

## EDGE ARTICLE

View Article Online  
View Journal | View IssueCite this: *Chem. Sci.*, 2020, **11**, 9426

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

Received 6th May 2020

Accepted 4th August 2020

DOI: 10.1039/d0sc02567d

rsc.li/chemical-science

## Boron tribromide as a reagent for anti-Markovnikov addition of HBr to cyclopropanes†

Matthew H. Gieuw,<sup>a</sup> Shuming Chen,<sup>b</sup> Zhihai Ke,<sup>a</sup> K. N. Houk<sup>\*b</sup> and Ying-Yeung Yeung<sup>†\*</sup>

Although radical formation from a trialkylborane is well documented, the analogous reaction mode is unknown for trihaloboranes. We have discovered the generation of bromine radicals from boron tribromide and simple proton sources, such as water or *tert*-butanol, under open-flask conditions. Cyclopropanes bearing a variety of substituents were hydro- and deuterio-brominated to furnish anti-Markovnikov products in a highly regioselective fashion. NMR mechanistic studies and DFT calculations point to a radical pathway instead of the conventional ionic mechanism expected for BBr<sub>3</sub>.

The Lewis acidic nature of organoboranes is well understood, but the participation of BR<sub>3</sub> in free-radical processes was largely overlooked until 1966.<sup>1</sup> Since the discovery of the potential of organoborane species to undergo radical reactions, many novel and synthetically useful transformations were developed.<sup>2</sup> Trialkylboranes (BR<sub>3</sub>) can easily undergo bimolecular homolytic substitution (S<sub>H</sub>2) at the boron atom to generate alkyl radicals (Scheme 1A). It was found that alkoxyl, dialkylaminyl, alkylthiyl and carbon-centered radicals, triplet ketones, and triplet oxygen can all initiate the radical reaction by substituting one of the alkyl groups of trialkylboranes to liberate alkyl radicals.<sup>3</sup> BEt<sub>3</sub>/O<sub>2</sub> is arguably the most studied organoborane radical-initiating system, with the peroxy radical being the key to propagate the reaction. Apart from being a radical initiator, BEt<sub>3</sub>, along with trace amount of O<sub>2</sub>, can also undergo conjugate addition to unsaturated ketones and aldehydes; addition to ethenyl- and ethynylloxiranes, azidoalkenes, and imines; and addition-elimination to nitroalkenes and nitroarenes, styryl sulfones, sulf-oxides and sulfinimides.<sup>3</sup> However, apart from changing BEt<sub>3</sub> to other trialkylboranes or catecholborane to carry out similar radical reactions, the radical-reaction potential of other organoboranes remains underexplored, given the ease and mild conditions under which they initiate radical chains, often with trace amount of O<sub>2</sub> in air at low temperature. The application of such a mild radical-initiation system to stereoselective radical reactions would drastically change the reaction outcome especially when intermediates and products are thermally unstable.<sup>4</sup>

Halogenation is an important class of transformations and the resultant halogenated products can easily be manipulated to give a wide range of functional molecules.<sup>5</sup> While trihaloboranes have been employed as halogenating or haloborating agents, their role in reactions is either ambiguous or thought to be exclusively Lewis acidic.<sup>6</sup> To date, the use of trihaloboranes as a halogen radical donor has not been reported. With BR<sub>3</sub>/O<sub>2</sub> being a versatile radical-initiator and conjugate-addition system, we envisioned that a suitable halogenated-borane might work similar to that of trialkylboranes in the generation of reactive, yet stable enough halogen radicals for selective halogenation reactions (Scheme 1B).

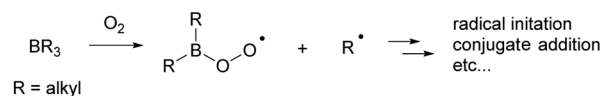
Trialkylboranes readily undergo S<sub>H</sub>2 reactions because the formation of stronger B–X (*e.g.* B–O) bonds *via* substitution is highly exothermic.<sup>3</sup> The BDEs (B–C) of BMe<sub>3</sub>, BEt<sub>3</sub>, B<sup>*i*</sup>Pr<sub>3</sub>, B<sup>*t*</sup>Pr<sub>3</sub>, and B<sup>*n*</sup>Bu<sub>3</sub> range from 344 to 354 kJ mol<sup>–1</sup> at 298 K, while their typical autoxidation products, B(OH)<sub>3</sub>, B(OMe)<sub>3</sub>, and B(OEt)<sub>3</sub>, have BDEs (B–O) ranging from 519 to 522 kJ mol<sup>–1</sup> at 298 K.<sup>7</sup> We hypothesized that organohaloboranes (BX<sub>a</sub>R<sub>3–a</sub>, X = halogen) with BDEs (B–X) similar to trialkylboranes would be a halogen

<sup>a</sup>Department of Chemistry, State Key Laboratory of Synthetic Chemistry, The Chinese University of Hong Kong, Shatin, NT Hong Kong, China. E-mail: yyyeung@cuhk.edu.hk

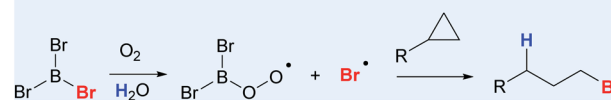
<sup>b</sup>Department of Chemistry and Biochemistry, University of California, Los Angeles, California 90095, USA. E-mail: houk@chem.ucla.edu

† Electronic supplementary information (ESI) available. CCDC 1941104. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0sc02567d

## (A) literature reports



## (B) this study: anti-Markovnikov hydrobromination



Scheme 1 Classical radical reactions with trialkylboranes and our work on radical bromination using BBr<sub>3</sub>.



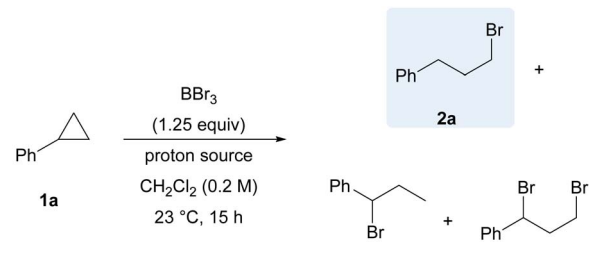
radical donor from a thermodynamic viewpoint. As the common trihaloboranes ( $\text{BX}_3$ )  $\text{BF}_3$ ,  $\text{BCl}_3$  and  $\text{BBr}_3$  have BDEs ( $\text{B-X}$ ) of 644.3, 442.3 and 367.1  $\text{kJ mol}^{-1}$  at 298 K, respectively,  $\text{BBr}_3$  was the logical option for our purpose.<sup>8</sup> Although the BDE ( $\text{B-I}$ ) of  $\text{BI}_3$  is the lowest among all trihaloboranes and found to be 278.2  $\text{kJ mol}^{-1}$  at 0 K,<sup>9</sup> it was not considered suitable as  $\text{I}_2$  has proven to be a very efficient radical quencher in such reactions,<sup>10</sup> and even rigorously purified  $\text{BI}_3$  invariably contains a trace amount of  $\text{I}_2$ .<sup>11</sup>

Compared to activated cyclopropanes,<sup>12</sup> oxidative functionalization of unactivated cyclopropanes gives a wide range of useful molecules that are otherwise not readily accessible, and protocols for the Markovnikov-selective functionalization of unactivated cyclopropanes have been reported.<sup>13–20</sup> Halolyses of cyclopropanes to give 1,3-dihaloalkanes by molecular halogens are also documented although the reactions commonly suffer from the formation of side products *via* electrophilic aromatic halogenation.<sup>21</sup> In contrast, obtaining products with anti-Markovnikov regioselectivity has been considered as one of the top challenges in industry.<sup>22–30</sup> Anti-Markovnikov functionalization of unactivated cyclopropanes mostly relies on photo-initiated radical processes with generally poor regioselectivity and limited scope.<sup>31–36</sup> To the best of our knowledge, anti-Markovnikov hydrohalogenation of cyclopropanes has not been reported.

Very recently, an anti-Markovnikov hydroboration for unactivated cyclopropanes has been reported using boron tribromide and phenylsilane.<sup>37</sup> The reaction was carried out under inert and anhydrous conditions, and mechanistic studies pointed to an ionic mechanism with Lewis acid–base interactions. We show that with a simple twist in the reaction conditions, which is to introduce oxygen, a drastically different reaction outcome and mechanism could be realized. We now report the study and application of  $\text{BBr}_3$  as a radical Br donor for the anti-Markovnikov addition of HBr to cyclopropanes.

With all these considerations in mind, we initially envisioned that  $\text{BBr}_3/\text{O}_2$  as a suitable system to generate bromine radicals, and cyclopropylbenzene (**1a**) as the model substrate to capture them. The radical reaction might then be terminated by another halogen radical from reagents such as *N*-chlorosuccinimide or *N*-iodosuccinimide. Unfortunately, messy mixtures were obtained for all entries (see the ESI, Scheme S1†). On the other hand, a simple proton source,  $\text{H}_2\text{O}$ , was found to be effective in terminating the radical species. In the control experiment with only  $\text{BBr}_3$  and cyclopropylbenzene (**1a**) (Scheme 2, entry 1), the anti-Markovnikov hydrobrominated product **2a** was obtained in 24% yield, together with the formation of Markovnikov product **3a** (trace) and dibrominated cyclopropane **4a** (11%). We reasoned that the proton source was the trace amount of moisture in commercial  $\text{BBr}_3$  solution.

Although it is well known that boron-based Lewis acids are moisture sensitive,<sup>38</sup> counter-intuitively, the addition of 1.5 equivalents of  $\text{H}_2\text{O}$  had a positive impact on the yield of **2a**, which was dramatically improved to 80% (Scheme 2, entry 2). Excess water led to a reduction in the yield of **2a** and the regioselectivity (Scheme 2, entry 3). Replacing water with ethanol as the proton source resulted in a significant drop in

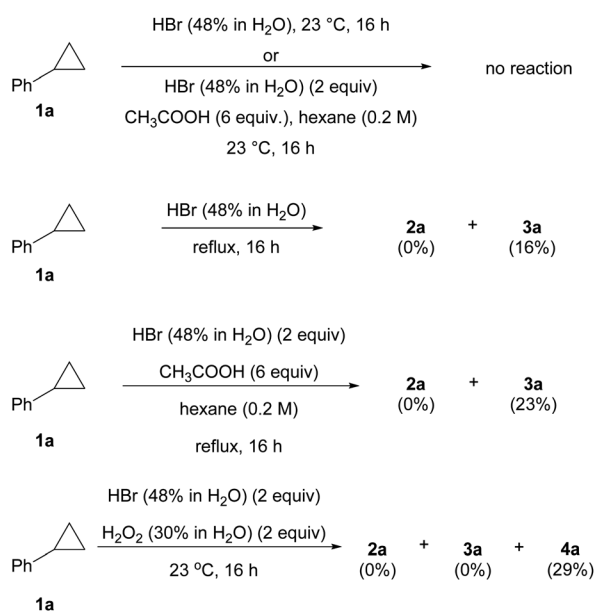


entry	proton source	<b>2a</b> (%)	<b>3a</b> (%)	<b>4a</b> (%)
1	none	24	0.4	11
2	$\text{H}_2\text{O}$ (1.5 equiv)	80	5	13
3	$\text{H}_2\text{O}$ (4.0 equiv)	51	8	7
4 <sup>a</sup>	$\text{EtOH}$ (1.5 equiv)	27	22	8
5 <sup>b</sup>	<i>i</i> PrOH (1.5 equiv)	81	4	9
6	<i>t</i> BuOH (1.5 equiv)	83	2.4	13
7	$\text{CF}_3\text{CH}_2\text{OH}$ (1.5 equiv)	81	3	14

**Scheme 2** Reaction optimization. Conditions: reactions were carried out under ambient conditions and quenched by saturated  $\text{NaHCO}_3$  solution. Yields were measured by  $^1\text{H}$  NMR with  $\text{CH}_2\text{Br}_2$  as the internal standard. <sup>a</sup>24% of **1a** was recovered. <sup>b</sup>6% of **1a** was recovered.

reaction efficiency (Scheme 2, entry 4). In contrast, bulkier alcohols such as *i*-PrOH or *t*-BuOH (Scheme 2, entries 5 and 6) and less nucleophilic alcohols such as  $\text{CF}_3\text{CH}_2\text{OH}$  (Scheme 2, entry 7) gave comparable performance to that of water.

Further study revealed that achieving anti-Markovnikov addition of HBr to cyclopropanes in conventional systems is not a trivial task (Scheme 3). For instance, no reaction was observed when **1a** was treated with HBr in either aqueous or water/AcOH co-solvent systems at room temperature.<sup>29</sup> Heating both reactions only yielded the Markovnikov product **3a** in 16–23% yield, and no anti-Markovnikov product **2a** was detected.



**Scheme 3** Reactions of cyclopropane (**1a**) with hydrobromic acid.



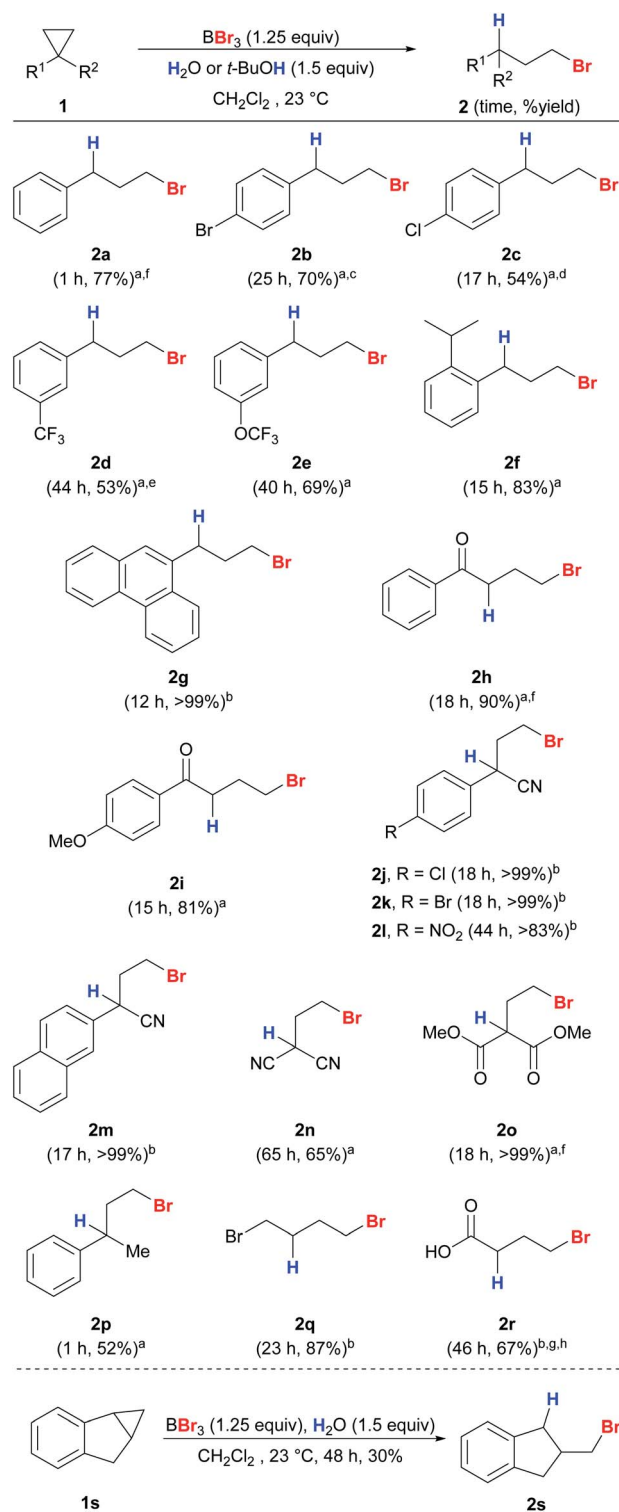
The classical radical bromination protocol with  $\text{BBr}_3/\text{H}_2\text{O}_2$  only furnished dibrominated product **4a** in 29% yield. Similar to the uniqueness of  $\text{BR}_3/\text{O}_2$  in several aforementioned radical reactions,<sup>4</sup> the incapability of these control experiments in producing **2a** as a product contrasted starkly with our  $\text{BBr}_3/\text{O}_2$  conditions, which generated a reactive yet selective bromine radical.

Next, we expanded the substrate scope to other unactivated cyclopropanes using either water or *t*-BuOH as the proton source (Scheme 4). Electron-neutral, deficient and sterically bulky substrates **1a–1g** gave the desired anti-Markovnikov products **2a–2g** in good yields and regioselectivity. Cyclopropanes with electron-deficient substituents including nitriles (**1j–n**) and ester (**1o**) also worked well with excellent regioselectivity. This protocol also exhibits high chemoselectivity towards cyclopropanes. Aryl methyl ether (**2i**), which is known to be easily cleaved by  $\text{BBr}_3$  even at low temperature, remained intact under our reaction conditions.<sup>39</sup> Due to the tendency of aryl vinyl ketones to polymerize, they are known to be unsuitable for 1,4-conjugate additions mediated by trialkylboranes.<sup>40</sup> Nevertheless, aryl cyclopropyl ketones (**1h–i**) were converted into the corresponding products in high yields, and polymerization was not observed. 1,1-Disubstituted (**1p**) and simple alkyl (**1q**) cyclopropanes were also compatible to give products **2p** and **2q**. When cyclopropyl carboxylic acid (**1r**) was used as the substrate, the unstable product **2r** was detected using HRMS and crude  $^1\text{H}$  NMR, and  $\gamma$ -butyrolactone was obtained ultimately through cyclization upon a basic work-up procedure. Indene-derived cyclopropyl substrate **1s** was also compatible to give **2s**. Scaled-up reactions were also performed on selected examples (**2a**, **2h**, **2o**, and **2r**) and excellent regioselectivities were still obtained.

Cyclopropanes **1t–1y** with secondary and tertiary alcohols also gave the corresponding anti-Markovnikov products in excellent yields and with high regioselectivities (Scheme 5). The structure of **2x** was confirmed unambiguously by X-ray crystallography.<sup>41</sup> The hydroxyl groups in the substrates were converted into bromides simultaneously by the action of  $\text{BBr}_3$  to give a series of useful dibromides.<sup>42</sup> We were interested in whether alcohol-containing substrates can be hydrobrominated in the absence of an external proton source. To our delight, **1t** was able to undergo anti-Markovnikov hydrobromination to give **2t** with only a slight drop in yield (76%), and **2u** was produced in quantitative yield. The hydroxyl groups in **1x** and **1y** appear to be crucial because a sluggish reaction was observed for 1-phenyl-2-methylcyclopropane that bears no hydroxyl substituent.

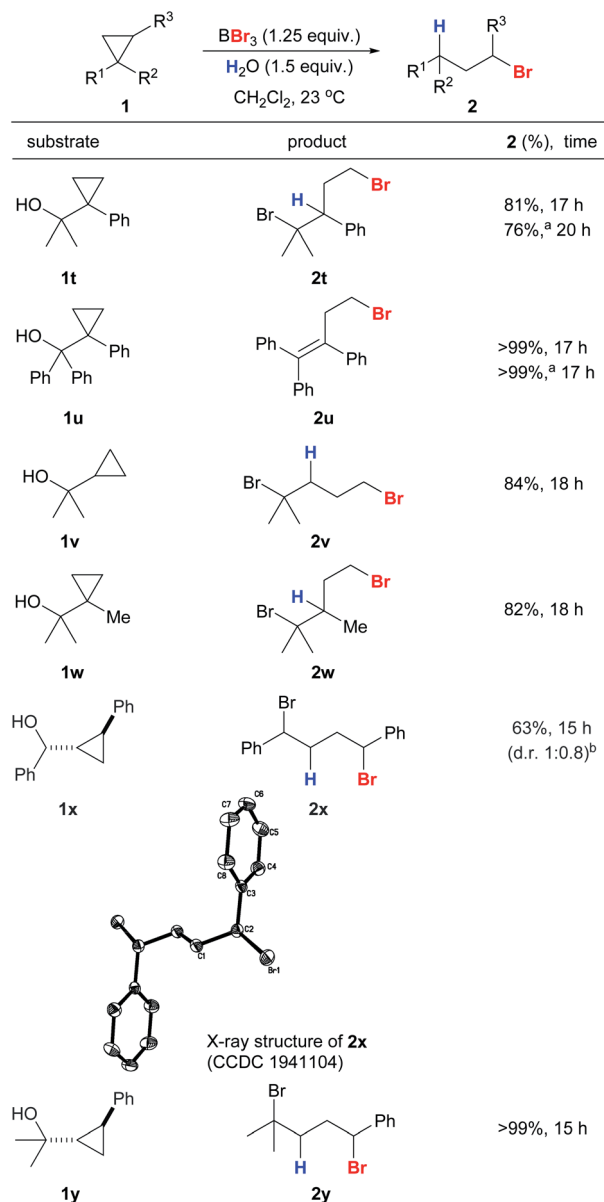
By substituting  $\text{H}_2\text{O}$  and *t*-BuOH with  $\text{D}_2\text{O}$  and *t*-BuOD, deuteriobrominations were also carried out and the corresponding mono-deuterium-labeled compounds were obtained smoothly (Scheme 6). Our protocol offered excellent regio-control in the mono-deuteration to give **2-D**. Unactivated (**1a** and **1e**) and activated cyclopropanes (**1j–k**, **1m**, and **1o**) with various substituents worked well and excellent levels of deuterium incorporation were achieved.

The conversion of products **2** into primary alcohols and amines through nucleophilic substitution proved



**Scheme 4** Reaction scope of anti-Markovnikov hydrobromination of cyclopropanes. Conditions: reactions were carried out with **1** (0.2 mmol) unless stated otherwise. Exact reaction conditions for each substrate are stated in the ESI.† <sup>a</sup>*t*-BuOH was used as the proton source. <sup>b</sup> $\text{H}_2\text{O}$  was used as the proton source. <sup>c</sup>4% of **3b** was detected. <sup>d</sup>5% of **3c** was detected. <sup>e</sup>7% of **3b** was detected. <sup>f</sup>The reaction was conducted on a 1 mmol scale. <sup>g</sup>The reaction was conducted on a 2 mmol scale. <sup>h</sup>The product cyclized quickly upon work-up and the yield was measured on the basis of the cyclized product  $\gamma$ -butyrolactone.

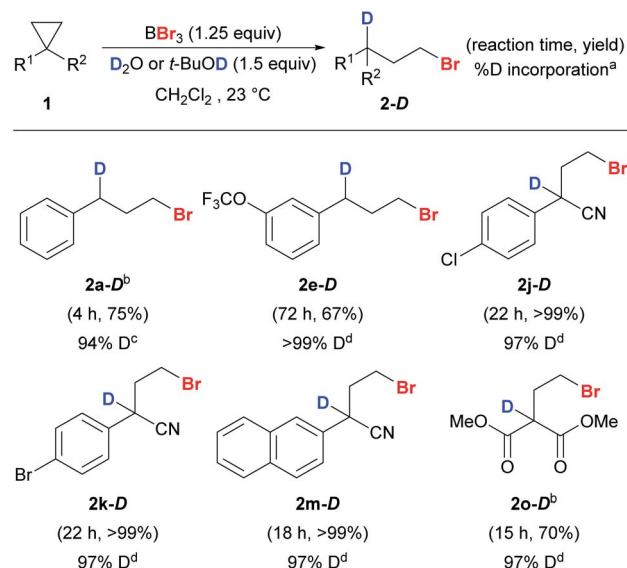




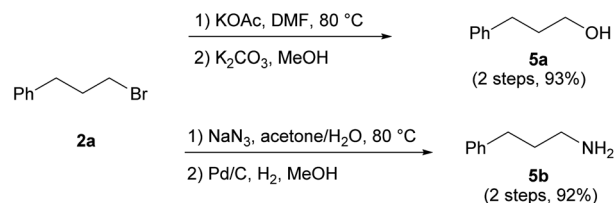
**Scheme 5** Reaction scope of anti-Markovnikov hydrobromination of cyclopropanes with hydroxyl substituents. Conditions: reactions were carried out with **1** (0.2 mmol). Exact reaction conditions for each substrate are stated in the ESI.† <sup>a</sup>Reaction was conducted in the absence of water. <sup>b</sup>Diastereoselectivity was determined by a  $^1\text{H}$  NMR experiment on the crude mixture.

straightforward. For instance, alcohol **5a** and amine **5b** were readily prepared from **2a** with high conversion (Scheme 7). As the direct synthesis of primary alcohols and amines through anti-Markovnikov hydration and hydroamination has proven to be challenging,<sup>22</sup> our protocol provides useful precursors for the synthesis of these highly desired compounds.

We envision a radical reaction pathway between  $\text{BBr}_3$  and  $\text{O}_2$ , but given the Lewis acidity of  $\text{BBr}_3$  and Lewis basicity of  $\text{H}_2\text{O}$  and alcohols, an acid-mediated pathway cannot be ruled out.<sup>38</sup> However, such a pathway appears highly unlikely, as the treatment of cyclopropanes with aqueous  $\text{HBr}$  yielded no anti-



**Scheme 6** Reaction scope of anti-Markovnikov deuteriobromination of cyclopropanes. Conditions: reactions were carried out with **1** (0.2 mmol) unless stated otherwise. Exact reaction conditions for each substrate are stated in the ESI.† <sup>a</sup>The % D incorporation was determined based on the integration of the residual proton signal in  $^1\text{H}$  NMR. <sup>b</sup>The reaction was conducted on a 1 mmol scale. <sup>c</sup> $t\text{-BuOH}$  was used as the deuterium source. <sup>d</sup> $\text{D}_2\text{O}$  was used as the deuterium source.



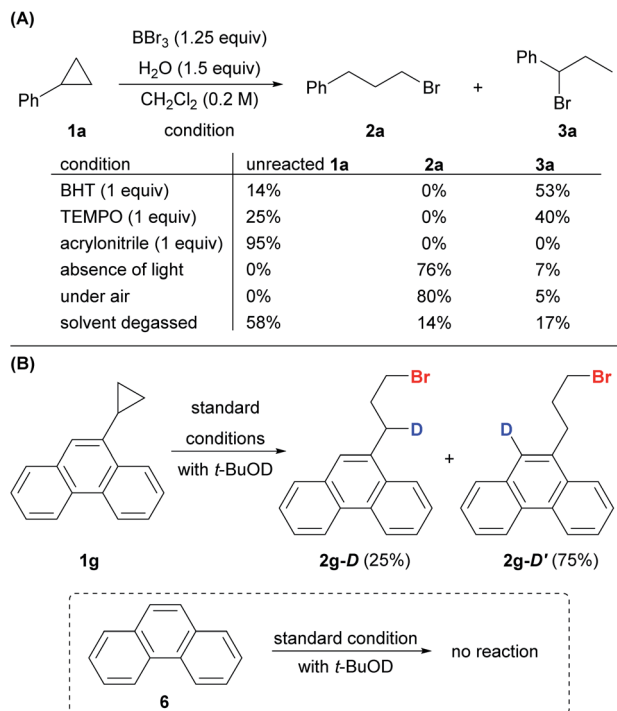
**Scheme 7** Synthetic utilities of **2a**.

Markovnikov product **2** (Scheme 3). Several control experiments were performed to further probe the reaction mechanism.

The addition of a radical scavenger, BHT or TEMPO, in slight excess of  $\text{BBr}_3$  completely shut down the formation of anti-Markovnikov product **2a**, and a significant amount of Markovnikov product **3a** was detected (Scheme 8A). The addition of the acceptor olefin acrylonitrile completely suppressed the reaction. The absence of light had no impact on the reaction, thereby eliminating the possibility of a photo-triggered pathway. The presence of oxygen was crucial for both the yield and the regioselectivity. The reaction proceeded smoothly to give the desired product **2a** (80%) in open air. In contrast, the yield of anti-Markovnikov product **2a** dropped to 14% and that of the Markovnikov product **3a** increased to 17% when the reaction was conducted with degassed  $\text{CH}_2\text{Cl}_2$  and **1a**. Deuteriobromination of **1g** was also conducted with  $t\text{-BuOD}$  as the deuterium source (Scheme 8B). Other than the benzylic deuteriation product **2g-D** (25%), a substantial amount of **2g-D'** (75%) was







Scheme 8 Control experiments.

obtained. In contrast, no aromatic deuteration was observed when phenanthrene (**6**) was used as the substrate under the same conditions. The formation of **2g-D'** could be attributed to the isomerization of benzylic radical species (also see the ESI, Fig. S1†). This preliminary evidence pointed at a radical mechanism, although a carbocation intermediate cannot be ruled out completely.

Consistent with literature reports on  $\text{BBr}_3$ ,<sup>43,44</sup> the reactivity of  $\text{BBr}_3$  towards homolytic debromination decreases sharply along the series  $\text{BBr}_3$ ,  $\text{BBr}_2\text{OR}$ , and  $\text{BBr}(\text{OR})_2$  as a consequence of  $\pi$ -bonding between oxygen and boron. With 0.5 equiv  $\text{BBr}_3$ , only 21% of **2a** was obtained even with a prolonged reaction time of 24 h. These data indicated that only the first equivalent of Br from  $\text{BBr}_3$  is crucial for the reactivity, and contribution from the possible  $\text{BBr}_a(\text{OR})_{3-a}$  byproducts should be insignificant.

A series of  $^1\text{H}$  and  $^{11}\text{B}$  NMR experiments were conducted to gain further insight. Upon mixing  $\text{BBr}_3$  with **1a** in the absence of  $\text{O}_2$  and a proton source, both **1a** and  $\text{BBr}_3$  were mostly consumed, and a new  $^{11}\text{B}$  signal at 64 ppm (see the ESI, Fig. S2†) emerged as a singlet, which is characteristic of an alkylidihaloborane species.<sup>45,46</sup> From  $^1\text{H}$  NMR, it is clear that **1a** is ring-opened (see the ESI, Fig. S4†), and the species has a similar NMR pattern to a hydroborated cyclopropane, which has been reported as a reaction intermediate in literature examples (see the ESI, Fig. S3†).<sup>37</sup> Direct bromoboration of alkynes or allenes with  $\text{BBr}_3$  is well documented.<sup>47,48</sup> While this new species cannot be clearly identified, it is speculated that it could be the direct bromoboration product or hydroxyboration product. Nevertheless, it is clear that the interaction between  $\text{BBr}_3$  and **1a** does not lead to the anti-Markovnikov product **2a** in the absence of  $\text{O}_2$  and a proton source.

When *i*-PrOH and  $\text{BBr}_3$  were mixed in  $\text{CD}_2\text{Cl}_2$  under air, the  $^{11}\text{B}$  signal of  $\text{BBr}_3$  (39 ppm) disappeared and a new signal at 25.0 ppm emerged. A new proton signal at  $-2.68$  ppm also appeared in the  $^1\text{H}$  NMR study of the same sample. The two new signals (25.0 ppm in  $^{11}\text{B}$  NMR and  $-2.68$  ppm in  $^1\text{H}$  NMR) diminished gradually upon the addition of **1a** and the amount of anti-Markovnikov product **2a** increased accordingly (see the ESI, Fig. S5†). On the other hand, a new  $^{11}\text{B}$  NMR signal at 18.9 ppm (but no signal at 25.0 ppm) was observed when the same mixture was prepared in the absence of  $\text{O}_2$  and attributed to the formation of the Lewis adduct between *i*-PrOH and  $\text{BBr}_3$  (see the ESI, Fig. S6†). Thus, it is reasonable to propose that the active species, responsible for initiating the anti-Markovnikov hydrobromination of cyclopropanes, was formed only in the presence of  $\text{O}_2$ .

A DFT computational study was also performed to shed light on the mechanism (Fig. 1). While there are no reports on radical reactions triggered by  $\text{BBr}_3/\text{O}_2$ , we speculate that the reaction mechanism might be analogous to the classical  $\text{BR}_3/\text{O}_2$  system in which the putative peroxy-boron species **A** is generated<sup>49</sup> at the initiation stage of the radical process (Fig. 1A) and corresponds to the new NMR signals (25.0 ppm in  $^{11}\text{B}$  NMR and  $-2.68$  ppm in  $^1\text{H}$  NMR).<sup>3,50,51</sup> Based on the calculated energy profile, species **A** is capable of brominating cyclopropane **1a** through a radical mechanism to give **B** (Fig. 1B). It is also calculated that **A** and **A'** could be in equilibrium, but species **A** ( $\Delta G = -7.6$  kcal mol $^{-1}$ ) was found to be a more competent Br donor than **A'** ( $\Delta G = 0.6$  kcal mol $^{-1}$ ) in the halogen atom transfer (XAT), potentially due to the intramolecular hydrogen bond that stabilizes the by-product **I** (Fig. 1C). It was also calculated that  $\text{BBr}_3$  can reversibly react with water to give adduct **C** ( $^{11}\text{B}$  NMR signal = 18.9 ppm). Species **C** is unable to serve as a Br radical donor to brominate cyclopropane **1a** ( $\Delta G = 69.6$  kcal mol $^{-1}$ ).

However, species **C** is capable of acting as a hydrogen radical donor to species **B**, furnishing the desired product **2a**. This result is in alignment with the proposal in the literature in which trialkylborane-ROH complexes ( $\text{R} = \text{H}, \text{Me}$ ) might act as H-donors as a result of the weakened O–H bond.<sup>52</sup> Species **D**, which is formed from species **C** after the hydrogen atom transfer (HAT), was calculated to be a competent Br radical donor to brominate cyclopropane **1a** to give **B**, thereby propagating the radical chain. Thus, we propose that oxygen is required only in the initiation stage for the generation of species **A**, while species **C** and **D** are responsible for propagation. Indeed, the reaction was sluggish under an inert atmosphere, while the re-introduction of oxygen into a system initially free of oxygen triggered the anti-Markovnikov hydrobromination (see the ESI, Scheme S2†). The HAT from species **A** to **1a** was also explored computationally, but species **A** could not be optimized as a stable energy minimum. Species **C** may also serve as a hydrogen radical donor and react with cyclopropane **1a** to give species **D** and **E**, which would go on to produce the Markovnikov product **3a**. However, this hydrogen atom transfer reaction is endergonic by 31.2 kcal mol $^{-1}$  (Fig. 1C), making it a minor pathway compared to the competing hydrogen atom transfer from **C** to **B** that gives **D** and **2a** (Fig. 1A). This result is



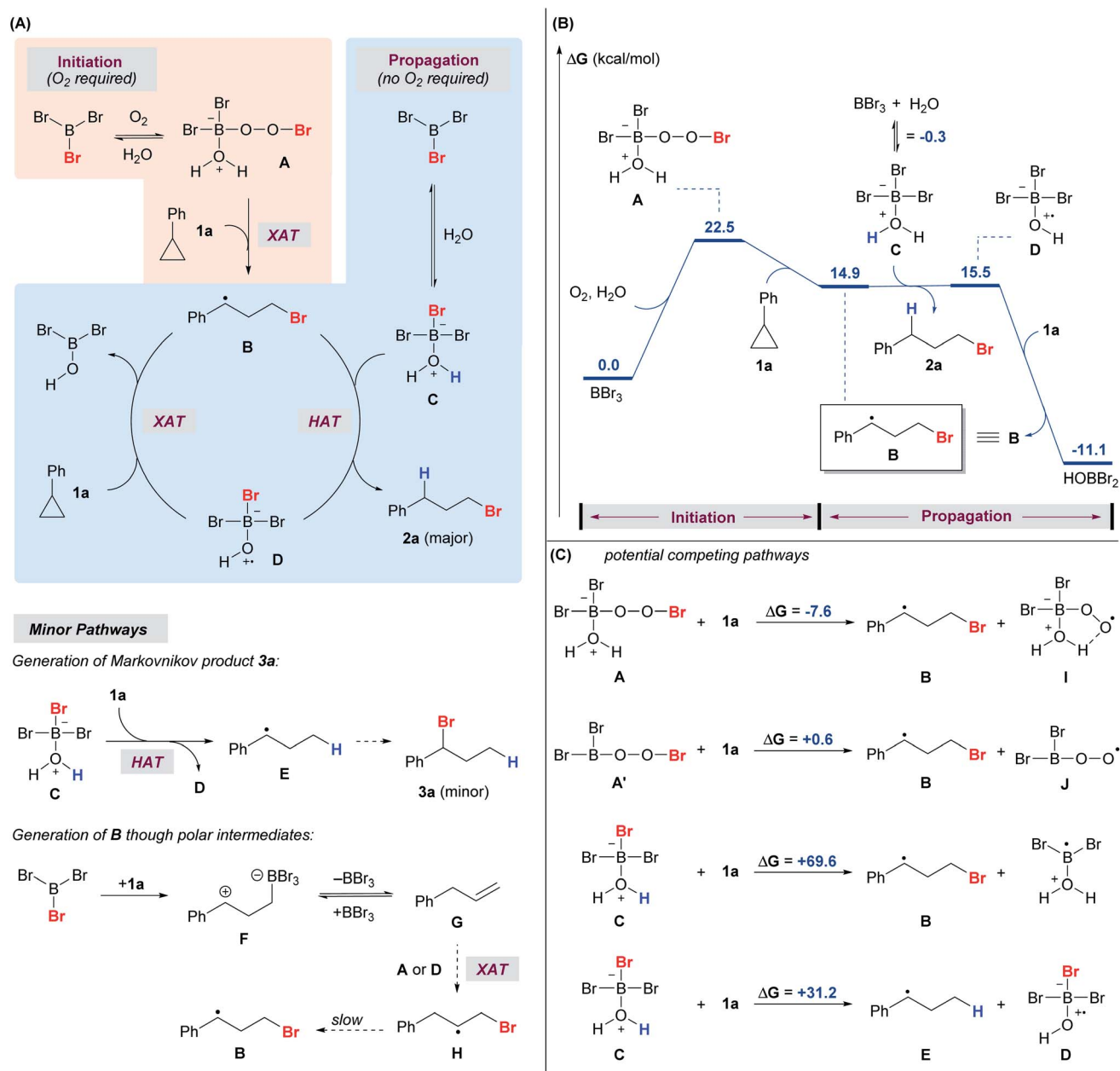


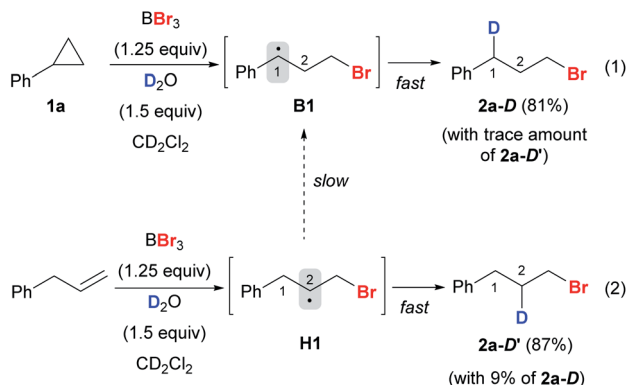
Fig. 1 Reaction mechanism. (A) Plausible reaction pathways. (B) Calculated free energy profile of the anti-Markovnikov hydrobromination of **1a** at the  $\omega$ B97X-D/6-311++G(d,p), SMD(CH<sub>2</sub>Cl<sub>2</sub>)/ $\omega$ B97X-D/6-311++G(d,p) level of theory. (C) Potential competing pathways.

consistent with the experimental observation that the Markovnikov product **3a** became dominant when the reaction was conducted under an inert atmosphere (Scheme 8A).

In the  $^1H$  NMR study of the reaction using **1a**, apart from **2a**, **3a** and **4a** (Scheme 2), a trace amount of allylbenzene was detected initially and diminished over time. We speculate that the allylbenzene (Fig. 1A, species **G**) might be formed through the zwitterionic species **F** as proposed in the recent studies by Wang and Shi.<sup>37,53</sup> The eventual disappearance of allylbenzene could be attributed to the radical bromination to give species **H** and the subsequent formation of **2a**.

In a deuterium labeling experiment with **1a** as the substrate and D<sub>2</sub>O as the deuterium source, we observed

exclusive deuterium incorporation at the benzylic carbon to give product **2a-D**, potentially through the C(1) radical species **B1** (Scheme 9, eqn (1)). However, the deuterium incorporation pattern is vastly different when using allylbenzene instead of **1a**, for which C(2) deuterated product **2a-D'** was obtained predominately (Scheme 9, eqn (2)) (also see the ESI, Fig. S7†). The formation of **2a-D'** from allylbenzene may proceed through the C(2) radical species **H1**. A small amount of **2a-D** (9%) was also detected in the reaction with allylbenzene, attributed to the slow 1,2-hydrogen shift<sup>54</sup> converting **H1** to the more stable benzylic radical **B1**. These results suggest that the 1,2-hydrogen shift between the radical species **H** and **B** (Fig. 1A) should be much slower than the radical protonation



Scheme 9 Mechanistic insights from deuteriobromination.

process, implying that allylbenzene is unlikely to be the key intermediate in the reaction.

## Conclusions

In summary, we have discovered and exploited the potential of  $\text{BBr}_3$  to serve as a bromine radical donor in the presence of  $\text{O}_2$  and a proton source. Through our protocol, cyclopropanes are opened regioselectively to obtain anti-Markovnikov hydro- and deuteriobrominated products in high yields. Mechanistic studies and DFT calculations demonstrate the importance of  $\text{O}_2$  in the radical initiation process. Further efforts to utilize this reactivity mode of  $\text{BBr}_3$  on different classes of substrates are currently underway in our laboratory.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the Hong Kong Special Administrative Region General Research Funding (grant no. CUHK14304918), The Chinese University of Hong Kong Direct Grant (grant no. 4053394), and Innovation and Technology Commission to the State Key Laboratory of Synthetic Chemistry (GHP/004/16GD). K. N. H thanks the National Science Foundation (Grant CHE-1764328) for financial support. Calculations were performed on the Hoffman2 cluster at the University of California, Los Angeles, and the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by the National Science Foundation (Grant OCI-1053575).

## Notes and references

- (a) A. G. Davies and B. P. Roberts, *Chem. Commun.*, 1966, 298–299; (b) A. G. Davies and B. P. Roberts, *J. Chem. Soc. B*, 1967, 17–22.
- Radicals in Organic Synthesis*, ed. P. Renaud and M. P. Sibi, Wiley-VCH, Weinheim, 2001.
- C. Ollivier and P. Renaud, *Chem. Rev.*, 2011, **101**, 3415–3434.
- (a) F. R. Mayo and C. Walling, *Chem. Rev.*, 1940, **27**, 351–412; (b) M. D. Bachi and E. Bosch, *Tetrahedron Lett.*, 1986, **27**, 641–644; (c) K. Nozaki, K. Oshima and K. Utimoto, *Tetrahedron Lett.*, 1988, **29**, 6127–6128; (d) K. Nozaki, K. Oshima and K. Utimoto, *Bull. Chem. Soc. Jpn.*, 1990, **63**, 2578–2583; (e) P. A. Evans and J. D. Roseman, *J. Org. Chem.*, 1996, **61**, 2252–2253.
- (a) M. Hudlicky and T. Hudlicky, Formation of carbon–halogen bonds, in *The Chemistry of Functional Groups, Supplement D*, ed. S. Patai and Z. Rappoport, John Wiley and Sons Ltd., New Jersey, 1983; (b) Formation of carbon–halogen bonds (Cl, Br, I), in *PATAI's Chemistry of Functional Groups*, ed. Y. Sasson, John Wiley and Sons Ltd, 2009.
- (a) *Boron Tribromide in Encyclopedia of Reagents for Organic Synthesis*, ed. A. Suzuki, S. Hara and X. Huang, John Wiley & Sons, Ltd., 2006; (b) *Boron Trichloride in Encyclopedia of Reagents for Organic Synthesis*, ed. N. Miyaura, Y. Yamamoto and N. Miyaura, John Wiley & Sons, Ltd., 2006; (c) P. Laszlo and M. Teston, *J. Am. Chem. Soc.*, 1990, **112**, 8750–8754.
- J. B. Holbrook, B. C. Smith, C. E. Housecroft and K. Wade, *Polyhedron*, 1982, **1**, 701–706.
- N. N. Greenwood, in *Comprehensive Inorganic Chemistry*, ed. A. F. Trotman-Dickenson, Pergamon Press, Oxford, 1973.
- J. D. Grant and D. A. Dixon, *J. Phys. Chem. A*, 2009, **113**, 777–787.
- (a) M. M. Midland and H. C. Brown, *J. Am. Chem. Soc.*, 1971, **93**, 1506–1508; (b) G. W. Kabalka, *J. Organomet. Chem.*, 1971, **33**, C25–C28.
- L. V. McCarry and D. R. Carpenter, *J. Electrochem. Soc.*, 1960, **107**, 38–42.
- (a) H.-U. Reissig and R. Zimmer, *Chem. Rev.*, 2003, **103**, 1151–1196; (b) M. Yu and B. L. Pagenkopf, *Tetrahedron*, 2005, **61**, 321–347; (c) F. De Simone and J. Waser, *Synthesis*, 2009, **20**, 3353–3374; (d) F. de Nanteuil, F. de Simone, R. Frei, F. Benfatti, E. Serrano and J. Waser, *Chem. Commun.*, 2014, **50**, 10912–10928; (e) T. F. Schneider, J. Kaschel and D. B. Werz, *Angew. Chem., Int. Ed.*, 2014, **53**, 5504–5523; (f) M. A. Cavitt, L. H. Phun and S. France, *Chem. Soc. Rev.*, 2014, **43**, 804–818; (g) Y. Xia, X. Liu, H. Zheng, L. Lin and X. Feng, *Angew. Chem., Int. Ed.*, 2015, **54**, 227–230; (h) Y. Xia, L. Lin, F. Chang, X. Fu, X. Liu and X. Feng, *Angew. Chem., Int. Ed.*, 2015, **54**, 13748–13752; (i) Y. Xia, L. Lin, F. Chang, Y. Liao, X. Liu and X. Feng, *Angew. Chem., Int. Ed.*, 2016, **55**, 12228–12232; (j) Y. Xia, F. Chang, L. Lin, Y. Xu, X. Liu and X. Feng, *Org. Chem. Front.*, 2018, **5**, 1293–1296.
- V. Nair, S. B. Panicker and S. Mathai, *Res. Chem. Intermed.*, 2003, **29**, 227–231.
- C. Rösner and U. Hennecke, *Org. Lett.*, 2015, **17**, 3226–3229.
- Y.-C. Wong, Z. Ke and Y.-Y. Yeung, *Org. Lett.*, 2015, **17**, 4944–4947.
- Z. Ke, Y.-C. Wong, J.-Y. See and Y.-Y. Yeung, *Adv. Synth. Catal.*, 2016, **358**, 1719–1724.
- M. H. Gieuw, V. M.-Y. Leung, Z. Ke and Y.-Y. Yeung, *Adv. Synth. Catal.*, 2018, **360**, 4306–4311.



- 18 V. M.-Y. Leung, M. H. Gieuw, Z. Ke and Y.-Y. Yeung, *Adv. Synth. Catal.*, 2020, **362**, 2039–2044.
- 19 N. O. Ilchenko, M. Hedberg and K. J. Szabó, *Chem. Sci.*, 2017, **8**, 1056–1061.
- 20 S. M. Banik, K. M. Mennie and E. N. Jacobsen, *J. Am. Chem. Soc.*, 2017, **139**, 9152–9155.
- 21 (a) K. J. Shea and P. S. Skell, *J. Am. Chem. Soc.*, 1973, **95**, 6728–6734; (b) D. E. Applequist and L. F. McKenzie, *J. Org. Chem.*, 1976, **41**, 2262–2266; (c) J. M. Tanko, R. H. Mas and N. K. Suleman, *J. Am. Chem. Soc.*, 1990, **112**, 5557–5562; (d) J. M. Tanko and M. Sadeghipour, *Angew. Chem., Int. Ed.*, 1999, **38**, 159–161.
- 22 J. Haggin, *Chem. Eng. News Archive*, 1993, **71**, 23–27.
- 23 J. Takaya and J. F. Hartwig, *J. Am. Chem. Soc.*, 2005, **127**, 5756–5757.
- 24 A. Takemiya and J. F. Hartwig, *J. Am. Chem. Soc.*, 2006, **128**, 6042–6043.
- 25 G. Dong, P. Teo, Z. K. Wickens and R. H. Grubbs, *Science*, 2011, **333**, 1609–1612.
- 26 S. Zhu, N. Niljianskul and S. L. Buchwald, *J. Am. Chem. Soc.*, 2013, **135**, 15746–15749.
- 27 A. E. Strom and J. F. Hartwig, *J. Org. Chem.*, 2013, **78**, 8909–8914.
- 28 D. J. Wilger, J.-M. M. Grandjean, T. R. Lammert and D. A. Nicewicz, *Nat. Chem.*, 2014, **6**, 720–726.
- 29 M. Galli, C. J. Fletcher, M. del Pozo and S. M. Goldup, *Org. Biomol. Chem.*, 2016, **14**, 5622–5626.
- 30 Q. Zhu, D. E. Graff and R. R. Knowles, *J. Am. Chem. Soc.*, 2018, **140**, 741–747.
- 31 F. R. Mayo and C. Walling, *Chem. Rev.*, 1940, **27**, 351–412.
- 32 C. S. Irving, R. C. Petterson, I. Sarkar, H. Kristinsson, C. S. Aaron, G. W. Griffin and G. J. Boudreaux, *J. Am. Chem. Soc.*, 1966, **88**, 5675–5676.
- 33 S. S. Hixson and D. W. Garrett, *J. Am. Chem. Soc.*, 1974, **96**, 4872–4879.
- 34 V. R. Rao and S. S. Hixson, *J. Am. Chem. Soc.*, 1979, **101**, 6458–6459.
- 35 K. Mizuno, J. Ogawa and Y. Otsuji, *Chem. Lett.*, 1981, **10**, 741–744.
- 36 C. R. Pitts, B. Ling, J. A. Synder, A. E. Bragg and T. Leckta, *J. Am. Chem. Soc.*, 2016, **138**, 6598–6609.
- 37 D. Wang, X.-S. Xue, K. N. Houk and Z. Shi, *Angew. Chem., Int. Ed.*, 2018, **57**, 16861–16865.
- 38 H. A. Skinner and N. B. Smith, *Trans. Faraday Soc.*, 1955, **51**, 19–22.
- 39 J. F. W. McOmie, M. L. Watts and D. E. West, *Tetrahedron*, 1968, **24**, 2289–2292.
- 40 A. Suzuki, M. Tabata and M. Ueda, *Tetrahedron Lett.*, 1975, **26**, 2195–2198.
- 41 CCDC 1941104 (2w) contains the supplementary crystallographic data for this paper.
- 42 J. D. Pelletier and D. Poirier, *Tetrahedron Lett.*, 1994, **35**, 1051–1054.
- 43 A. Suzuki, A. Arase, H. Matsumoto, M. Itoh, H. C. Brown, M. M. Rogic and M. W. Rathke, *J. Am. Chem. Soc.*, 1967, **89**, 5708–5709.
- 44 J. A. Baban, N. J. Goodchild and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1986, 157–161.
- 45 H. C. Brown and J. A. Sikorski, *Organometallics*, 1982, **1**, 28–37.
- 46 R. Soundararajan and D. S. Matteson, *Organometallics*, 1995, **14**, 4157–4166.
- 47 C. Wang, Z. Xu, T. Tobrman and E.-i. Negishi, *Adv. Synth. Catal.*, 2010, **352**, 627–631.
- 48 M. F. Lappert and B. Prokai, *J. Organomet. Chem.*, 1964, **1**, 384–400.
- 49 A. M. Kosmas, C. Mpellos, Z. Salta and E. Drougas, *Chem. Phys.*, 2010, **371**, 36–42.
- 50 P. Renaud, A. Beauseigneur, A. Brecht-Forster, B. Becattini, V. Darmency, S. Kandhasamy, F. Montermini, C. Olliver, P. Panchaud, D. Pozzi, E. M. Scanlan, A.-P. Schaffner and V. Weber, *Pure Appl. Chem.*, 2007, **79**, 223–233.
- 51 D. P. Curran and T. R. McFadden, *J. Am. Chem. Soc.*, 2016, **138**, 7741–7752.
- 52 (a) D. A. Spiegel, K. B. Wiberg, L. N. Schacherer, M. R. Medeiros and J. L. Wood, *J. Am. Chem. Soc.*, 2005, **127**, 12513–12515; (b) D. Pozzi, E. M. Scanlan and P. Renaud, *J. Am. Chem. Soc.*, 2005, **127**, 14204–14205; (c) M. R. Medeiros, L. N. Schacherer, D. A. Spiegel and J. L. Wood, *Org. Lett.*, 2007, **9**, 4427–4429.
- 53 Z.-Y. Zhang, Z.-Y. Liu, R.-T. Guo, Y.-Q. Zhao, X. Li and X.-C. Wang, *Angew. Chem., Int. Ed.*, 2017, **56**, 4028–4032.
- 54 J. W. Wilt and O. Kolewe, *J. Am. Chem. Soc.*, 1965, **87**, 2071–2072.

