Dalton Transactions

Frontier

Efficient synthetic methods for the installation of boron-nitrogen bonds in conjugated organic molecules

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

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Polycyclic aromatic hydrocarbons in which one or more CC units have been replaced by isoelectronic BN units have attracted interest as potentially improved organic materials in various devices. This promise has been hampered by a lack of access to gram quantities of these materials. However, the exploitation of keystone reactions such as ring closing metathesis, borylative cyclization of amino styrenes and electrophilic borylation has lead to strategies for access to workable amounts of material. These strategies can be augmented by judicious postfunctionalization reactions to diversify the library of materials available. This Frontier article highlights some of the recent successes and shows that the long promised applications of BN-doped PAHs are beginning to be explored in a meaningful way.

Introduction

Interest in polycyclic organic molecules with extended conjugation has intensified in the last few decades due to the need for robust conductive materials for applications in organic light emitting diodes (OLEDs),[1] organic field effect transistors (OFETs)[2] and organic photovoltaics (OPVs).[3-5] A subfield of this research area involves materials in which one or more -C=C- units within an extended conjugated framework has been replaced with the isoelectronic and isosteric -B=N- diatomic. The idea is that the introduction of BN units will not significantly affect the steric attributes of the molecule, but will perturb the electronic structure and distribution within the molecule[6, 7] through introduction of a dipole, offering a means of tuning the molecular properties relevant to function within such devices as those mentioned above.

The BN for CC substitution strategy has its roots in the seminal discovery of borazine by Stock and Pohland in 1926,[8] and was first explored in detail by Dewar and co-workers beginning in the late 1950's.[9] However, activity in the area has never been so intense as in the last decade, as summarized in recent reviews,[7, 10] and there are an ever-increasing number of examples of new BN analogs of all-carbon conjugated frameworks. Despite these advances, and the assertion in many of the reports of the potential applications for the BN isosteres in devices requiring organic semiconductors, until recently, few reports actually demonstrate their efficacy in this regard. Furthermore, it is fair to say that real applications of such materials remain a futuristic proposition.

Why is this? Issues of stability and sensitivity to ambient conditions are important, but can be overcome by various strategies.[11] We opine that a primary reason stems from the lack of general, high yielding synthetic routes to significant quantities of these materials. This is required not only to adequately assess the performance of these materials in device applications but also to give realistic hope for widespread applications—even if only in niche markets. In order to assess and realize the potential of such materials, advances in synthesis are therefore required. In this Frontier article, we highlight promising methodologies from the past few years that illustrate the progress being made in addressing the problems of synthetic generality, scalability and scope.

Methods for 1,2-azaborine synthesis

As benzene is the fundamental building block for all-carbon polycyclic aromatic hydrocarbons (PAHs), the C_4BN core of 1,2-azaborines can be regarded as the foundation of larger BN substituted extended systems. Access to the 1,2-azaborine heterocycle relies mainly on two routes that are most commonly employed (Scheme 1). In the first, a ring closing metathesis reaction establishes the 6 membered ring and dehydrogenation using Pd/C aromatizes the ring system. First developed by Ashe and Fang,[12] the methodology was further refined by Liu and co-workers to the extent that it could be carried out with readily available starting materials on a multigram scale to give the cornerstone complex **1** shown in Scheme 1a.[13] This compound is a convenient and versatile starting material for a wide range of derivatives with various groups at B in the 1,2-azaborine function. Postfunctionalization of a key building block represents a fruitful strategy for expanding the range of derivatives available for BN analogs of cyclic aromatic hydrocarbons, and this is a prime example of how such methodology can be used to access a library of compounds. One drawback of the RCM route shown in Scheme 1a is that functionalization of the carbon positions of the 1,2-azaborine ring is not readily accommodated. However,

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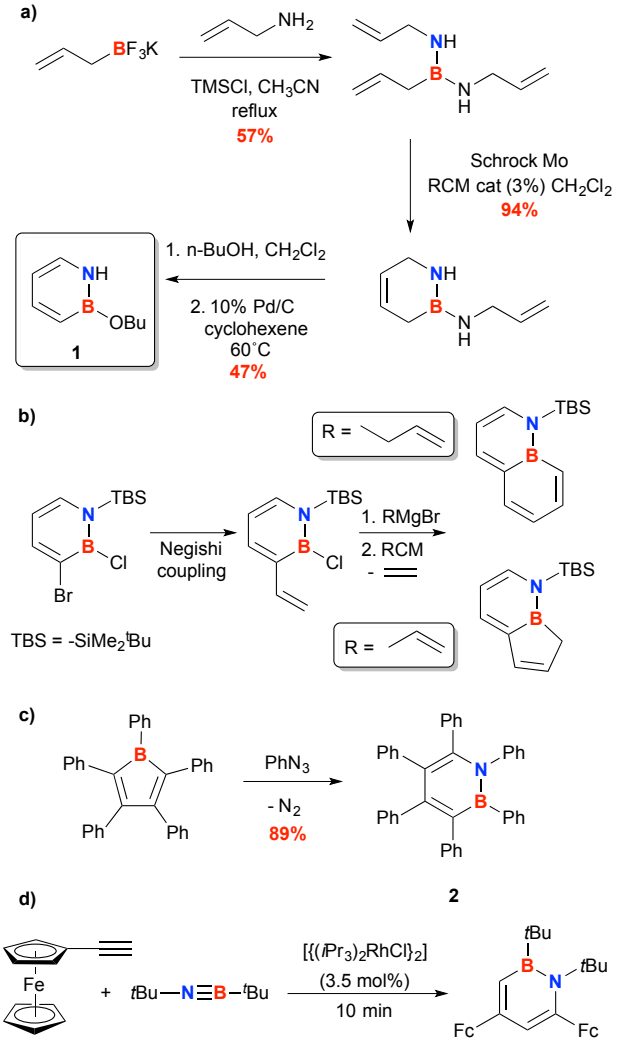
a recent report from the Liu group has shown that iridium catalyzed borylation of the carbon next the nitrogen in the 1,2-azaborine ring is possible[14] and the position next to boron is susceptible to electrophilic substitution.[15] The Liu group has used the latter reaction to elaborate 1,2-azaborines into bicyclic BN isosteres of naphthalene and the indenyl anion that are otherwise difficult to access (Scheme 1b).[16] These methods for functionalizing the positions alpha to the heteroatoms have been combined to prepare a monomer suitable for the synthesis of regioregular azaborine oligomers and a polymer that is a 1,2-azaborine analog of a polyphenylene material through Suzuki-Miyaura polycondensation methodology.[17] Thus, although still in its infancy, the elaboration of readily available 1,2-azaborine building blocks into more complex BN PAH molecules is an extremely promising strategy for accessing these materials.

More comprehensive substitutions about the 1,2-azaborine ring can alternatively be addressed using a second common route to this ring system, namely ring expansion reactions of antiaromatic borole rings via reaction with organic azides

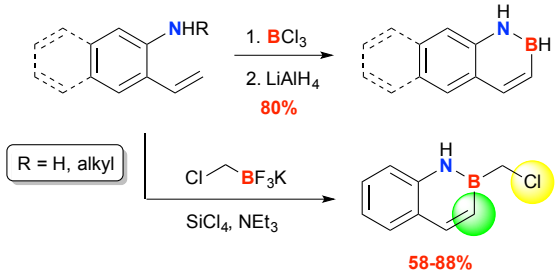


Scheme 1. a) Synthesis of 1,2-azaborines using ring closing metathesis/dehydrogenation. b) Postfunctionalization of 1,2-azaborines to prepare BN isosteres of bicyclic molecules. c) Synthesis of highly substituted 1,2-azaborines using the ring expansion of boroles. d) Direct synthesis of a ferrocenyl substituted 1,2-azaborine by rhodium catalysed coupling.

(Scheme 1c). While this method is to some extent limited by the need to access the borole starting materials, recent progress in the chemistry of antiaromatic boroles[18] has made their use as reagents more convenient. This route provides for the synthesis of heavily substituted 1,2-azaborine derivatives exemplified by the hexaphenyl complex **2**, prepared recently by the Braunschweig group.[19] The mechanism of this reaction has been explored by Martin et al.,[20] and it has been further exploited to prepare novel BN-azo dye complexes through manipulation of the steric attributes of the reagents employed.[21] The potential for postfunctionalization of compounds like **2** is high, given that the synthesis of boroles can be readily adapted to incorporate a variety of aryl groups on both the carbon and boron atoms of the borole ring.[18] Finally, in a novel rhodium-catalysed method[22] the ferrocenyl substituted 1,2-azaborine was prepared on a gram scale by coupling two equivalents of ethynyl ferrocene with an imino borane (Scheme 1d). While the methodology may in the long run be limited by the availability of iminoborane coupling partners, this direct synthesis from multiple components is a significant development in 1,2-azaborine synthesis.

Borylative cyclization of amino styrenes

A series of recent studies has expanded the scope of a method first introduced in Dewar's pioneering studies[23] on BN analogs of aromatic hydrocarbons. The borylative cyclization of ortho amino styrenes can lead directly to BN analogs of naphthalenes and anthracenes[24] in reasonably high yielding reactions (Scheme 2). This is related to the electrophilic borylation strategies described in the next section in that the amine reacts with the boron halide reagent to establish and anchor the B-N linkage, and the Lewis acidity of the boron centre in this intermediate then facilitates the formation of the final BN heterocycle. There is significant versatility in this synthesis in that a variety of R groups on the



Scheme 2. Borylative cyclization of *ortho* amino styrenes.

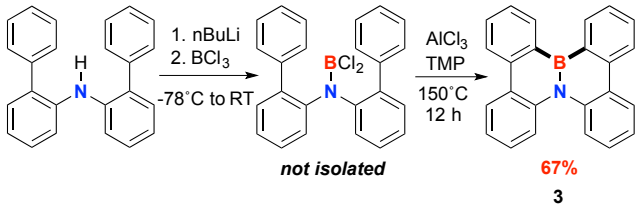
amine function can be accommodated, and the substituent on boron can also be manipulated. For example, Molander *et al.* have prepared an extensive library of naphthyl azaborines by incorporating the chloromethyl function on boron as shown in yellow in Scheme 2;[25, 26] this group may then be functionalized through nucleophilic substitution or coupling reactions. Furthermore, they have demonstrated that the position next to boron can be subjected to cross coupling reactions to institute both aromatic[27] and alkyl[28] substituents in this

position (shown in green, Scheme 2). This again illustrates that postfunctionalization of a key building block can be an effective strategy to a range of BN materials.

Electrophilic borylation

The above methods are reliable but focus on relatively simple families of BN PAHs. Extended structures present more difficult synthetic challenges for which the above-described methods are generally not effective. Furthermore, as structures become more extensive, the number of possible BN isosteres grows dramatically and methodologies that target specific isomers become a potential issue. For example, even for the simplest PAH, naphthalene, there are six possible isomers that contain BN units; Scheme 2 shows just one these. The positioning and orientation of BN units within a PAH framework potentially has an influence on the redox and photophysical properties of the isostere[29] and so as structures become more complex, the issue of selectively targeting a specific BN isomer comes to the fore—and remains a challenge.

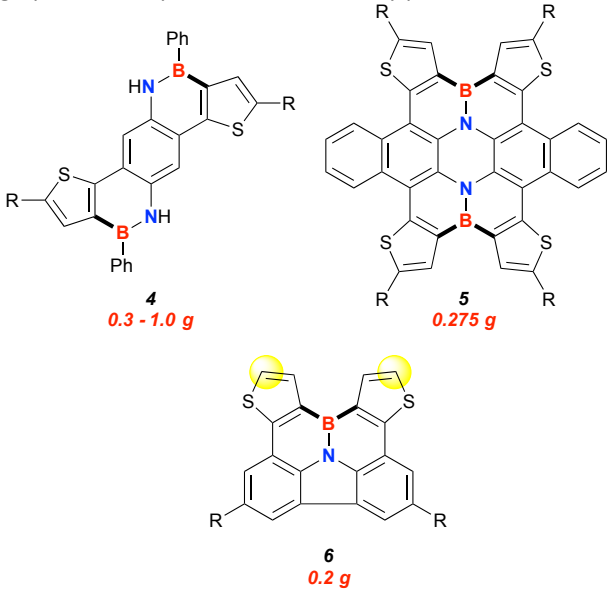
Electrophilic borylation is not a new methodology, having been employed by Dewar and co-workers in the early days of BN PAH chemistry.[9] However, recent activity that creatively applies this electrophilic borylation strategy has resulted in significant progress for the assembly of large BN PAH molecules. Hatakeyama and Nakamura[30] demonstrated the promise of this strategy in their gram scale synthesis of the BN-fused PAH molecule shown in Scheme 3. Although the conditions for the ring closure are fairly harsh, compound **3** can be prepared in moderate yield in > 3 g amounts. As a result, this was one of the first studies to report conductivity measurements on a BN PAH.



Scheme 3. Synthesis of 4b-aza-12b-boradibenzo[*g*,*p*]chrysene; TMP = 2,2,6,6-tetramethylpiperidine. The bonds in **bold** are forged by electrophilic borylation.

These authors subsequently adapted this strategy to prepare an azaboradibenzo[6]helicene derivative of **3** whose conducting properties were dependent on the homochiral form of the compound.[31] The observed carrier inversion behaviour was attributed to the differences in crystal packing observed in the racemate vs. the single enantiomer of the compound. The thorough assessment of the properties of these compounds, and their performance in devices, were made possible by the efficient access to multigram quantities using this effective methodology.

This synthetic strategy is now being used by other groups to access more complex BN PAHs with semi-embedded BN units (Scheme 4). The embedding of the BN fragment is important because of the stability towards ambient air and moisture this engenders,[32] and even partially embedded BN units less prone to hydrolysis.[33] Some recent examples of such materials are given in Scheme 4. The frameworks necessary to enact electrophilic borylation are assembled using standard C-C coupling chemistry and the crucial B-C bond forming reaction sequence of Scheme 3 is applied in the last step to afford significant quantities of these relatively complex materials. Compound **4** is a heteroacene compound,[34] while compounds **5**[35] and **6**[36] are heterosuperbenzenes that model BN-doped graphene. Compound **6** can be readily postfunctionalized



Scheme 4. Other BN PAHs prepared using electrophilic borylation. The bonds in **bold** are formed by this reaction and the amount of material available from the published syntheses is given.

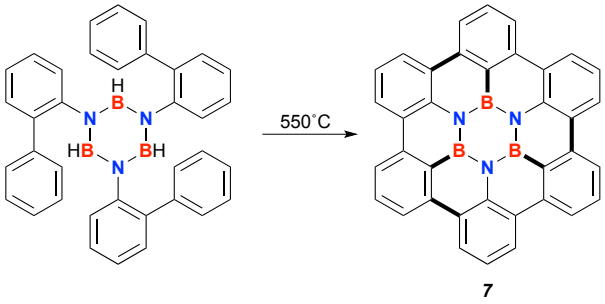
at the positions highlighted by yellow circles through bromination and C-C coupling chemistry, indicating that the partial embedding of the BN function allows it to withstand the conditions of these reactions. The facility and versatility of this electrophilic borylation reaction is illustrated by a growing number of examples[29, 37-41] of its application in the past year and offers much promise for the large scale synthesis of large BN-doped PAH materials.[42]

Conclusions and future outlook

Much progress has been made even in the last 5 years concerning the synthesis of BN doped PAH materials. The advent of keystone reactions such as ring closing metathesis, borylative cyclization of amino styrenes and electrophilic borylation can be augmented with a variety of postfunctionalization strategies to access meaningful amounts of material. This has allowed for not only their full characterization, but an assessment of their promise as materials in device applications.

Challenges remain, however, particularly for the efficient, scalable synthesis of BN-doped PAHs with the BN units *fully* embedded in the PAH framework. Few examples[32, 43] of such

compounds exist, and their laborious synthesis has prevented extensive assessment of their properties and development of their chemistry. The challenges involved in the preparation of such compounds are illustrated by the recent report from the Bettinger group in which they detail the synthesis of the heterosuperbenzene **7**, shown in Scheme 5.[44] While a remarkable achievement, only very small amounts of pure material were obtainable using a method involving pyrolysis of a triaryl borazine precursor at 550˚C to form the B-C and C-C bonds shown in bold in Scheme 5. Photochemical routes were also explored,[45] and hold some promise, but clearly



Scheme 5. BN-hexa-peri-hexabenzocoronene.

development of new keystone reactions needs to occur before gram quantities of such materials are available.

Acknowledgements

Funding for this work was provided by NSERC of Canada in the form of a Discovery Grant and an Accelerator Supplement to W.E.P. W.E.P. also thanks the Canada Research Chair secretariat for a Tier I CRC (2013–2020).

Notes and references

1. M. A. Wolak, J. Delcamp, C. A. Landis, P. A. Lane, J. Anthony and Z. Kafafi, *Adv. Funct. Mater.*, 2006, **16**, 1943-1949.
2. G. S. Tulevski, C. Nuckolls, A. Afzali, T. O. Graham and C. R. Kagan, *Appl. Phys. Lett.*, 2006, **89**, 183101.
3. Y. Shu, Y.-F. Lim, Z. Li, B. Purushothaman, R. Hallani, J. E. Kim, S. R. Parkin, G. G. Malliaras and J. E. Anthony, *Chem. Sci.*, 2011, **2**, 363-368.
4. A. A. Gorodetsky, M. Cox, N. J. Tremblay, I. Kymissis and C. Nuckolls, *Chem. Mater.*, 2009, **21**, 4090-4092.
5. J. E. Anthony, *Nat Mater*, 2014, **13**, 773-775.
6. Z. Liu and T. B. Marder, *Angew. Chem. Int. Ed.*, 2008, **47**, 242-244.
7. P. G. Campbell, A. J. V. Marwitz and S.-Y. Liu, *Angew. Chem. Int. Ed.*, 2012, **51**, 6074-6092.
8. A. Stock and E. Pohland, *Ber. Dtsch. Chem. Ges.*, 1926, **59**, 2210-2215.
9. M. J. S. Dewar, V. P. Kubba and R. Pettit, *J. Chem. Soc.*, 1958, 3073-3076.
10. M. J. D. Bosdet and W. E. Piers, *Can. J. Chem.*, 2009, **87**, 8-29.
11. J. F. Araneda, B. Neue and W. E. Piers, *Angew. Chem. Int. Ed.*, 2012, **51**, 9977-9979.
12. A. J. Ashe and Fang, *Org. Lett.*, 2000, **2**, 2089-2091.
13. E. R. Abbey, A. N. Lamm, A. W. Baggett, L. N. Zakharov and S.-Y. Liu, *J. Am. Chem. Soc.*, 2013, **135**, 12908-12913.
14. A. W. Baggett, M. Vasiliu, B. Li, D. A. Dixon and S.-Y. Liu, *J. Am. Chem. Soc.*, 2015, **137**, 5536-5541.
15. J. Pan, J. W. Kampf and A. J. Ashe, *Org. Lett.*, 2007, **9**, 679-681.
16. A. N. Brown, B. Li and S.-Y. Liu, *J. Am. Chem. Soc.*, 2015, **137**, 8932-8935.
17. A. W. Baggett, F. Guo, B. Li, S.-Y. Liu and F. Jäkle, *Angew. Chem. Int. Ed.*, 2015, **54**, 11191-11195.
18. H. Braunschweig and T. Kupfer, *Chem. Commun.*, 2011, **47**, 10903-10914.
19. H. Braunschweig, C. Hörl, L. Mailänder, K. Radacki and J. Wahler, *Chem. Eur. J.*, 2014, **20**, 9858-9861.
20. S. A. Couchman, T. K. Thompson, D. J. D. Wilson, J. L. Dutton and C. D. Martin, *Chem. Commun.*, 2014, **50**, 11724-11726.
21. H. Braunschweig, M. A. Celik, F. Hupp, I. Krummenacher and L. Mailänder, *Angew. Chem. Int. Ed.*, 2015, **54**, 6347-6351.
22. H. Braunschweig, K. Geetharani, J. O. C. Jimenez-Halla and M. Schäfer, *Angew. Chem. Int. Ed.*, 2014, **53**, 3500-3504.
23. M. J. S. Dewar and R. Dietz, *J. Chem. Soc.*, 1959, 2728-2730.
24. J. S. A. Ishibashi, J. L. Marshall, A. Mazière, G. J. Lovinger, B. Li, L. N. Zakharov, A. Dargelos, A. Graciaa, A. Chrostowska and S.-Y. Liu, *J. Am. Chem. Soc.*, 2014, **136**, 15414-15421.
25. G. A. Molander, S. R. Wisniewski and J. Amani, *Org. Lett.*, 2014, **16**, 5636-5639.
26. G. A. Molander, J. Amani and S. R. Wisniewski, *Org. Lett.*, 2014, **16**, 6024-6027.
27. G. A. Molander and S. R. Wisniewski, *J. Org. Chem.*, 2014, **79**, 6663-6678.
28. G. A. Molander, S. R. Wisniewski and K. M. Traister, *Org. Lett.*, 2014, **16**, 3692-3695.
29. X.-Y. Wang, A. Narita, X. Feng and K. Müllen, *J. Am. Chem. Soc.*, 2015, **137**, 7668-7671.
30. T. Hatakeyama, S. Hashimoto, S. Seki and M. Nakamura, *J. Am. Chem. Soc.*, 2011, **133**, 18614-18617.
31. T. Hatakeyama, S. Hashimoto, T. Oba and M. Nakamura, *J. Am. Chem. Soc.*, 2012, **134**, 19600-19603.
32. M. J. D. Bosdet, W. E. Piers, T. S. Sorensen and M. Parvez, *Angew. Chem. Int. Ed.*, 2007, **46**, 4940-4943.
33. B. Neue, J. F. Araneda, W. E. Piers and M. Parvez, *Angew. Chem. Int. Ed.*, 2013, **52**, 9966-9969.
34. X. Wang, F. Zhang, J. Liu, R. Tang, Y. Fu, D. Wu, Q. Xu, X. Zhuang, G. He and X. Feng, *Org. Lett.*, 2013, **15**, 5714-5717.
35. X.-Y. Wang, F.-D. Zhuang, R.-B. Wang, X.-C. Wang, X.-Y. Cao, J.-Y. Wang and J. Pei, *J. Am. Chem. Soc.*, 2014, **136**, 3764-3767.
36. X.-Y. Wang, D.-C. Yang, F.-D. Zhuang, J.-J. Liu, J.-Y. Wang and J. Pei, *Chem. Eur. J.*, 2015, **21**, 8867-8873.
37. X.-Y. Wang, F.-D. Zhuang, X.-C. Wang, X.-Y. Cao, J.-Y. Wang and J. Pei, *Chem. Commun.*, 2015, **51**, 4368-4371.
38. C. Ma, J. Zhang, J. Li and C. Cui, *Chem. Commun.*, 2015, **51**, 5732-5734.

39. G. Li, Y. Zhao, J. Li, J. Cao, J. Zhu, X. W. Sun and Q. Zhang, *J. Org. Chem.*, 2015, **80**, 196-203.
40. X. Liu, P. Wu, J. Li and C. Cui, *J. Org. Chem.*, 2015, **80**, 3737-3744.
41. B. Su, Y. Li, R. Ganguly, J. Lim and R. Kinjo, *J. Am. Chem. Soc.*, 2015, **137**, 11274-11277.
42. X.-Y. Wang, J.-Y. Wang and J. Pei, *Chem. Eur. J.*, 2015, **21**, 3528-3539.
43. M. J. D. Bosdet, W. E. Piers, T. S. Sorensen and M. Parvez, *Can. J. Chem.*, 2010, **88**, 426-433.
44. M. Krieg, F. Reicherter, P. Haiss, M. Ströbele, K. Eichele, M.-J. Treanor, R. Schaub and H. F. Bettinger, *Angew. Chem. Int. Ed.*, 2015, **54**, 8284-8286.
45. M. Muller, S. Behnle, C. Maichle-Mossmer and H. F. Bettinger, *Chem. Commun.*, 2014, **50**, 7821-7823.

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