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A Boronium Ion with Exceptional Electrophilicity**

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During our studies on aromatic borylation,[1] we considered the combination of a highly electrophilic R_2BNTf_2 reagent with a base that would neutralize the $HNTf_2$ byproduct of borylation without deactivating the electrophile. In principle, these requirements might be satisfied by 1,8-bis(dimethylamino)naphthalene (**1**), a hindered and exceptionally basic aniline that finds numerous applications as a basic catalyst or reagent due to its legendary lack of nucleophilicity.[2, 3] Strong electrophiles interact weakly, if at all, with the amine nitrogens, and very few examples are known where stable bonds to nitrogen can be formed between **1** and electrophilic groups larger than hydrogen.[2, 4-7] Among these exceptional cases, cyclic boronium structures **2** and **3** are relatively stable because the subunits BH_2 and BF_2 have minimal steric requirements.[5] However, the more hindered BMe_2 derivative **4** has not been detected and no analogous BR_2 structures are known.[5a, 8] In view of this long history, we were somewhat surprised to find that an adduct is readily formed simply upon mixing **1** with the 9-BBN bistriflimide reagent **5a** despite the transannular steric demands of the 9-BBN core and the need to form adjacent quaternary bonds to boron as well as nitrogen.[9, 10] The remarkable structural features and unusual reactivity of this adduct are the subject of the following communication.

The previously unreported **5a** was easily prepared from the commercially available 9-BBN dimer and bis(trifluoromethanesulfonyl)imide upon heating in toluene. Combination of the bulky boron reagent **5a** with a stoichiometric amount of **1** in CD_2Cl_2 at room temperature formed a deep red solution that turned colorless within seconds of mixing the reagents. Analysis of the resulting solution by ^{11}B NMR spectroscopy revealed a signal at δ 16.2 ppm, suggesting that a single tetracoordinate[11] boron atom is present in the product. The ^{19}F NMR spectrum showed a single peak at δ -79.4 ppm, which is characteristic of bistriflimide anion,[12] so the boron-containing fragment was thus identified to be a cation. The ^{1}H NMR spectrum suggested that the solution structure of the cation is highly symmetrical on the NMR timescale at room temperature. Only four groups of protons corresponding to the diamine subunit **1** were observed, including one sharp singlet for all four methyl groups, and a well-resolved (at 500 MHz) AMX system for the aromatic protons. Other peaks in the ^{1}H and ^{13}C NMR spectra were also consistent with a symmetrical time-averaged structure for the cation (for example, a single ^{13}C methyl peak at δ 57.1 ppm, and only 3 peaks for the 9-BBN cage carbons). Since the covalent adduct **6** (X = NTf_2) is ruled by observation of the bistriflimide anion,[12b] and the tricoordinate cationic borenium structure **7** (X = NTf_2) is not consistent with the observed ^{11}B NMR chemical shift, the most plausible structure for the species formed from **1** and **5a** is the exceptionally hindered boronium salt **8a**. Formation of **8a** may follow the logical sequence in Scheme 1, but alternative mechanisms have not been excluded.[13] Formation of >95% **8a** depends on

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the low nucleophilicity of the counterion, and only partial conversion to the boronium ion was observed when **5b** was used instead of **5a**. Thus, when equimolar **1** and the triflate reagent **5b** were mixed in CD_2Cl_2, the resulting solution showed both the starting **1** and the product **8b** (ca. 1.2:1 ratio by ^1H NMR assay).

The low temperature ^1H NMR behavior of **8a** in CD_2Cl_2 is complex and indicates the presence of unsymmetrical species. Decreasing the temperature broadens the ^1H NMR singlet corresponding to the N-methyl groups, until it turns into a broad set of at least three maxima that are not fully resolved even at -80°C. Additional information about the solution structure is provided by the very different shielding of the two bridgehead hydrogen atoms of the 9-BBN cage observed in the low temperature ^1H NMR spectra. While the spectrum taken at room temperature shows only one peak for both bridgehead protons, two distinct resonances are observed at -80 °C. One of the bridgehead hydrogens gives rise to a peak at an unremarkable δ 1.57 ppm, while the other hydrogen appears at δ 0.33 ppm. Such prominent shielding by the aromatic ring is consistent with the 9-BBN cage being tilted toward one side of the naphthalene plane to place the shielded proton above the aromatic **π**-system.

Slow cooling of the solution of **8a** in a mixture of CH_2Cl_2 and hexanes produced large platelike crystals, suitable for X-ray diffraction studies.[14] Due to strain imposed by the hindered environment, the structure of **8a** is non-symmetrical, the B-N bonds are very long, and both the 9-BBN cage and the bis(dimethylamino)naphthalene unit are severely twisted. While the C15-B1-C19 angle (106°) and C-B bond lengths (1.63 Å, B1-C15; 1.61 Å, B1-C19) are within the expected range for 9-BBN derivatives,[9a, 15] the C20-C19-C15-C22 and C18-C19-C15-C16 dihedral angles are in excess of 10°. Furthermore, strong distortion of the diamine base is evidenced by the N2-C9-C1-N1 dihedral angle of 28.9°, compared to 20.3° in **1**.[16] On the other hand, the aniline N⋯N distance in **8a** (2.65 Å) is substantially shorter than that reported for **1** (2.79 Å), and only slightly exceeds that in salts of protonated **1**, such as the sulfonimide salt **1·HNMs$_2$** (2.60 Å).[17]

The arrangement of the 9-BBN cage in crystals of **8a** is also noteworthy. The bridgehead carbons C15 and C19 are quite distinct, and C15 is pseudo-axial with respect to the distorted half-chair boron heterocycle. This places C15-H above the aromatic **π**-system, consistent with the low temperature ^1H NMR result indicating substantial shielding of one of the bridgehead protons. Another prominent structural detail is the length of the B-N bonds (B1-N1 1.72 Å; B1-N2 1.73 Å), compared to values of 1.58-1.60 Å in simpler boronium cations such as $[H_2B(NMe_3)(MeIm)]^+$ or $[H_2B(NH_2Me)(MeIm)]^+$ (MeIm = 1-methylimidazole).[18,19] Since the 1.72-1.73 Å distance greatly exceeds the sum of covalent radii for B and N atoms (1.55 Å),[20] the calculated Pauling bond order for both B-N bonds in **8a** is only ca. 0.55.[21]

The unusual structural features prompted computational modeling of the cation **8a**.[22a] Gas phase geometry optimization at the M06-2X/6-31G(d,p) level produced a structure that is in close agreement with the X-ray data (for example, B-N bond lengths are within 0.01 Å of the experimental values).[22b] NBO analysis[22c] performed on the optimized structure indicates that the boron atom carries the bulk of the positive charge (NBO charge 0.97), and Wiberg bond orders of the two B-N bonds are 0.52 and 0.53.

It was also of interest to compare the interactions of other amines with the potent Lewis acid **5a** in solution. When triethylamine was combined with **5a** in CD_2Cl_2, clean formation of the borenium ion **10** was observed (Scheme 2). No evidence for a boronium structure **11** was detected, even when excess triethylamine was used. The borenium character of 10 is substantiated by a strongly deshielded ^{11}B NMR peak at δ 85.1 ppm, as well as the bistriflimide anion peak at δ -79.5 ppm in the ^{19}F NMR spectrum,[12a] evidence that rules out the alternative structure **9**. For simplicity, **9** is tentatively shown as a precursor of **10**, although direct conversion from **5a** is not ruled out.

In contrast to triethylamine, 4-(dimethylamino)pyridine (DMAP) reacted with a stoichiometric amount of **5a** to afford mostly the isolable boronium cation **14** according to the ^{11}B NMR shift of δ 3.0 ppm (CD_2Cl_2, rt) along with traces of the borenium cation **13** (δ 66.5 ppm).[23] A much better way to generate **13** *in situ* was to protonate the amine borane complex **12** with Tf_2NH. This method confirmed the chemical shift of **13** and afforded solutions also containing relatively minor amounts of the boronium salt **14** (ca. 7-11:1 **13:14**). However, the more hindered 2,6-di-*tert*-butyl-4-methylpyridine did not interact with **5a** at room temperature according to ^{1}H and ^{11}B NMR assay.

The most remarkable feature of the borenium salt **10** is the absence of any stabilizing **π**-donor or *n*-donor substituents at boron, in contrast to **13** and to all previously reported persistent borenium ions generated in the condensed phase.[24, 25] A comparison of ^{11}B NMR shifts for **10** (δ 85.1 ppm) and **13** (δ 66.5 ppm) indicates extensive cation stabilization by **π** delocalization between DMAP and the boron atom. Other **π**-stabilized borenium cations have been observed in the ^{11}B chemical shift range of δ 58.2 to 66 ppm,[1, 24, 25] suggesting that **10** may be an exceptionally electrophilic member of the borenium family of structures.

High electrophilicity of boron cations is crucial for potential applications in electrophilic aromatic borylation.[1, 26] Thus, different combinations of the bistriflimide **5a** with basic amines generated reagents that react with electron-rich heterocycles to provide B-heteroaryl 9-BBN derivatives along with the protonated amines. The reagent consisting of **5a** and the non-complexing 2,6-di-*tert*-butyl-4-methylpyridine was the most reactive, and borylated N-methylindole in seconds at room temperature to afford **16a** (>95% conversion by NMR spectroscopy), while the cationic reagents **8a** and **10** required several hours at 50 °C for similar conversion. No added base was needed with **8a** or **10** because both reagents already contain a “built-in” base (proton sponge **1** and triethylamine, respectively) to neutralize the $HNTf_2$ that forms during borylation. On the other hand, neither **13** nor **14** reacted with N-methylindole under these conditions. [27]

While the boronium salt **8a** is less potent than the reagent from **5a** and 2,6-di-*tert*-butyl-4-methylpyridine, **8a** is a far more convenient borylating agent. Practical access to **8a** on gram scale is possible using a one-pot procedure from 9-BBN, **1**, and $HNTf_2$ without having to isolate the highly sensitive **5a** (see Supporting Information). Crystallized **8a** is much easier to handle compared to **5a**, and even survives up to a month of exposure to dry air (dessicator over Drierite), in contrast to **5a** or **10**. Furthermore, the aromatic borylation products obtained using **8a** are easy to isolate (Table 1). Crystalline products **16a-d** were obtained in high purity simply by extracting the reaction mixtures with hexanes, where neither the unreacted **8a** nor the byproduct **1·HNTf$_2$** is soluble, followed by solvent evaporation. This procedure minimizes the risk of competing protodeboronation using **8a**, but it is not feasible with the reagent from **5a** and 2,6-di-*tert*-butyl-4-methylpyridine due to differences in reagent solubility.

The structures of boranes **16a-d** were established by multinuclear NMR spectroscopy, as well as X-ray crystallography in the case of **16a**.[28] Borylation of N-methylindole afforded exclusively the 3-substituted regioisomer, in sharp contrast to the previously reported reaction with $B(C_6F_5)_3$, which produces the 2-borylated N-methylindole.[29] Pyrrole **15c** gave a mixture of mono-borylated regioisomers along with some of the diborylated **16c** using one equivalent of **8a** (ca. 80% conversion of **15c**), but two equivalents of the borylating agent cleanly produced the diborylated pyrrole **16c**. In the reaction with unsubstituted indole, the known N-borylation product was produced first,[30] followed by much slower C3-borylation to afford **16d**.

Several reactions of **8a** suggest that it is in equilibrium with the starting **1** and **5a**. Thus, equimolar **8a** and Tf_2NH produced the protonated diamine (**1·HNTf$_2$**) and released **5a** (NMR assay). Furthermore, reaction of **8a** with triethylammonium bistriflimide (Et_3NH^+ Tf_2N^-) yielded **1·HNTf$_2$** and the tricoordinate cation **10**, representing an unusual route from boronium to borenium ions involving the formal migration of the 9-BBN fragment to a different amine. These events can be understood if dissociation of **8a** to **1** + **5a** is the first step. The same dissociative mechanism may also help explain the borylations of Table 1, although the identity of the key boron electrophile is not clear. Depending on the timing of bond dissociation and borylation events, a role for the tricoordinate borenium ion **7**[1] or even a dicoordinate borinium ion[26a] cannot be ruled out at this point. The equilibrium between **8a** and **1** + **5a** is not directly observable by ^1H NMR spectroscopy, but the analogous process does occur in the related system **8b** and **1** + **5b**, containing the more nucleophilic triflate anion (*vide supra*).

To summarize, the covalent boron bistriflimide **5a** was used to access the unusual boron salts **8a** and **10** by exploiting the excellent leaving group ability of bistriflimide anion. The triethylamine-derived **10** expands the range of borenium salts observed in the condensed phase, proving that resonance delocalization of the positive charge is not required for a persistent borenium cation. The hindered boronium salt **8a** cautions against interpreting the name “proton sponge” too literally: in fact, this study proves that **1** can act as a chelating ligand for species much larger than a proton. Also, the unusual structure of **8a** raises a rhetorical question: is there a distinct boundary between the cationic species called “boronium” (tetra-substituted B), “borenium” (tri-substituted B), and “borinium” (di-substituted B), according to Nöth’s terminology?[24] While **8a** should be most appropriately called a boronium salt, the long B-N distances increase the “borinium-like” character, and the unusual reactivity adds a small hint of a borenium ion (**7**). Aside from the structural features of **8a**, the chemoselectivity of its formation also deserves attention. In view of earlier reports that strong electrophiles attack the aromatic system of **1**[3] or abstract hydride from one of the *N*-methyl groups,[3a, 31] it is quite intriguing that the reaction between **1** and **5a** proceeds to form **8a**, the most hindered of all plausible products. As evidenced by the electrophilic borylations (Table 1), the steric hindrance of **8a** is responsible for extraordinary reactivity compared to less hindered boronium salts such as **14**.[32]

Supplementary Material

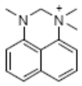
Refer to Web version on PubMed Central for supplementary material.

References

1. De Vries TS, Prokofjevs A, Harvey JN, Vedejs E. J Am Chem Soc. 2009; 131:14679–14687. [PubMed: 19824728]
2. Alder RW, Bowman PS, Steele WRS, Winterman DR. Chem Commun (London). 1968:723–724.
3. Reviews: Barner BA, Faler CA, Joullié MM. 1,8-Bis(dimethylamino)naphthalene e-EROS Encyclopedia of Reagents for Organic Synthesis. 10.1002/047084289X.rb144.pub2, and references therein; Pozharskii AF, Ozeryanskii VA. The Chemistry of Anilines, Part 1. Rappoport Z. John Wiley & Sons Ltd.Chichester2007:931–1026.
4. N-Monomethylation of 1,8-bis(dimethylamino)naphthalene: Alder RW, Goode NC. J Chem Soc Chem Commun. 1976:108–109.

5. a) Axtell DD, Cambell AC, Keller PC, Rund JV. J Coord Chem. 1976; 5:129–134.b) Onak T, Rosendo H, Siwapinyoyos G, Kubo R, Liauw L. Inorg Chem. 1979; 18:2943–2945.c) Keller PC, Rund JV. Inorg Chem. 1979; 18:3197–3199.d) Hartman JS, Shoemaker JAW. Polyhedron. 2000; 19:165–176.
6. Only one transition metal complex of 1,8-bis(dimethylamino)-naphthalene has been structurally characterized: Yamasaki T, Ozaki N, Saika Y, Ohta K, Goboh K, Nakamura F, Hashimoto M, Okeya S. Chem Lett. 2004; 33:928–929.
7. 1,8-Bis(dimethylamino)naphthalene as a proposed ligand for metals: Lucht BL, Bernstein MP, Remenar JF, Collum DB. J Am Chem Soc. 1996; 118:10707–10718.; Farzaneh F, Majidian M, Ghandi M. J Mol Catal A: Chem. 1999; 148:227–233.; Collman JP, Zhong M, Zhang C, Costanzo S. J Org Chem. 2001; 66:7892–7897. [PubMed: 11701055]
8. The BCl_2 analog has been claimed, but definitive evidence has not been reported (see reference 5a).
9. For 9-BBN-derived boronium salts containing relatively non-hindered pyridine ligands, see: Ma K, Bats JW, Wagner M. Acta Crystallogr Sect E: Struct Rep Online. 2001; E57:o846–o848.; Köster R, Grassberger MA. Justus Liebigs Ann Chem. 1968; 719:169–186.; Hünig S, Wehner I. Heterocycles. 1989; 28:359–363.
10. Cyclic aminoboranes derived from 1,8-diaminonaphthalene and 9-BBN: Bar-Haim G, Kol M. J Org Chem. 1997; 62:6682–6683.; Bar-Haim G, Shach R, Kol M. Chem Commun. 1997:229–230.
11. Nöth, H.; Wrackmeyer, B. Nuclear Magnetic Resonance Spectroscopy of Boron Compounds. Springer; Berlin: 1978.
12. Tf_2N^- salts: Arvai R, Toulgoat F, Langlois BR, Sanchez J-Y, Médebielle M. Tetrahedron. 2009; 65:5361–5368.; b) A single ^{19}F peak at δ -79.8 ppm is observed at -80 °C vs. δ -79.4 ppm at rt, typical of Tf_2N^- anion. Covalent bistriflimide **5a** gives a signal at δ -70.0 ppm.
13. Alternatives to consider include an electron transfer process, a process involving borinium intermediates, or a direct displacement mechanism from **5a** and **1** to **8a** via a transition state that resembles **7**.
14. See Supporting Information for X-ray crystallography details. **CCDC-791459** contains the supplementary crystallographic data for **8a**. The cif file can be obtained free of charge from Cambridge Crystallographic Data Center (http://www.ccdc.cam.ac.uk); b) The counterion displays a number of close contacts to the cation, the shortest being the distance between a bistriflimide oxygen and an *N*-methyl hydrogen (2.49Å).
15. Yalpani M, Boese R, Köster R. Chem Ber. 1990; 123:1275–1283.Brock CP, Fu Y, Niedenzu K, Nöth H. Main Group Met Chem. 1992; 15:53–60.Wrackmeyer B, Schwarze B, Milius W. J Organomet Chem. 1995; 489:201–205.
16. Einspahr H, Robert J-B, Marsh RE, Roberts JD. Acta Crystallogr Sect B: Struct Crystallogr Cryst Chem. 1973; 29:1611–1617.
17. Henschel D, Moers O, Lange I, Blaschette A, Jones PG. Z Naturforsch, B: J Chem Sci. 2002; 57b: 777–790.
18. Fox PA, Griffin ST, Reichert WM, Salter EA, Smith AB, Tickell MD, Wicker BF, Cioffi EA, Davis JH Jr, Rogers RD, Wierzbicki A. Chem Commun. 2005:3679–3681.Soutullo MD, Odom CI, Smith AB, McCreary DR, Sykora RE, Salter EA, Wierzbicki A, Davis JH Jr. Inorg Chim Acta. 2007; 360:3099–3102.
19. A B-N bond distance of 1.61 Å has been reported for a 9-BBN-derived boronium ion with bipyridyl as the nitrogen ligand (ref. 9a).
20. Cordero B, Gómez V, Platero-Prats AE, Revés M, Echeverría J, Cremades E, Barragán F, Alvarez S. Dalton Trans. 2008:2832–2838. [PubMed: 18478144]
21. Pauling L. J Am Chem Soc. 1947; 69:542–553.
22. a) Gaussian 09, Revision A.02 suite of computational programs was used. See Supporting Information for full details; Zhao Y, Truhlar DG. Theor Chem Acc. 2008; 120:215–241.; NBO Version 3.1, Glendening ED, Reed AE, Carpenter JE, Weinhold F.
23. Narula CK, Nöth H. Inorg Chem. 1985; 24:2532–2539.
24. a) Piers WE, Bourke SC, Conroy KD. Angew Chem Int Ed. 2005; 44:5016–5036.b) Kölle P, Nöth H. Chem Rev. 1985; 85:399–418.

25. Reports of π-stabilized borenium cations published after ref. 24a: Uddin MK, Nagano Y, Fujiyama R, Kiyooka S, Fujio M, Tsuno Y. Tetrahedron Lett. 2005; 46:627–630.; Chiu C, Gabbaï FP. Organometallics. 2008; 27:1657–1659.; Matsumoto T, Gabbaï FP. Organometallics. 2009; 28:4252–4253.; Other recently reported borenium ions: Kato T, Tham FS, Boyd PDW, Reed CA. Heteroatom Chem. 2006; 17:209–216.; Bonnier C, Piers WE, Parvez M, Sorensen TS. Chem Commun. 2008:4593–4595.; Dureen MA, Lough A, Gilbert TM, Stephan DW. Chem Commun. 2008:4303–4305.; Ott H, Matthes C, Ringe A, Magull J, Stalke D, Klingebiel U. Chem Eur J. 2009; 15:4602–4609. [PubMed: 19308982] ; see also ref. 26a.
26. Del Grosso A, Pritchard RG, Muryn CA, Ingleson MJ. Organometallics. 2010; 29:241–249.. For a review of transition metal catalyzed borylation, see I A, Mkhalid I, Barnard JH, Marder TB, Murphy JM, Hartwig JF. Chem Rev. 2010; 110:890–931. [PubMed: 20028025]
27. The reagent from **5a** + 2,6-di-*tert*-butyl-4-methylpyridine (DTBMP) did not borylate toluene or benzofuran at rt, but *N,N*-diethylaniline reacted slowly with **5a** + DTBMP at rt, or with **8a** at 50 °C.
28. See Supporting Information for X-ray crystallography details. **CCDC-791460** contains the supplementary crystallographic data for **16a**. The cif file can be obtained free of charge from Cambridge Crystallographic Data Center (http://www.ccdc.cam.ac.uk).
29. Focante F, Camurati I, Nanni D, Leardini R, Resconi L. Organometallics. 2004; 23:5135–5141.
30. Wrackmeyer B, Maisel HE, Schwarze B, Milius W, Köster R. J Organomet Chem. 1997; 541:97–107.Wrackmeyer B, Schwarze B. J Organomet Chem. 1997; 534:207–211.
31. A cationic product *i* has been reported from treatment of **1** with the potent electrophile $B(C_6F_5)_3$: Di Saverio A, Focante F, Camurati I, Resconi L, Beringhelli T, D'Alfonso G, Donghi D, Maggioni D, Mercandelli P, Sironi A. Inorg Chem. 2005; 44:5030–5041. [PubMed: 15998031] .



i

32. Boronium salt **14** is more stable than **8a**, but more reactive than unhindered analogues (ref. 24b): methanolysis of **14** or **8a** occurs to ca. 90% conversion within ca. 14 h at 50 °C or 10 min at rt, respectively.

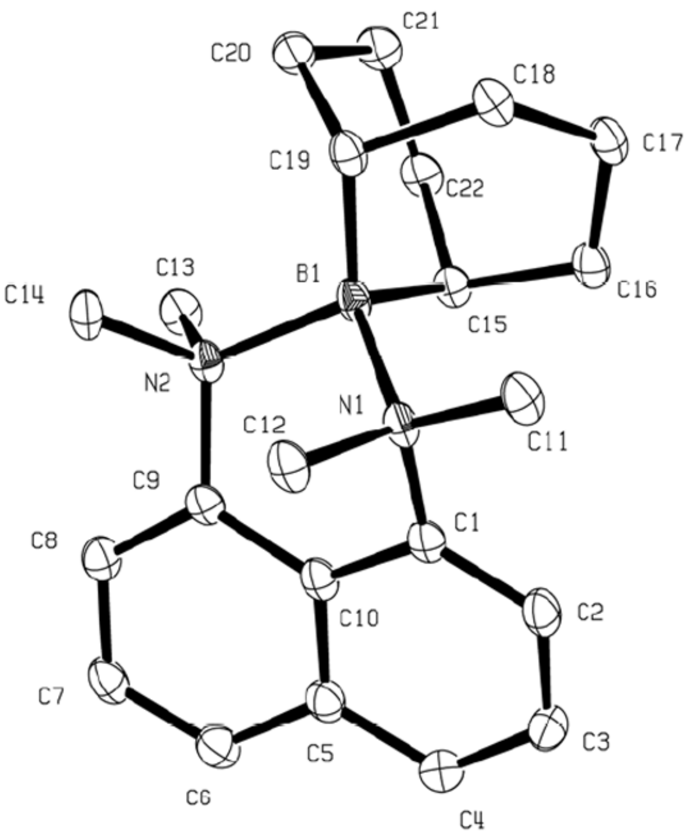
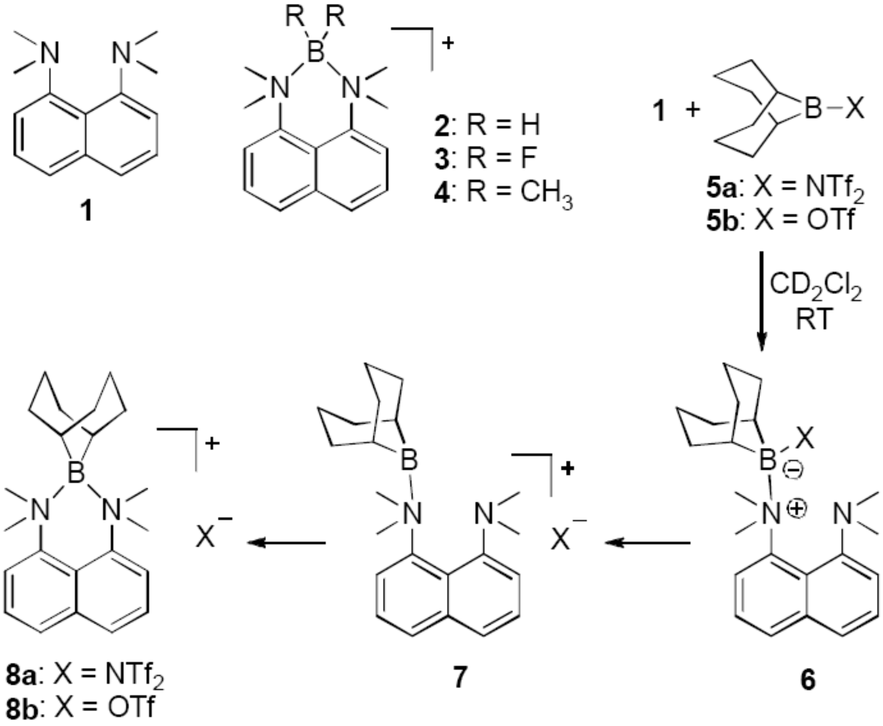
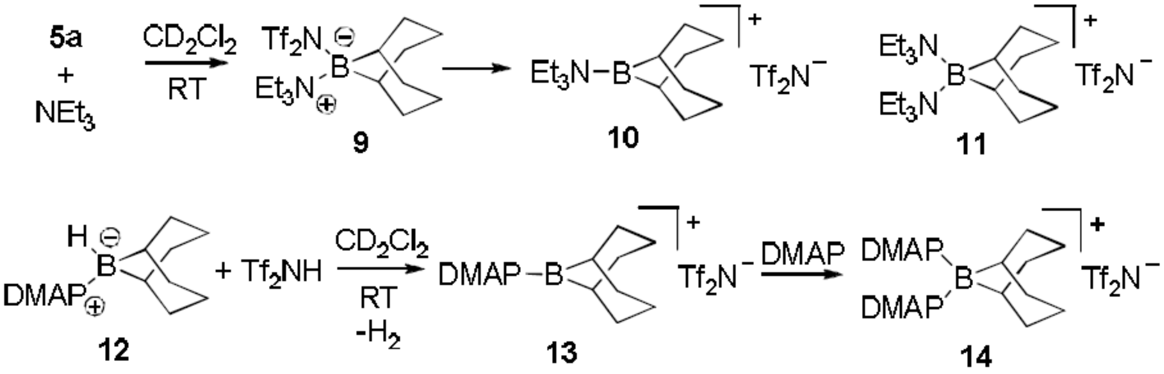


Figure 1.
ORTEP drawing of **8a** (50% probability thermal ellipsoids). The counterion and hydrogen atoms are omitted for clarity.


1
2: R = H
3: R = F
4: R = CH3
1 + B−X
5a: X = NTf2
5b: X = OTf
CD2Cl2
RT
6
7
X−
8a: X = NTf2
8b: X = OTf

Scheme 1.

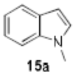
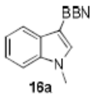
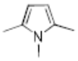
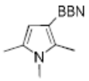
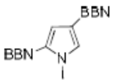
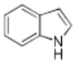
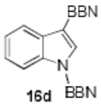

5a
+
NEt3
CD2Cl2
RT
Tf2N
B
Et3N
9
Et3N–B
Tf2N−
10
Et3N
B
Et3N
Tf2N−
11
H
B
DMAP
12
+ Tf2NH
CD2Cl2
RT
-H2
DMAP–B
Tf2N−
13
DMAP
DMAP
B
DMAP
Tf2N−
14

Scheme 2.

Table 1

Borylation of nitrogen heterocycles using **8a**.[a]

$$\text{Het-H} + \mathbf{8a} \xrightarrow[50\,^{\circ}\text{C}]{\text{CH}_2\text{Cl}_2} \text{Het-BBN} + \mathbf{1}\cdot\text{HNTf}_2$$

Het-H	Product, Het-BBN	Time	Yield, %
 **15a**	 **16a**	1.5h	96
 **15b**	 **16b**	1.5h	98
 **15c**	 **16c**	3.5h	97[b]
 **15d**	 **16d**	5.5d	97[b]

[a] 1.05 equiv of **8a**; CH_2Cl_2; 50 °C.

[b] 2.10 equiv of **8a**