Aromatic Substitution with Hypercloso C(BCH$_3$)$_{11}$: A New Mechanism

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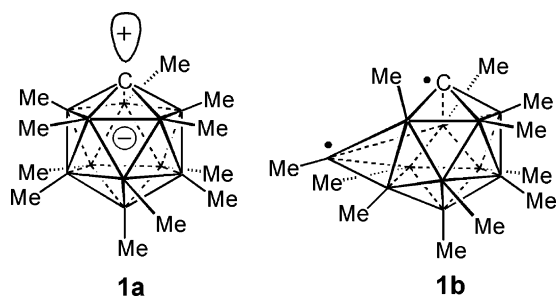
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We report aromatic substitution with the reactive intermediate C(BCH$_3$)$_{11}$ (**1**, Chart 1),[1] formally a hypercloso cation HC(BCH$_3$)$_{11}$$^+$ with a deprotonated carbon vertex but, according to calculations,[2] better viewed in the ground state as a closo cluster with a 5-fold symmetric carbenoid/carbonium ylide structure C(BMe)$_{11}$ ↔ $^+$C$^-$(BMe)$_{11}$ (**1a**) carrying a vacant exocyclic orbital on carbon.[3] The reaction yields highly hindered C-arylated and B-permethylated carborate anions (Me = CH$_3$):

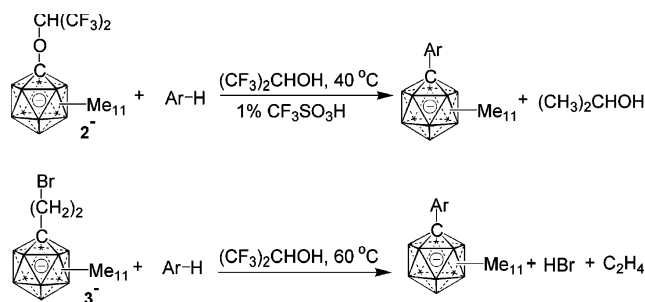$$ArH + \mathbf{1} \rightarrow Ar-C(BMe)_{11}^- + H^+ \qquad (1)$$

In the process, **1** exhibits a novel selectivity, unrelated to its known[1] electrophilic affinity for lone pairs. To account for this result, we propose that this aromatic substitution proceeds by a new mechanism with a norcaradiene-like transition state. The properties of **1** may be relevant for the reactions and structures of the isomeric "boronium ylides"[2] with a naked boron vertex, which occur as intermediates in electrophile-induced nucleophilic substitution (EINS) on polyhedral boranes.[4−6]

Chart 1. Structure of **1**: Left, Carbenoid/Carbonium Ylide. Right, A Possible Biradicaloid Form

1a   **1b**

Two sources of **1** were used (Scheme 1) and yielded indistinguishable results, confirming the intermediacy of free **1**, deduced previously from the observed solvolytic zero kinetic order in the nucleophile:[1] (i) Solvolysis of 1-(CF$_3$)$_2$CHO−C(BMe)$_{11}$$^-$ (**2**$^-$) with excess trapping agent yielded substitution products in high isolated yield. Addition of hydroquinone in one run had no effect. (ii) Solvolytic Grob fragmentation of ∼3−8-fold excess of 1-Br(CH$_2$)$_2$−C(BMe)$_{11}$$^-$ (**3**$^-$) over the trapping partner yielded

**Scheme 1.** Aromatic Substitution with **1**

the same products, now with C$_2$H$_4$ and HBr as byproducts. The latter was quenched with 2,6-di-*tert*-butylpyridine (**4**), added either before or after the reaction, with identical results. The trapping was nearly quantitative, and as expected, the product was mostly **2**$^-$.

Lone-pair nucleophiles gave the expected[1] products. Reactions of **3**$^-$ with pyridine and NaN$_3$ yielded C$_5$H$_5$N$^+$−C(BMe)$_{11}$$^-$ and 1-N$_3$−C(BMe)$_{11}$$^-$, respectively; in pure (CF$_3$)$_2$CHOH, **3**$^-$ produced **2**$^-$, and in CF$_3$CH$_2$OH, it afforded CF$_3$CH$_2$O−C(BMe)$_{11}$$^-$.

All monosubstituted benzenes, *o*-xylene (**5**), naphthalene (**6**), and biphenylene (**7**) gave substitution products according to eq 1. However, **4**, *m*-xylene (**8**), *p*-xylene (**9**), acenaphthylene (**10**), pleiadiene (**11**),[7] and pyrene (**12**) did not react (Chart 2).

Chart 2. Aromatic Substitution with **1**: Reactive Sites in Hydrocarbons
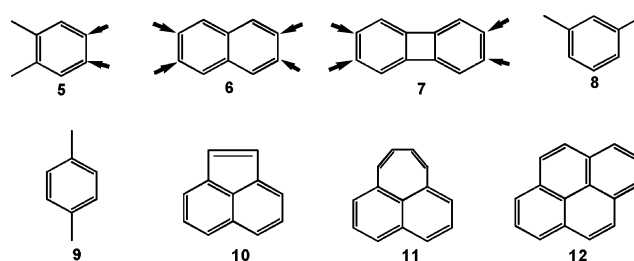
The absence of detectable ortho substitution with **1** is attributed to the steric demands of the methyl groups adjacent to its carbon vertex. This also explains the lack of substitution in **9** and in the peri positions of **6**, **7**, and **10−12**, in which a second ring plays the role of an ortho substituent. Remarkably, starting with

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Table 1. Trapping of **1** with Substituted Benzenes (PhX) and with Aromatic Hydrocarbons[a]

X	m/p		rel		m/p(Ph·)		rel(Ph·)[b]	
	2[c,d,e]	3[c,f,g]	2[h,i]	3[h]	c,j	c,k	h,j	h,k
NO$_2$	1.4	1.4	0.9	0.8[l]	0.4	0.3	2.0	3.0
CF$_3$	1.3	1.3			1.0		1.4	
CN	3.4	3.6	0.9		0.5	0.3	2.9	2.6
CH$_3$	1.6	1.5	1		1.4	1.2	1	1
Cl	1.3	1.4			1.7	1.7	1.0	0.9
Br	1.2[m]	1.0	1.7[n]		1.7	1.9	0.8	1.6
I	0.6	0.7						
CH$_3$O	0.5	0.4	1.1	1.1[l]	1.2	1.2	0.9	0.7
(CH$_3$)$_2$N	0.4	0.3						
5	*o*	*o*						
6	*p*	*p*		(1[q])				
7	*p*	*p*		(2.1[q])				
C$_6$D$_6$			1.1[r]	1.2[r]				
1,3,5-C$_6$H$_3$D$_3$	1.3[s]	1.4[s]						

[a] The products were separated by reverse phase HPLC. Structures were assigned by ^{1}H and ^{13}C NMR. Product ratios were determined by NMR of reaction mixtures. Fluorobenzene produced a complex mixture of cage fluorinated products that we were unable to separate by HPLC and was excluded from the study. [b] Only the meta and para isomers are counted as products in total yield evaluation. [c] The ratio of meta over para isomer. Not corrected for the 2:1 statistical advantage favoring the meta position. [d] In (CF$_3$)$_2$CHOH/1% triflic acid at 40 °C, [**2**] = 17 mM, [ArH] = 0.5 M, in competition experiments [ArH] = [toluene] = 0.25 M. [e] Total isolated yield of both isomers, based on **2**, 80−90%. [f] In (CF$_3$)$_2$CHOH at 60 °C, [**3**] = 8−25 mM, [ArH] = 3−11 mM, in competition experiments [ArNO$_2$] = [ArOMe] and [**6**] = 1.5[**7**]. [g] Total reactivity (both products) relative to toluene. [h] Total isolated yield based on ArH, 60−90%. The remainder of **3** was isolated as **2**. [i] Relative reactivities from competition experiments. [j] From ref 9. [k] From ref 8. [l] From a competition between X = NO$_2$ and X = CH$_3$O. [m] In the presence of hydroquinone, 1.25. [n] In the presence of hydroquinone, 1.6. [o] Only the 4-substituted isomer is formed. [p] Only the 2-substituted isomer is formed. [q] From a competition between **7** and **6**, corrected for the 1.5 to 1 ratio of trap concentrations. [r] Reactivity ratio of C$_6$H$_6$ over C$_6$D$_6$. [s] Product ratio of Ar = C$_6$H$_2$D$_3$ over Ar = C$_6$H$_3$D$_2$.

3$^-$ and 4-bromotrimethylsilylbenzene, ipso substitution of the trimethylsilyl group took place in a ∼30% yield, and 60% of **2**$^-$ was also isolated.

The meta to para substitution ratios in monosubstituted benzenes suggest that in intramolecular competition **1** is slightly electrophilic, but this is not reflected in the relative substrate reactivity. Together, the data in Table 1 exclude polar mechanisms, especially the anticipated electrophilic aromatic substitution. A radical mechanism can be envisaged: (i) the ground state of a Wheland complex might be a biradical, cyclohexadienyl attached to −C(BMe)$_{11}$•, instead of an ylide, benzenonium attached to −C(BMe)$_{11}$$^-$; (ii) **1** might have a triplet ground state (instead of the calculated[2] singlet). However, an ordinary radical aromatic substitution mechanism does not account for the failure of **4**, **8**, and **10**−**12** to react, nor is it particularly favored by a comparison with the selectivity in aromatic substitution by the phenyl radical[8,9] (Table 1) and by the finding that addition of a radical scavenger had no effect.

The other known nonpolar mechanism is insertion into CH bonds.[10] The nearly identical reactivity of C$_6$H$_6$ and C$_6$D$_6$ and the small isotope effect in benzene-1,3,5-d_3 show that such insertion is not involved in the rate-determining step. Rather, the rate-determining step of the substitution appears to generate an intermediate that is subsequently deprotonated.

Most important, all mechanisms invoking an attack by **1** on one of the aromatic CH vertices fail to account for the inertness of **8**, given the reactivity of **5** and toluene, and the inertness of **10**−**12**, given the reactivity of **6**.

We propose that **1** cycloadds in a rate-determining step to two adjacent vertices of the substrate, neither of which is allowed to have an ortho substituent. Removal of a proton from one of the attacked vertices and a loss of one of the two partial bonds between the reagent and the substrate then convert the cyclic intermediate into the product. The choice of the aromatic vertex to be deprotonated determines which of the two new bonds is kept and, hence, the regioselectivity. The need for both ortho positions to be free is rationalized by the steric demands of the methyl substituents. Inspection of computer models also makes it clear that ipso substitution of the trimethylsilyl group is not hindered by its bulkiness.

If the reaction proceeds by an attack on a bond, it should be favored by high π bond order at the center of the reacting HCHCCHCH unit. This indeed seems to be so: (i) one of the larger rate effects found in Table 1 is the reactivity ratio of **7** over **6** (the order of the reacting 2−3 bond is higher in **7** because resonance structures with a cyclobutadiene central ring have smaller weight); and (ii) the reaction fails with **11**, whose 2−3 bond is sterically qualified but is nearly single.

Both new partial bonds formed in the rate-determining step could originate in the naked carbon of **1** (Scheme 2A), in which case the intermediate would have a partially formed three-membered ring. Then, in symmetric substrates such as benzene, both aromatic CH vertices under attack would remain equivalent, and either could be deprotonated in the next step with the same likelihood. Since the isotopic effect in the C$_6$H$_6$/C$_6$D$_6$ competition is only ∼1.15, an even smaller effect would be expected on the rate of the reaction of benzene-1,3,5-d_3. However, one would expect a significant isotope effect on product ratio, as the removal of a proton from the attacked DCCH bond should be faster than the removal of a deuteron. For instance, the rate-determining hydrogen removal step in the reaction of singlet oxygen or triazolinedione with alkenes exhibits an isotopic effect of 1.4.[11]

Alternatively (Scheme 2B), **1** could participate through one of its five edges or trigonal faces adjacent to the naked carbon vertex. One of the new partial bonds would be made by the vertex carbon, and one would be made by one of its five boron neighbors, or two adjacent neighbors. In the cycloadduct, the two aromatic CH vertices would be nonequivalent and it would be the one attached to the carbon of **1** that would have to lose a proton or a deuteron to form the product. The isotope effect would be determined already in the first reaction step and should be less than 1.15.

The isotopic effect actually observed in the trapping with benzene-1,3,5-d_3 is ∼1.35 and argues in favor of Scheme 2A.

Initial computational results are also more compatible with Scheme 2A. A diligent search up to the CCSD(T)/cc-pVDZ// B3LYP/6-31G* level of optimization of a simplified model, CB$_{11}$H$_{11}$, produced structures with a stretched C−B edge resembling **1b**, but only at energies at least 45 kcal/mol above that of the C_{5v} symmetry structure. B3LYP/631G* optimizations of the geometry of CB$_{11}$H$_{11}$ at 50 different starting points generated by random displacements of atoms from the C_{5v} symmetric structure identified 11 low-symmetry minima in the potential energy surface, but all were at least 27 kcal/mol higher in energy. Results of a few calculations on the CB$_{11}$Me$_{11}$ analogues gave no reason to expect that this number will be reduced significantly by the presence of the methyl groups. The results make it very unlikely that a structure

Scheme 2. Aromatic Substitution with **1**: Cluster Participation through a Vertex (A) and through an Edge (B)
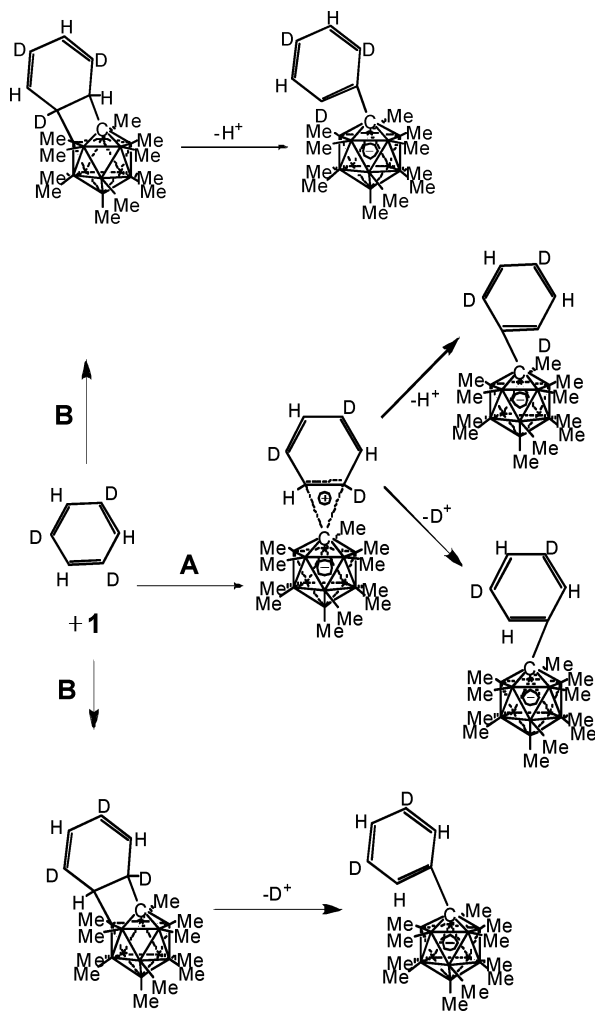
such as **1b** represents the ground state of **1** or even that it intervenes along the substitution reaction path.

The structure **1a** fits the observed reactions with lone-pair carrying electrophiles, but at first sight suggests that aromatic substitution with **1** will proceed along the standard electrophilic substitution path. However, density functional theory (DFT) calculations[2] suggested that the formal positive and negative charges actually mostly reside in different orbitals of the same carbon atom, such that the electronic structure is reminiscent of an S_2 state of a carbene more than the charge-separated state of an ylide. It is then reasonable that the first step of the aromatic substitution should resemble the addition of singlet carbene to an aromatic ring. The separation of charges in the first intermediate in Scheme 2A is undoubtedly also only formal, making it compatible with the near absence of polar effects on the reaction rate. Attempts to optimize the geometry of the proposed reaction intermediate and to examine its electronic structure have so far been fruitless and may require the inclusion of solvent.

We conclude that **1** performs aromatic substitution to yield sterically crowded products not easily accessible otherwise and does so by an unprecedented mechanism, compatible with its previously proposed unusual electronic structure.

Supporting Information Available: Experimental details and results of ab initio computations. This material is available free of charge via the Internet at http://pubs.acs.org.

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