Park and S. Chang, *Tetrahedron*, 2012, **68**, 5162–5166; (c) J. Dong, F. Wang and J. You, *Org. Lett.*, 2014, **16**, 2884–2887.
- 22 For selected reviews, see: (a) C. Liu, J. Yuan, M. Gao, S. Tang, W. Li, R. Shi and A. Lei, *Chem. Rev.*, 2015, **115**, 12138–12204; (b) C. Liu, H. Zhang, W. Shi and A. Lei, *Chem. Rev.*, 2011, **111**, 1780–1824; (c) C. S. Yeung and V. M. Dong, *Chem. Rev.*, 2011, **111**, 1215–1292.
- 23 For a recently reported example of Heck-type reaction of o-carborane with styrene, see: H. Lyu, Y. Quan and Z. Xie, *Angew. Chem., Int. Ed.*, 2015, **54**, 10623–10626.
- 24 Y. Quan and Z. Xie, *J. Am. Chem. Soc.*, 2014, **136**, 15513–15516.
- 25 Y. Quan and Z. Xie, *Angew. Chem., Int. Ed.*, 2016, **55**, 1295–1298.
- 26 Selected examples for catalytic B–H activation of C₂B₁₀H₁₂: (a) E. L. Hoel, M. Talebinasab-Savari and M. F. Hawthorne, *J. Am. Chem. Soc.*, 1977, **99**, 4356–4367; (b) M. G. L. Mirabelli and L. G. Sneddon, *J. Am. Chem. Soc.*, 1988, **110**, 449–453; (c) K. Cao, Y. Huang, J. Yang and J. Wu, *Chem. Commun.*, 2015, 7257–7260; (d) Z. Zheng, W. Jiang, A. A. Zinn, C. B. Knobler and M. F. Hawthorne, *Inorg. Chem.*, 1995, **34**, 2095–2100; (e) Z. Zheng, C. B. Knobler, M. D. Mortimer, G. Kong and M. F. Hawthorne, *Inorg. Chem.*, 1996, **35**, 1235–1243; (f) Z. Qiu, Y. Quan and Z. Xie, *J. Am. Chem. Soc.*, 2013, **135**, 12192–12195; (g) Y. Quan and Z. Xie, *J. Am. Chem. Soc.*, 2015, **137**, 3502–3505; (h) D. Liu, L. Dang, Y. Sun,



- H.-S. Chan, Z. Lin and Z. Xie, *J. Am. Chem. Soc.*, 2008, **130**, 16103–16110.
- 27 Selected examples for stoichiometric B–H activation of $C_2B_{10}H_{12}$: (a) E. L. Hoel and M. F. Hawthorne, *J. Am. Chem. Soc.*, 1973, **95**, 2712–2713; (b) M. R. Churchill, J. J. Hackbarth, A. Davison, D. D. Traficante and S. S. Wreford, *J. Am. Chem. Soc.*, 1974, **96**, 4041–4042; (c) G.-X. Jin, J.-Q. Wang, C. Zhang, L.-H. Weng and M. Herberhold, *Angew. Chem., Int. Ed.*, 2005, **44**, 259–262; (d) M. Herberhold, H. Yan, W. Milius and B. Wrackmeyer, *Angew. Chem., Int. Ed.*, 1999, **38**, 3689–3691; (e) R. Zhang, L. Zhu, G. Liu, H. Dai, Z. Lu, J. Zhao and H. Yan, *J. Am. Chem. Soc.*, 2012, **134**, 10341–10344; (f) Z. Wang, H. Ye, Y. Li, Y. Li and H. Yan, *J. Am. Chem. Soc.*, 2013, **135**, 11289–11298; (g) J.-Y. Bae, Y.-J. Lee, S.-J. Kim, J. Ko, S. Cho and S. O. Kang, *Organometallics*, 2000, **19**, 1514–1521; (h) Z. J. Yao, W. B. Yu, Y. J. Lin, S. L. Huang, Z. H. Li and G. X. Jin, *J. Am. Chem. Soc.*, 2014, **136**, 2825–2832; (i) Y. Quan, Z. Qiu and Z. Xie, *J. Am. Chem. Soc.*, 2014, **136**, 7599–7602; (j) A. V. Puga, F. Teixidor, R. Sillanpää, R. Kivekäs and C. Viñas, *Chem. Commun.*, 2011, **47**, 2252–2254; (k) G. Barberà, C. Viñas, F. Teixidor, R. Sillanpää and R. Kivekäs, *Inorg. Chem.*, 2006, **45**, 3496–3498; (l) A. M. Spokoiny, M. G. Reuter, C. L. Stern, M. A. Ratner, T. Seideman and C. A. Mirkin, *J. Am. Chem. Soc.*, 2009, **131**, 9482–9483; (m) M. Y. Tsang, C. Viñas, F. Teixidor, J. G. Planas, N. Conde, R. SanMartin, M. T. Herrero, E. Domínguez, A. Lledós, P. Vidossich and D. Choquesillo-Lazarte, *Inorg. Chem.*, 2014, **53**, 9284–9285; (n) N. Fey, M. F. Haddow, R. Mistry, N. C. Norman, A. G. Orpen, T. J. Reynolds and P. G. Pringle, *Organometallics*, 2012, **31**, 2907–2913.
- 28 Selected examples for catalytic B–H activation of $CB_{11}H_{12}^-$ and $C_2B_9H_{11}^{2-}$: (a) J. D. Hewes, C. W. Kreimendahl, T. B. Marder and M. F. Hawthorne, *J. Am. Chem. Soc.*, 1984, **106**, 5757–5759; (b) E. Molinos, G. Kociok-Köhn and A. S. Weller, *Chem. Commun.*, 2005, 3609–3611; (c) E. Molinos, S. K. Brayshaw, G. Kociok-Köhn and A. S. Weller, *Organometallics*, 2007, **26**, 2370–2382; (d) I. Rojo, F. Teixidor, R. Kivekäs, R. Sillanpää and C. Viñas, *J. Am. Chem. Soc.*, 2003, **125**, 14720–14721. Selected examples for stoichiometric B–H activation of $CB_{11}H_{12}^-$ and $C_2B_9H_{11}^{2-}$: (e) R. E. King, S. B. Miller, C. B. Knobler and M. F. Hawthorne, *Inorg. Chem.*, 1983, **22**, 3549–3554; (f) F. Teixidor, J. Casabó, A. M. Romerosa, C. Viñas, J. Rius and C. Miravittles, *J. Am. Chem. Soc.*, 1991, **113**, 9895–9896; (g) M. G. Davidson, M. A. Fox, T. G. Hibbert, J. K. Howard, A. Mackinnon, I. S. Neretin and K. Wade, *Chem. Commun.*, 1999, 1649–1650; (h) V. I. Bregadze, I. D. Kosenko, I. A. Lobanova, Z. A. Starikova, I. A. Godovikov and I. B. Sivaev, *Organometallics*, 2010, **29**, 5366–5372; (i) J. N. Francis, C. J. Jones and M. F. Hawthorne, *J. Am. Chem. Soc.*, 1972, **94**, 4878–4881.
- 29 Selected examples for catalytic B–H activation of boranes: (a) H. C. Johnson, C. L. McMullin, S. D. Pike, S. A. Macgregor and A. S. Weller, *Angew. Chem., Int. Ed.*, 2013, **52**, 9776–9780; (b) E. W. Corcoran and L. G. Sneddon, *J. Am. Chem. Soc.*, 1984, **106**, 7793–7800; (c) E. W. Corcoran and L. G. Sneddon, *J. Am. Chem. Soc.*, 1985, **107**, 7446–7450; (d) M. J. Pender, P. J. Carroll and L. G. Sneddon, *J. Am. Chem. Soc.*, 2001, **123**, 12222–12231; (e) T. Peymann, C. B. Knobler and M. F. Hawthorne, *J. Am. Chem. Soc.*, 1999, **121**, 5601–5602; (f) R. Wilczynski and L. G. Sneddon, *Inorg. Chem.*, 1981, **20**, 3955–3962.
- 30 J. He, M. Wasa, K. S. L. Chan and J.-Q. Yu, *J. Am. Chem. Soc.*, 2013, **135**, 3387–3390.
- 31 For detailed experimental procedures and complete characterization data, see ESI.†
- 32 F. Teixidor, G. Barberà, A. Vaca, R. Kivekäs, R. Sillanpää, O. Oliva and C. Viñas, *J. Am. Chem. Soc.*, 2005, **127**, 10158–10159.
- 33 A. S. Dudnik and V. Gevorgyan, *Angew. Chem., Int. Ed.*, 2010, **49**, 2096–2098.
- 34 R. Giri, N. Maugel, J.-J. Li, D.-H. Wang, S. P. Breazzano, L. B. Saunders and J.-Q. Yu, *J. Am. Chem. Soc.*, 2007, **129**, 3510–3511.
- 35 X. Jie, Y. Shang, P. Hu and W. Su, *Angew. Chem., Int. Ed.*, 2013, **52**, 3630–3633.

