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Enhanced methods for the undecachlorination of $[\text{HCB}_{11}\text{H}_{11}]^-$ and syntheses of $[\text{XCB}_{11}\text{Cl}_{11}]^-$ from $[\text{HCB}_{11}\text{Cl}_{11}]^-$ (X = Cl, Br, I, NH_2)[†]

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Utilizing $\text{SbCl}_3/\text{SbCl}_5$ mixtures at reflux, or of TCCA in a solid–solid reaction at 200 °C (with properly described precautions) are described as reliable and convenient procedures for the conversion of $[\text{HCB}_{11}\text{H}_{11}]^-$ into $[\text{HCB}_{11}\text{Cl}_{11}]^-$. Procedures for the derivatization of the carbon vertex of $[\text{HCB}_{11}\text{Cl}_{11}]^-$ to prepare $[\text{XCB}_{11}\text{Cl}_{11}]^-$ salts (X = Cl, Br, I, NH_2) are also formulated.

Anions based on the 1-carba-*closo*-dodecaborate cage (hereafter: carboranes)¹ are a class of weakly coordinating anions² with many desirable properties.^{3,4} The parent carborane $[\text{HCB}_{11}\text{H}_{11}]^-$ can be substituted at the boron and carbon positions while maintaining cage integrity; these synthetic efforts have been thoroughly reviewed.^{3,4} Among the various substituted carboranes, $[\text{HCB}_{11}\text{Cl}_{11}]^-$ possesses an attractive combination of weak basicity, resistance to oxidation, robustness, and solubility.^{5,6} It has allowed isolation of one of the strongest possible purely Brønsted acids $\text{H}[\text{HCB}_{11}\text{Cl}_{11}]$, which is stable to sublimation at 200 °C.^{7,8} It has also been used in the isolation of highly reactive carbocations, main group cations,^{9–13} as well as shown to be a competent counteranion in high-temperature, transition metal-catalyzed olefin polymerization.¹⁴ Accordingly, development of a reliable and convenient synthesis of $[\text{HCB}_{11}\text{Cl}_{11}]^-$ has attracted considerable attention.

The synthesis of $[\text{HCB}_{11}\text{Cl}_{11}]^-$ by Reed *et al.*, originally reported in 1998, utilizes ICl as the chlorination agent in triflic acid as solvent at 220 °C (Fig. 1).^{7,15} It is consistently reproducible, but requires an expensive pressure-rated reactor, which also dramatically limits the reaction scale (to about 2 g in Reed's procedure). In addition, it is a lengthy process, taking weeks to the isolation of the pure product. An alternative method that can use non-gaseous reagents at atmospheric

pressure and in regular glassware would clearly be advantageous.

In 2010, we reported two procedures that represented a significant improvement: reactions of $\text{Cs}[\text{HCB}_{11}\text{H}_{11}]$ with either SO_2Cl_2 or SbCl_5 at reflux.¹⁶ Both employed readily available and inexpensive liquid reagents as solvents. The SO_2Cl_2 procedure in particular seemed nearly perfect, because of the low

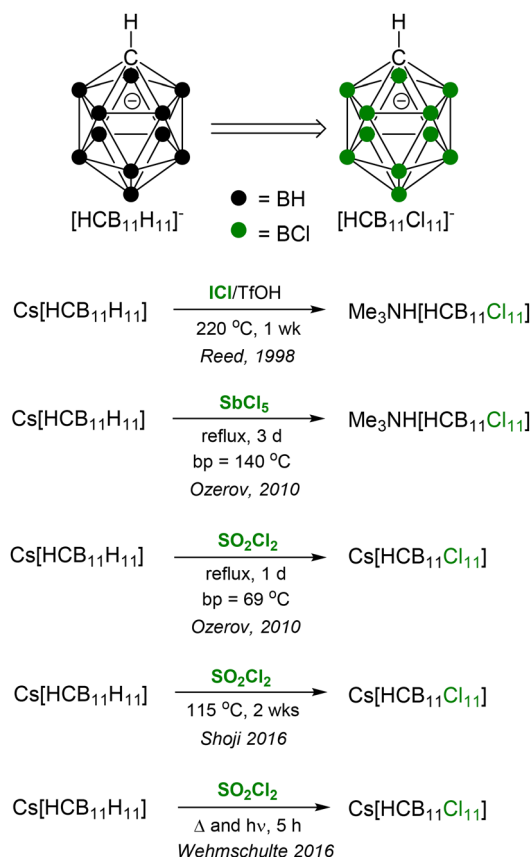


Fig. 1 Previously reported methods for the synthesis of $[\text{HCB}_{11}\text{Cl}_{11}]^-$. Details of workup and cation exchange not shown.

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We first examined the reaction of Cs[HCB₁₁H₁₁] with SbCl₃ alone as a control. Refluxing the mixture for 3 d led to only a modest amount of cage chlorination (Cl₁ to Cl₃, MS evidence). But when this mixture (after cooling) was treated with an excess of SbCl₅ and then allowed to reflux for 16 h, MS evidence indicated near-quantitative conversion to [HCB₁₁Cl₁₁][−]. Encouraged by this finding, we performed chlorinations of 0.5 g and of 6 g Cs[HCB₁₁H₁₁] with SbCl₃/SbCl₅ mixtures, overnight under reflux. In both cases, complete conversion to

We also decided to explore trichloroisocyanuric acid (TCCA) as an alternative chlorinating agent. TCCA is a very inexpensive common water treatment material (known as “pool chlorine” in the US). Mixing 100 mg of Cs[HCB₁₁H₁₁] and TCCA (16 equiv.) as solids, and heating them in a glass flask with stirring at 200 °C for 16 h resulted in complete chlorination of the boron positions and the conversion to [HCB₁₁Cl₁₁][−] and [ClCB₁₁Cl₁₁][−] (MS evidence). Treatment of this mixture with excess Na₂SO₃ served to cleave the C–Cl bond in the latter, and led to the isolation of [HNMe₃][HCB₁₁Cl₁₁] in 91% yield upon further workup. However, we observed that the solid–solid reaction of TCCA with Cs[HCB₁₁H₁₁] tends to turn violent at the initial stages of mixing, or after heating is initiated, depending on the reaction mass and particle size. At the 100 mg scale or less, the violent nature of this event is tolerable for use in a fume hood with standard personal protective equipment. But at larger scales, the violence of the event becomes closer to what would be described as an “explosion”, and we strongly advise against attempts at >100 mg scale of Cs

[HCB₁₁H₁₁]. Besides the obvious safety concern, larger scale reactions led to significantly lower yields of the isolated [HNMe₃][HCB₁₁Cl₁₁]. It is not clear whether the lower yields are a result of chemical degradation in the runaway event, or also of the physical dispersal of the material. Furthermore, it is not clear to us that the observed violent events are a consequence of the runaway exothermic chlorination alone, or also of the triggered violent decomposition of TCCA. After all, the desired chlorination reaction is not conceived to generate gases which was clearly the case in the runaway event observations.

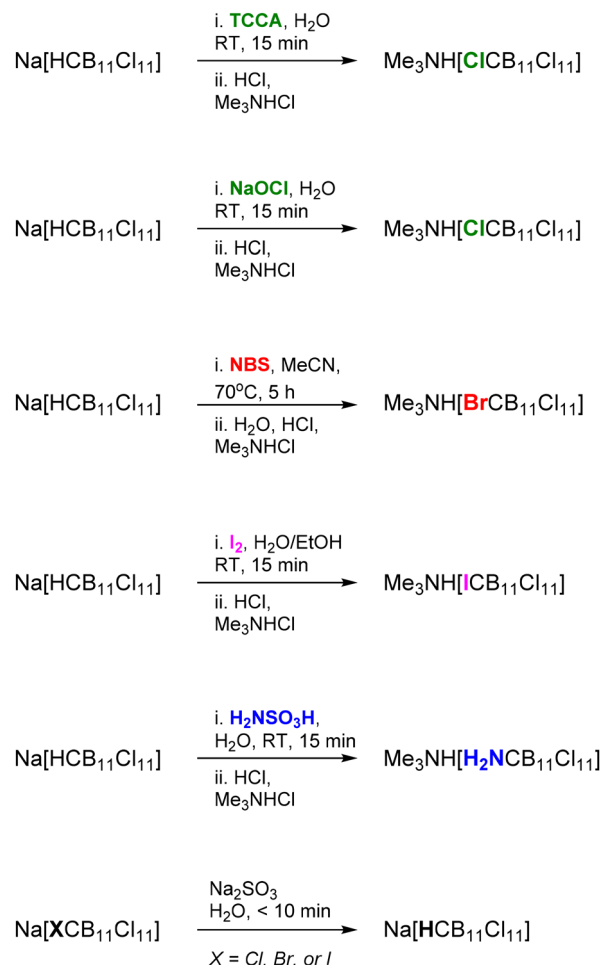
We explored the analogous use of other inexpensive N-Cl reagents *N*-chlorosuccinimide (NCS) and 1,3-dichloro-5,5-dimethylhydantoin (DCDMH). However, we observed only incomplete chlorination of the cage in these attempts.

Next, we attempted to obviate the undesired runaway event *via* initial chlorination of Cs[HCB₁₁H₁₁] in a solvent as a heat sink. Treatment of Cs[HCB₁₁H₁₁] with TCCA at ambient temperature in dichloromethane appeared to be safe, and did lead to partial chlorination of the cage. However, we observed that the subsequent evaporation of the solvent and treatment of the partially chlorinated residue with TCCA could still lead to the undesired runaway event. Cs[HCB₁₁H₁₁] was also only partially chlorinated with TCCA in boiling water. Moreover, on one occasion, a boiling water reaction detonated about an hour after being brought to reflux; we strongly advise against performing such reactions.

However, we were able to find success in scaling up TCCA reactions in the presence of ostensibly inert solids as ballast mass (Scheme 1). We safely performed the reaction a 1 g scale of Cs[HCB₁₁H₁₁] with 200 g NaCl and 13.5 g TCCA (16 equiv.) in the solid state at 200 °C and analogously, with 275 g of sand instead of NaCl. No runaway observations were noted. The reaction with sand produced a better yield (77%) of a purer [HNMe₃][HCB₁₁Cl₁₁] upon workup than the one with NaCl. We surmise that the ballast mass serves as an inert heat sink that prevents a runaway thermal reaction.

The melting points of TCCA and of the presumed products derived from it (cyanuric acid, mono- and dichlorocyanuric acid) are above 200 °C, so the reaction is ostensibly proceeding in the solid. It is likely that the vapor pressure of TCCA at 200 °C is sufficient for some amount of mass transport taking place *via* the gas phase, in addition to the solid–solid contact.

Having observed C-chlorination with TCCA, we separately investigated the conversion of the C–H functionality in [HCB₁₁Cl₁₁][−] to simple C–X groups under milder conditions (Scheme 2). [HCB₁₁Cl₁₁][−] can be deprotonated, at least partly, by relatively weak bases on the order of alkoxide/hydroxide.²⁶ We observed little difference in the ¹¹B NMR spectra between solutions of Na[HCB₁₁Cl₁₁] alone in water, and in the presence of 1 equiv. of NaOH. However, even partial deprotonation is kinetically sufficient. We found that treatment of Na[HCB₁₁Cl₁₁] with NaOH (1.2 equiv.) in water, followed by TCCA (1 equiv.), resulted in full conversion to [ClCB₁₁Cl₁₁][−] after 15 min (¹¹B NMR evidence). Me₃NH[ClCB₁₁Cl₁₁] was isolated in 81% yield upon workup. Similarly, NaOCl can be used



Scheme 2 Elaboration of the carbon vertex in [HCB₁₁Cl₁₁][−].

instead of TCCA. When aqueous Na[HCB₁₁Cl₁₁]/NaOH was treated with H₂NSO₃H or with I₂ (in EtOH), [H₂NCB₁₁Cl₁₁][−] and [ICB₁₁Cl₁₁][−] were cleanly produced *in situ*, and isolated in high yield as Me₃NH⁺ salts. The analogous reaction with Br₂ did not lead to high conversion to [BrCB₁₁Cl₁₁][−] and the reaction with H₂O₂ did not produce any C-hydroxylated derivative. However, we were able to isolate Me₃NH[BrCB₁₁Cl₁₁] in high yield after workup from a reaction of Na[HCB₁₁Cl₁₁] with *N*-bromosuccinimide in acetonitrile at 70 °C. On the other hand, no reaction took place between Na[HCB₁₁Cl₁₁] and *N*-hydroxysuccinimide under the same conditions.

To the best of our knowledge, of the dodecahalogenated [XCB₁₁X₁₁][−] anions (X = halogen), only [BrCB₁₁Br₁₁][−] was previously reported, *via* sealed tube synthesis with HOTf/Br₂ at 250 °C.²⁷ A few carboranes of a general formula [H₂N-CB₁₁X₁₁][−] have been reported, but they were prepared *via* halogenation of an H₂N-C containing carborane precursor.^{28–30} H₂NSO₃H has been used to aminate the [B₁₂H₁₂]^{2−} cage.²²

Dehalogenation of the isolated [HalCB₁₁Cl₁₁][−] anions (Hal = Cl, Br, I) was easily accomplished in aqueous solution by treatment with sodium sulfite at ambient temperature. The carbon in [HalCB₁₁Cl₁₁][−] is effectively playing a role of a more electronega-



In summary, we have demonstrated two new methods for the synthesis of the valuable $[\text{HCB}_{11}\text{Cl}_{11}]^-$ anion – using either a $\text{SbCl}_3/\text{SbCl}_5$ mixture, or TCCA in a solid-solid reaction. Compared to the previously reported methods, these offer improved convenience, reduced times, and greater reproducibility without requiring any equipment besides standard laboratory glassware. In particular, the TCCA method is arguably the most convenient to date, considering the simplicity of workup and the low cost of TCCA.

The data supporting this article have been included as part of the ESI.†

There are no conflicts to declare.

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