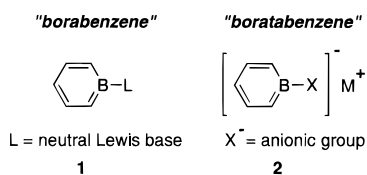# Nucleophilic Aromatic Substitution Reactions of Borabenzene-Trimethylphosphine: A Versatile Route to 1-Substituted Boratabenzenes

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Although borabenzene complexes (**1**) are one of the simplest families of heterocycles, very little is known about their chemistry.[1] As part of a program directed toward the development of applications of borabenzenes in organic synthesis, we have initiated studies of their fundamental reactivity. Aromatic substitution, which has been investigated thoroughly in the case of benzenes[2] and pyridines[3] but was not known for borabenzenes, has been a focus of our initial work. In the context of a synthesis of lithium 1*H*-boratabenzene,[4] we have described

an example of a borabenzene adduct undergoing nucleophilic aromatic substitution.[5] In this communication, we establish that borabenzene-PMe₃ reacts cleanly with a wide variety of anionic nucleophiles to afford 1-substituted boratabenzenes (**2**), and present mechanistic evidence that the substitution proceeds through an addition−elimination pathway (eq 1).
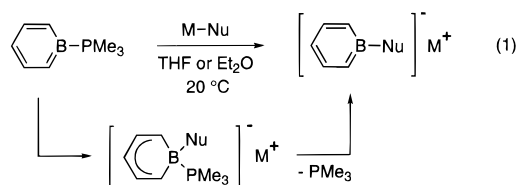
Because a boratabenzene (**2**) can serve as a surrogate in organometallic chemistry for the ubiquitous cyclopentadienyl group (i.e., as a π-bound, anionic six-electron ligand),[6] the synthesis of boratabenzene derivatives with different steric and electronic properties is of current interest.[7] The pioneering work of Ashe and Herberich has provided routes to boratabenzenes

Table 1. Synthesis of 1-Substituted Boratabenzenes through Aromatic Substitution of Borabenzene-PMe₃ (Eq 1)

Nucleophile	Product	Yield (%)
LiAlH₄		71
Li—≡—SiMe₃		68
Li—NMe₂		78
Na—OEt		78
K−PPh₂		91

bearing carbon and nitrogen substituents on boron.[8] We have found that aromatic substitution reactions of a borabenzene complex (**1**) afford convenient access to these as well as to three new classes of substituted boratabenzenes from a single precursor. As illustrated in Table 1, treatment of readily available borabenzene-PMe₃[9] with 1 equiv of an anionic hydrogen,[4] carbon, nitrogen, oxygen, or phosphorus nucleophile produces the boratabenzene derivative in good to excellent yield.

In analogy with the chemistry of benzene derivatives,[2] three of the most likely mechanisms for nucleophilic aromatic substitution of borabenzenes are the dissociative, borabenzyne, and associative pathways illustrated in Scheme 1.[10] In our mechanistic studies, we have focused on the reaction of borabenzene-PMe₃ with lithium trimethylsilylacetylide (eq 2).[11,12]
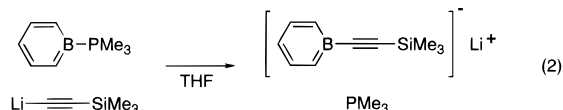
The dissociative pathway for aromatic substitution proceeds via free borabenzene, a species of significant interest that has thus far eluded detection.[13−15] To test for the intermediacy of free borabenzene, we treated borabenzene-PMe₃ with 3 equiv of PMe₃-*d*₉ (eq 3). If a dissociative mechanism were operative,

(1) (a) Boese, R.; Finke, N.; Henkelmann, J.; Maier, G.; Paetzold, P.; Reisenauer, H. P.; Schmid, G. *Chem. Ber.* **1985,** *118,* 1644−1654. (b) Boese, R.; Finke, N.; Keil, T.; Paetzold, P.; Schmid, G. *Z. Naturforsch., B* **1985,** *40,* 1327−1332. (c) Hoic, D. A.; Wolf, J. R.; Davis, W. M.; Fu, G. C. *Organometallics* **1996,** *15,* 1315−1318.

(2) For leading references, see: March, J. *Advanced Organic Chemistry*; Wiley: New York, 1992; Chapter 13.

(3) For leading references, see: Boulton, A. J.; McKillop, A. In *Comprehensive Heterocyclic Chemistry*; Boulton, A. J., McKillop, A., Eds.; Pergamon: New York, 1984; Vol. 2, Chapter 2.02.

(4) Hoic, D. A.; Davis, W. M.; Fu, G. C. *J. Am. Chem. Soc.* **1995,** *117,* 8480−8481.

(5) Herberich (Herberich, G. E.; Greiss, G.; Heil, H. F.; Muller, J. *J. Chem. Soc., Chem. Commun.* **1971,** 1328−1329) and Ashe (Ashe, A. J., III; Butler, W.; Sandford, H. F. *J. Am. Chem. Soc.* **1979,** *101,* 7066−7067) have established that boratabenzenes (**2**) which are π-bound to transition metals can undergo nucleophilic aromatic substitution.

(6) For a review of boratabenzene chemistry, see: Herberich, G. E.; Ohst, H. *Adv. Organomet. Chem.* **1986,** *25,* 199−236.

(7) For applications of boratabenzene-metal complexes in catalysis, see: (a) Bazan, G. C.; Rodriguez, G.; Ashe, A. J., III; Al-Ahmad, S.; Muller, C. *J. Am. Chem. Soc.* **1996,** *118,* 2291−2292. (b) Bonnemann, H.; Brijoux, W.; Brinkmann, R.; Meurers, W. *Helv. Chim. Acta* **1984,** *67,* 1616−1624.

(8) For the synthesis and isolation of alkali metal 1-substituted boratabenzenes, see: (a) Li(C₅H₅BPh): Ashe, A. J., III; Shu, P. *J. Am. Chem. Soc.* **1971,** *93,* 1804−1805. (b) Na(C₅H₅BPh), Na(C₅H₅BMe), K(C₅H₅BPh), K(C₅H₅BMe): Herberich, G. E.; Becker, H. J.; Carsten, K.; Engelke, C.; Koch, W. *Chem. Ber.* **1976,** *109,* 2382−2388. (c) Li(C₅H₅BNMe₂): Herberich, G. E.; Schmidt, B.; Englert, U.; Wagner, T. *Organometallics,* **1993,** *12,* 2891−2893. (d) Li(C₅H₅BMe), Li(C₅H₅BCMe₃), Li(C₅H₅BNMe₂), Li(C₅H₅BNEt₂), Li(C₅H₅BOCMe₂CMe₂OSiMe₃), Li(C₅H₅BOCMe₂CMe₂-OLi): Herberich, G. E.; Schmidt, B.; Englert, U. *Organometallics* **1995,** *14,* 471−480. (e) Li(C₅H₅BN(*i*-Pr)₂), Li(C₅H₅BNMeBn): Ashe, A. J., III; Kampf, J. W.; Muller, C.; Schneider, M. *Organometallics* **1996,** *15,* 387−393.

(9) Synthesized in three steps from commercially available 1-trimethylsilyl-1,4-pentadiyne (ref 1c). Preliminary experiments indicate that other borabenzene−ligand complexes can also be used in certain instances.

(10) (a) We agree with a referee that, a priori, the borabenzyne mechanism is the least likely of these three possibilities. (b) We have also considered a radical process involving electron transfer (for a review, see: Norris, R. K. In *Comprehensive Organic Chemistry*; Trost, B. M., Ed.; Pergamon: New York, 1991; Vol. 4, Chapter 2.2.). The highly reproducible kinetics that we observe for the reaction of borabenzene-PMe₃ with lithium trimethylsilylacetylide, essentially independent of the presence or absence of light or oxygen, suggests, however, that a radical pathway is not operative.

(11) It is important to note that we have not detected the presence of an intermediate in any of the reactions of borabenzene-PMe₃ with lithium trimethylsilylacetylide that we have monitored by NMR spectroscopy.
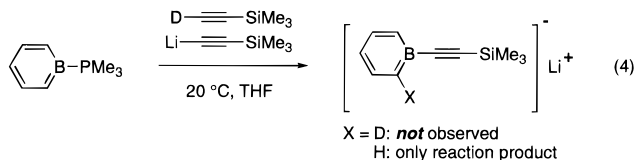
(12) Because a trace of an impurity can catalyze substitution reactions of borabenzene-PMe₃ (Stockman, K. Unpublished results), it is necessary to crystallize and then sublime borabenzene-PMe₃ in order to obtain reproducible kinetic data.

Scheme 1. Three Possible Mechanisms for Nucleophilic Aromatic Substitution of Borabenzene-PMe$_3$
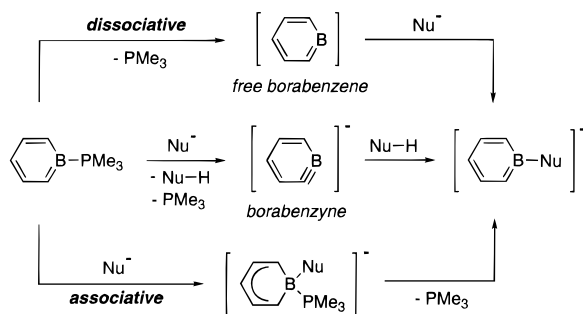
then exchange of borabenzene-bound PMe$_3$ with free PMe$_3$-d_9 should occur under the typical reaction conditions. However, no release of PMe$_3$ is observed, a result which rules out the dissociative pathway for substitution (Scheme 1).
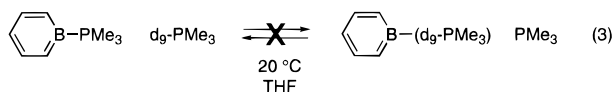
Substitution via a borabenzyne intermediate represents another potential mechanism for the reaction of borabenzene-PMe$_3$ with highly basic nucleophiles such as lithium trimethylsilylacetylide.[16] To address this possibility, we conducted this reaction in the presence of ~5 equiv of 1-deuterio-2-trimethylsilylacetylene (eq 4). If lithium borabenzyne were formed as an intermediate in the substitution process, then under these conditions deuterium should be present in the ortho position of the boratabenzene product. However, no deuterium incorporation is detectable by ^{2}H NMR spectroscopy.[17]

Although inconsistent with the borabenzyne or the dissociative mechanisms for nucleophilic aromatic substitution, the

above observations are consistent with an associative pathway (Scheme 1). To provide additional support for this mechanism, we have conducted the competition experiment illustrated in eq 5. π-Complexation of benzene derivatives to Cr(CO)$_3$ is known to facilitate nucleophilic aromatic substitution reactions,[18] and we have found that π-complexation of borabenzene-PMe$_3$ greatly enhances its reactivity toward substitution.
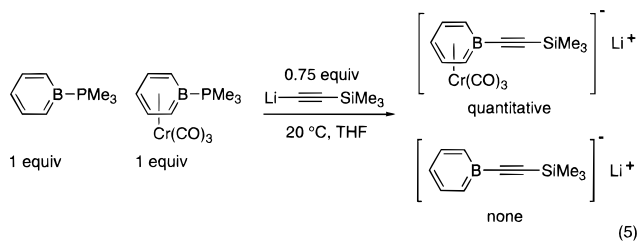
Finally, we have determined that the reaction of borabenzene-PMe$_3$ with lithium trimethylsilylacetylide is first-order in borabenzene-PMe$_3$ and half-order in lithium trimethylsilylacetylide. The half-order dependence on the concentration of lithium trimethylsilylacetylide likely reflects a requirement for deaggregation[19] prior to nucleophilic addition to borabenzene-PMe$_3$. The activation parameters for the substitution process, determined over a 271−318 K temperature range, are $E_a = 18.1$ kcal/mol, $\Delta H^\ddagger$ (296 K) = 17.5 kcal/mol, and $\Delta S^\ddagger$ (296 K) = −14.5 cal K^{-1} mol^{-1}.

In summary, we have developed a versatile synthesis of 1-substituted boratabenzenes from a single, readily available borabenzene precursor, thereby providing access to boratabenzenes with a wide range of steric and electronic properties. Our mechanistic studies of this reaction support an associative (addition−elimination) pathway for aromatic substitution. Current efforts in this laboratory are focused on further investigation of the fundamental chemistry of borabenzenes and on the development of catalysts which bear boratabenzenes as ligands.

Supporting Information Available: A listing of experimental procedures and compound characterization data (40 pages). See any current masthead page for ordering and Internet access instructions.

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(14) For computational studies of borabenzene, see: (a) Schulman, J. M.; Disch, R. L.; Sabio, M. I. *J. Am. Chem. Soc.* **1982**, *104*, 3785−3788. (b) Raabe, G.; Heyne, E.; Schleker, W.; Fleischhauer, J. *Z. Naturforsch., A* **1984**, *39*, 678−681. (c) Raabe, G.; Schleker, W.; Heyne, E.; Fleischhauer, J. *Z. Naturforsch., A* **1987**, *42*, 352−360. (d) Schulman, J. M.; Disch, R. L. *Organometallics* **1989**, *8*, 733−737. (e) Cioslowski, J.; Hay, P. J. *J. Am. Chem. Soc.* **1990**, *112*, 1707−1710.

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(16) For a discussion of benzyne chemistry, see ref 2.

(17) In an additional labeling study, we have established that when borabenzene-(PMe$_3$-d_9) is treated with lithium trimethylsilylacetylide, all of the deuterium remains in the phosphine methyl groups.

(18) For leading references, see: Semmelhack, M. F. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon: New York, 1995.

(19) For structural studies of lithium *tert*-butylacetylide, see: (a) Fraenkel, G. *Polym. Prepr., Am. Chem. Soc. Div. Polym. Chem.* **1986**, *27*, 132−133. (b) Fraenkel, G.; Pramanik, P. *J. Chem. Soc., Chem. Commun.* **1983**, 1527−1529. (c) Bauer, W.; Seebach, D. *Helv. Chim. Acta* **1984**, *67*, 1972−1988. (d) Geissler, M.; Kopf, J.; Schubert, B.; Weiss, E.; Neugebauer, W.; Schleyer, P. v. R. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 587−588.