Rapid, iterative syntheses of unsymmetrical di- and triarylboranes from crystalline aryldifluoroboranes†

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A one-pot procedure to synthesise aryldifluoroboranes, ArBF₂, from bench-stable arylsilanes is presented. These ArBF₂ react conveniently with aryllithium reagents to form unsymmetrical ArAr′BF and BArAr′Ar′′ in high yield. Examples of all three classes of borane have been characterised crystallographically, allowing for elucidation of geometric and crystal packing trends in crystalline ArBF₂.

Introduction

Triarylboranes, bolstered by over a century of continuous research, find importance across chemical disciplines such as in metal-free catalysis,1–2 anion sensing,3 optoelectronic materials,4 and cell imaging.5 Their uniquely advantageous properties are governed, in part, by the electron deficiency of the central boron atom, whose unoccupied p orbital can both mediate reactivity and be part of an extended conjugated π-system as an electron acceptor.

Equally important is the nature of the aryl groups, which must be tailored to fine-tune the desired steric and electronic properties of triarylboranes, such as their Lewis acidity, solubility in aqueous and/or organic media, and kinetic stability to hydrolysis. As was recently highlighted by Marder and co-workers in an extensive synthetic review,6 numerous methods have been reported to synthesise triarylboranes by substitution reactions of aryl nucleophiles with commercial BX₃ (X = H, OR, F, Cl, Br) sources. However, such substitutions overwhelmingly produce symmetrically substituted BAr₃ or BAr₂Ar′ (Ar = aryl) due to the presence of several complex equilibria,7 the importance of each being governed by the natures of the BX₃ source, nucleophile, and extrinsic conditions. This inherently limits reaction control, and consequently the potential diversity, and thus applications, of the resultant boranes.

Further diversification to fully unsymmetrical BArAr′Ar′′, meanwhile, has hitherto proven to be a significant contemporary synthetic challenge, thereby limiting modern advances in our understanding and application of boron-containing compounds. A small number of BArAr′Ar′′ have been prepared using M/B (M = Li, MgBr) exchange with ArBX₂ (X = H, Br, OR), or Pd-catalysed cross-coupling to symmetric boranes,13–14 usually requiring multi-step protocols. These studies have demonstrated the possible applications of BArAr′Ar′′ in fluorescence imaging and small-molecule sensing for biological systems, though their synthetic routes were target-specific, rather than general. Jäkle and co-workers first approached a more iterative BArAr′Ar′′ synthesis via Me₃Sn/B exchange with ArBBr₂,followed by transmetallation with aryl-magnesium, -copper, or -tin reagents (Scheme 1, top).15–19 However, the toxicity of Me₃Sn and ArCu reagents is a drawback to such an approach. Only recently,

Scheme 1

Iterative approaches to triarylborane synthesis.
Marder and co-workers reported the stepwise transmetallation of K[ArBF₄] complexes with 2,6-disubstituted aryllithium or Grignard reagents to generate triarylboranes (Scheme 1, middle). In both this and the Sn-mediated cases, reactions can take days with poor-to-moderate overall yields.

In light of the promising properties of triarylboranes highlighted above, iterative syntheses of BArArBF₂ through stepwise arylation of a reactive boron centre represents an attractive avenue for development of new boron-containing molecules and materials. An ideal synthetic approach for the preparation of diverse triarylboranes would be capable of selectively substituting accessible boron sources rapidly and in high yields, using convenient aryl nucleophiles. This would improve both the simplicity and scope of modern borane synthesis, and notably enable the synthesis of BArArBF₂ in which each aryl substituent possesses uniquely tailored, application-driven steric and electronic properties.

Herein, we demonstrate that crystalline ArBF₂ are easily accessed from air-stable silanes in a one-pot protocol, which has allowed for their multigram-scale isolation and their use as privileged reagents in organometallic boron chemistry. Specifically, they react conveniently with aryllithium reagents in rapid and selective transmetallations to form unsymmetrical ArArBF₂ and BArArBF₂ in one pot, in high yield and within minutes, from which LiF is the sole by-product (Scheme 1, bottom). These boranes have been comprehensively characterised in the solid state and in solution, including the first crystal structures of unsymmetrical ArArBF₂.

**Results and discussion**

**Syntheses of aryldifluoroboranes (3)**

Our synthetic route was developed from a previous reaction of PhBCl₂ with main-group fluoroanions, which gave PhBF₂ in >95% yield after vacuum distillation.²¹ We have instead proceeded via reaction of bench-stable ArSiMe₂R, R = Me except for 1b, where R = H) with BBr₃ in CH₂Cl₂ to form ArBBr₂ (2) in situ followed by solvent removal and direct addition of Na[BF₄] (Scheme 2). The desired ArBF₂, 3, are formed in moderate-to-high isolated yields and high purity but can be further purified by vacuum sublimation and/or recrystallisation. These conditions tolerate arenes with steric hindrance (3a–b), polycyclic aromatic systems (3c–e), multiple boryl substituents (3f–g), and heteroarenes (3h).

Isolated 3 are typically colourless, crystalline solids that sublime readily upon heating or in vacuo, including 3a, which was previously reported to be a colourless liquid.²² In all cases, they are highly soluble in common organic solvents and easily handled using standard glove box techniques. Exposure to moisture, however, results in fuming and formation of [ArBO]₃, ArH, and BF₃ as hydrolysis products, determined by NMR spectroscopy.

Boron tribromide was preferred for the Si/B exchange step due to greater reactivity towards ArSiMe₃ than BCl₃ and demonstrated reactivity with sterically demanding silanes, e.g., 1a.²³ Reactions were performed with dimethylsilane 1b due to the steric hindrance of the C₆Me₅ group preventing preparation of the corresponding trimethylsilane. This increased bulk slowed the Si/B exchange step, with incomplete conversion revealing intermediate Si–H bromination. Electron-deficient arenes were previously found not to undergo the necessary Si/B exchange,²⁴ and we have found that ArNMe₂ derivatives are also incompatible due to the formation of inert BBr₃ adducts (Fig. S1†).

No [ArBF₄]⁻ was observed even when using excess Na[BF₄], indicating the weaker Lewis acidity of 3 than BF₃, which is supported by F⁻ exchange energy calculations (Table S1) and a previous NMR study of related ArBF₂.²⁵ Our route thus complements a recent synthesis of [ArBF₃]⁻ reported by Perrin and co-workers using an ostensibly similar metathesis of ArB(OH)₂ with [BF₄]⁻ in alcoholic solvents.²⁶

**Spectroscopic and crystallographic studies of 3**

Consistent with previously reported NMR spectra,²⁷ the ¹¹B NMR spectra of 3 (C₆D₆, 298 K) give rise to broad triplets at approximately 25 ppm (¹¹B ν ca. 75 Hz), whereas the ¹⁹F NMR spectra give rise to pseudo-doublets (quadrupole-collapsed equal-intensity quartets) between ca. −57 and −90 ppm. The ¹¹B and ¹⁹F chemical shifts calculated for 3 in C₆D₆ using DFT agree well with the experimental values (Table S2†).

The crystal structures of 3 at 150 K (Fig. 1, top), refined to high accuracy using non-spherical atomic scattering factors (see the ESI†), reveal B–F bonds shorter than in BF₃ (in Å, 1.26–1.31),²⁸ similar to previously reported ArBF₂ (1.307(2)–
1.3146(15) \textsuperscript{29,30} B–BF\textsubscript{2} (1.24(3)–1.359(5))\textsuperscript{31–34} and Pt–BF\textsubscript{2} (1.324(7)–1.359(5))\textsuperscript{32,35–37} systems, but contracted in comparison to [ArBF\textsubscript{3}]\textsuperscript{−}, e.g., [N\textsubscript{n}Bu\textsubscript{4}]\textsubscript{+}[PhBF\textsubscript{3}] (1.409(3)–1.426(2)).\textsuperscript{38}

When ordered in terms of steric bulk, the B–F bonds elongate only subtly from 3\textsubscript{h} (least hindered) to 3\textsubscript{a} (most), but are significantly shorter in 3\textsubscript{b}, comparably to EindBF\textsubscript{2} and TerBF\textsubscript{2}.\textsuperscript{29,30} In contrast, a more conspicuous contraction of the B–C bond occurs with increasing bulk in 3. These trends are attributed to, at least in part, steric pressure caused by crystal packing (vide infra), as no obvious trends in geometric parameters were observed in solution-phase optimised geometries (Table S3†), which otherwise agree well with the experimental data.

The crystal structures of 3 exhibit diverse solid-state interactions (Fig. 1, bottom). Their planarity facilitates π–π stacking wherein the BF\textsubscript{2} moieties are situated over comparatively electron-rich aryl rings in adjacent molecules, except for 3\textsubscript{b}, which is non-planar (\textsuperscript{1}F1–B–C1–C2 = 60.58(15)\textdegree) and prefers fluorour layers containing zig-zag chains of B–F contacts. Interestingly, 3\textsubscript{g} and 3\textsubscript{h} adopt B–F contacts at only one face of the boron atom, which is flanked by a π–π stacking/B–S interaction (Fig. 2). The contacts are weaker in 3\textsubscript{b} (in Å, 3.326), 3\textsubscript{g} (3.070) and 3\textsubscript{h} (3.210) than BF\textsubscript{3} (2.68–2.71),\textsuperscript{28} but still within the sum of van der Waals radii (3.39).\textsuperscript{39} In contrast, steric crowding in EindBF\textsubscript{2} and TerBF\textsubscript{2} prevents any notable contacts to boron.\textsuperscript{29,30}

The large difference in torsion angle and packing motif between 3\textsubscript{a} and 3\textsubscript{b} is notable, given that they differ only by the presence of meta-methyl groups in 3\textsubscript{b}. The C\textsubscript{i}–C\textsubscript{o}–C\textsubscript{Me} angle in 3\textsubscript{a} (123.02(6)\textdegree) suggests a slight repulsion of the ortho-methyl groups from the BF\textsubscript{2} moiety to facilitate planarity, but this is seemingly blocked in 3\textsubscript{b} (120.36(11), 120.60(11)\textdegree) and thus torsion occurs. This is attributed to a resonance effect from boron in 3\textsubscript{a}, rather than crystal packing, as it is reflected in the optimised geometries (123.04, 123.14° in 3\textsubscript{a} vs. 120.67, 120.76° in 3\textsubscript{b}). The planarity and presence of π–π stacking in 3\textsubscript{a} may also rationalise its crystallinity versus heavier MesBX\textsubscript{2}, which are minimally volatile liquids at ambient temperature.\textsuperscript{30,41} This is supported by calculated solution-phase 3a/MesBX\textsubscript{2} head-to-tail dimers, which show considerable disruption of stacking by twisting of the larger BX\textsubscript{2} moieties out of plane (Fig. S3†). The enthalpies and Gibbs energies reflect this, being most exothermic and least endergonic for 3\textsubscript{a} (Fig. S3†).
Syntheses of di- (4) and triarylborationes (5/6)

To establish the utility of 3 in organoboron chemistry, deriva-
tisation with aryl nucleophiles was performed (Scheme 3). Stoichiometric reactions with simple, moderately sterically shielded aryllithium or Grignard reagents, i.e., MesLi and C₆F₅MgBr, were found to selectively produce unsymmetrical ArArBF (4a–d) in quantitative yield after ca. 2 min at ambient temperature. These could be isolated in high yield after recrystallisation or derivatised in one pot to unsymmetrical naphthyl- (5a, 5b) and ferrocenyl-substituted (6) boranes with the respective aryllithium reagent in similarly rapid conversion and high yield. The generation of less hindered ArArBF using 3d shows that steric freedom in 3 does not negatively impact selectivity upon transmetallation under these circumstances. Furthermore, the convenient generation of unsymmetrical C₆F₅-substituted boron using C₆F₅MgBr in Et₂O is especially notable considering the importance of electron-withdrawing groups in boron chemistry. By contrast, typical approaches have used C₆F₅Cu and introduced C₆F₅ as a final step. Overall, these reactions demonstrate that 4 are versatile precursors that, for the first time, allow for direct access to unsymmetrical boranes within minutes.

Reactions of 3 with less hindered NaphLi and ArF⁺MgBr [ArF⁺ = 3,5-(CF₃)₂C₆H₃] were found to result in distributions of the desired ArArBF, symmetrical BAr(ArF⁺), and unreacted 3, and were investigated by NMR spectroscopy (Table S1†). Under typical conditions, i.e., in Et₂O at ambient temperature, 3b and NaphLi afforded the desired ArArBF in only ca. 10% NMR yield, though symmetrical BAr(ArF⁺), 5c was generated quantitatively with 2 equiv. of NaphLi. This yield increased to ca. 40 and 60% in benzene and pentane, respectively, though cooling the reaction in pentane to −35 °C had no effect on yield. The steric profile of 3 also began to influence product distribution, as 3a and 3d afforded the corresponding ArArBF in 40 and 10% yields upon reaction with NaphLi in pentane. Notably, the use of electron withdrawing ArF⁺MgBr significantly improved selectively, as reactions of 3a with ArF⁺MgBr in Et₂O afforded ArArBF in 70% yield despite the more polar solvent and absence of ortho-substitution. In contrast, bulky dibromoborane 2b showed no selectivity during transmetallation with MesLi or NaphLi.

These findings highlight the specific utility of fluoroboranes in transmetallations with aryllithium and Grignard reagents. We attribute this to the high electrophilicity of boron improving the rate of B–C bond formation, while the strength of the B–F bond mitigates F⁻ dissociation and subsequent overreaction. The observed effects of solvent, sterics of the borane and aryl nucleophile, and electronics of the nucleophile, on selectivity serve as complements to previous observations on solvent and electronic effects in reactions of B(OR)₃ (R = alkyl) with Grignard reagents.

Spectroscopic and crystallographic studies of 4–6

The asymmetry of 4–6 was established by complete assignment of the multi-nuclear NMR spectra (see the ESI†). The transformations of 3 to 4, and then 4 to 5/6, were easily monitored by ¹¹B and ¹⁹F NMR spectroscopy, the former revealing high-frequency shifts to ca. 50, then 75 ppm, and the later showing shifts to >−40 ppm before disappearing entirely. The calculated ¹¹B chemical shifts of 4–6 agree well with experimental data,
Conclusions

In conclusion, we have developed a facile and general synthetic route to solid aryldifluoroboranes, allowing for their crystallographic study. This has revealed subtle trends in solid-state geometric parameters as a function of the steric demands of the aryl group, as well as the diversity of their crystal packing motifs. Furthermore, they are shown to react selectively with aryllithium reagents to form unsymmetrical di- and triarylboranes within minutes, with a selectivity that arises from steric and electronic factors. Thus, aryldifluoroboranes may provide an accessible avenue for modular borane synthesis with broad potential application in organoboron chemistry; investigations into further preparation and functionalisation of such unsymmetrical species are currently underway.

Data availability

The data that supports the findings of this article are included in the ESI†

Author contributions

Experiments and computations were designed and performed by D. T. Data analysis and manuscript preparation were performed by D. T. The project was overseen by M.-A. L.

Conflicts of interest

There are no conflicts to declare.

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