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Conformational control of nonplanar free base porphyrins:
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1,3-Carboboration of Iodonium Ylides

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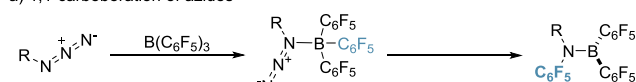
Herein, we disclose the utilisation of iodonium ylides to access a range of boron dienolates. Heating of acyclic iodonium ylides in the presence of different aryl boranes lead to the formation of rare 1,3-carboration products. This methodology could not be expanded to cyclic iodonium ylides which instead formed a Lewis acid-base adduct. Products proved to be remarkably stable under a wide range of conditions allowing for their long term storage.

The versatility of organoboranes in synthesis is beyond dispute.[1] From reaction intermediates (amination reactions[2]) to substrates (cross-coupling reactions[3]) and catalysts (e.g. Lewis acid catalysis[4] or frustrated Lewis pair chemistry[5]) they represent an invaluable tool in the arsenal of the synthetic chemist. One such class of boranes, which has come to the forefront of modern Lewis acid chemistry, is that of the highly electrophilic fluorophenyl boranes.[6] These boranes demonstrate relatively high stability towards boron-carbon hydrolytic cleavage. However, the bond is sufficiently labile to allow for its utilisation in a range of carboborations of sp- and sp^2-hybridised bonds.[7] Of these, 1,1-carboboration is the most widely explored, partly thanks to the Wrackmeyer reaction, and enables facile access to substituted olefins.[8]
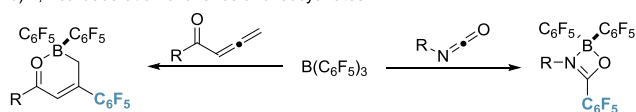
To date, alkynes remain the 'go-to' substrate for 1,1-carboborations with numerous examples reported.[9] However, recently, organic azides have been shown to undergo 1,1-carboborations with $B(C_6F_5)_3$ to generate imines. This reaction was shown to proceed *via* an initial adduct formation between

$B(C_6F_5)_3$ and RN_3 followed by a Staudinger type reaction (Scheme 1a).[10] Conversely, metal-free 1,2-carboboration reactions are much rarer, especially for sp-hybridised systems which to date are limited to highly electrophilic borocations.[11] 1,2-carboboration of sp^2-centres has been exemplified through the use of allenyl esters and ketones with $B(C_6F_5)_3$[12] and recently isocyanates leading to 4-membered cyclic compounds exhibiting frustrated Lewis pair characteristics (Scheme 1b).[13] 1,2-carboboration of cyclic iminium ions with $B(C_6F_5)_3$, has also been reported under photochemical conditions leading to highly desirable tertiary amines.[14] These transformations demonstrate the proclivity of $B(C_6F_5)_3$ to effect selectively 1,2-aryl transfers. However, the corresponding 1,3-aryl transfers are still an under-represented class of transformations. Aryl transfer reactions utilising electrophilic boranes and diazo species have been reported by Stephan, however these reactions were limited to the transfer of the C_6F_5 moiety.[15]
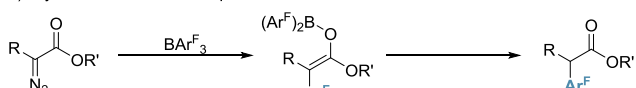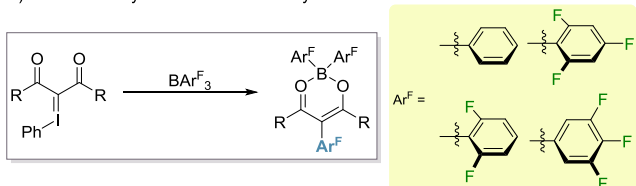
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Scheme 1 Reported aryl transfer reactions from electrophilic boranes (**a–c**) and this work (**d**).

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Recently, our group reported that transfer of other halogenated aryl groups to diazo species is possible (Scheme 1c).[16] Given the analogous nature between diazo species and iodonium ylides as carbene precursors,[17] we envisaged that a similar aryl transfer should be viable. To this end, we divulge the reaction of iodonium ylides with a library of boranes (BAr$^F_3$; Ar^F = 3,4,5-F$_3$C$_6$H$_2$ (**1a**), 2,4,6-F$_3$C$_6$H$_2$ (**1b**), 2,6-F$_2$C$_6$H$_3$ (**1c**), C$_6$H$_5$ (**1d**) and C$_6$F$_5$ (**1e**)) displaying varying levels of Lewis acidity (Scheme 1d).

Initial studies of the reaction of dimethyl 2-(phenyl-λ^3-iodaneylidene)malonate [PhIC(CO$_2$Me)$_2$] **2a** with borane **1a** in refluxing dichloromethane led to a pale-yellow homogeneous solution. The colouration can be attributed to the generation of iodobenzene.[18] Subsequent workup and isolation afforded **3a** as colourless crystals in 45% yield. The ^{11}B{^{1}H} NMR spectrum of **3a** shows a broad resonance at δ = 7.5 ppm, while the ^{1}H and ^{19}F NMR spectra were consistent with the incorporation of the 3,4,5-trifluorophenyl moiety showing two C$_6$H$_2$F$_3$ ring environments in a 2:1 ratio. The yield could be improved by conducting the reaction in either chloroform or toluene (56% and 74% respectively) at 50 °C. Recrystallisation from a dichloromethane/pentane solution led to single crystals whose exact nature was elucidated by single crystal X-ray diffraction (Figure 1). Compound **3a** crystallised in the *P-1* space group with four molecules present in the unit cell. The solid-state structure shows the C$_2$O$_2$B ring is non-planar and instead adopts an envelope-type geometry, with the boron heteroatom sitting out of the plane and a fold angle (the angle between the OBO and OCCO mean planes) of 23.3(3)°. The boron heteroatom is four coordinate and is slightly distorted from a tetrahedral geometry, with an O–B–O bond angle of 107.52(18)° (see ESI for further bond angles). The B–O bond lengths (1.523(3) Å and 1.525(3) Å) were found to be slightly longer than typically observed (1.468 Å in BO$_4^-$)[19] and the C–O bond lengths were found to be 1.287(3) and 1.288(3) Å, which is approximately intermediate between a single and double C–O bond character.[19]
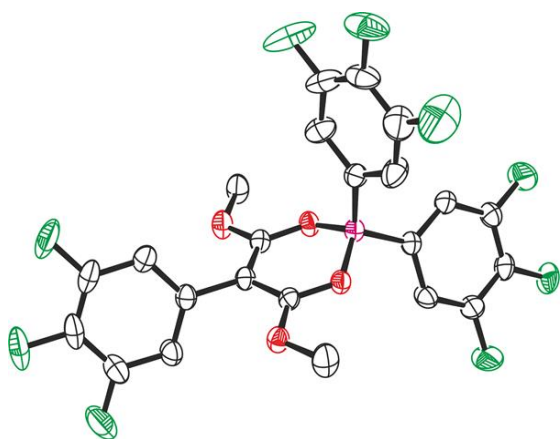

Figure 1 Solid-state structure of **3a**. C: black, B: pink, O: red, F: green. Thermal ellipsoids drawn at 50% probability. H atoms omitted for clarity.
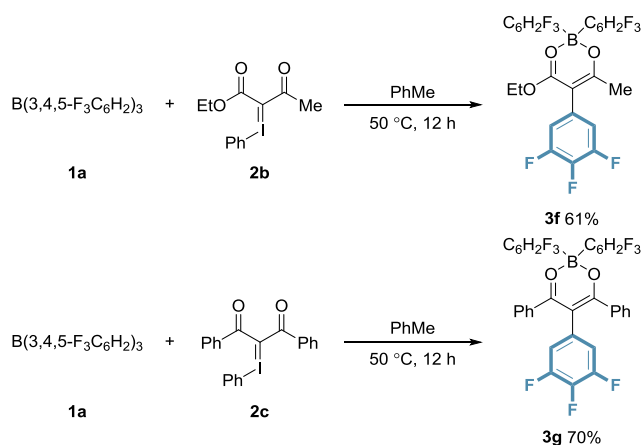
This suggests resonance character is exhibited in the core C$_2$O$_2$B six-membered ring, which is further observed in the C–C

bond lengths, which are again in between single and double bond character (1.389(3) Å and 1.396(3) Å). These metrics are comparable to related diketone structures reported by Chujo.[20] The analogous reaction of hypervalent iodine starting material **2a** with equimolar quantities of boranes **1b–d** proceeded in a similar fashion furnishing the aryl transfer products in moderate to good yields (up to 67%) (Scheme 2). All products (**3a-d**) exhibited a broad resonance in the ^{11}B{^{1}H} NMR spectrum between δ = 6.6 and 9.2. As with **3a**, ^{1}H NMR data confirmed the incorporation of the fluoraryl moiety and the ^{19}F spectrum resonances were consistent with two inequivalent fluoroaryl rings. Where yields are concerned, a tentative relationship to Lewis acidity could be made. As shown in Scheme 2, an increase in borane Lewis acidity (as determined by the Gutmann-Beckett method)[21] provided a seemingly positive effect on the product yield. A notable exception is the reaction with B(C$_6$F$_5$)$_3$ (**1e**) which led to an inseparable mixture of products (see ESI for crystal data of **3e**), despite having a Lewis acidity comparable to B(3,4,5-C$_6$F$_3$H$_2$)$_3$. The characterization of by-products and intermediates is always useful in evaluating mechanistic pathways. In this context we re-examined the reaction of both **1b** and **1e** with **2a** on a larger scale as these produced the lowest isolated yields. Multinuclear NMR studies provided complex spectra from which no obvious hydrolysis product or reaction intermediate could be unambiguously identified. Attempted recrystallizations using layering and solvent diffusion techniques from a variety of solvent mixtures also proved unsuccessful.
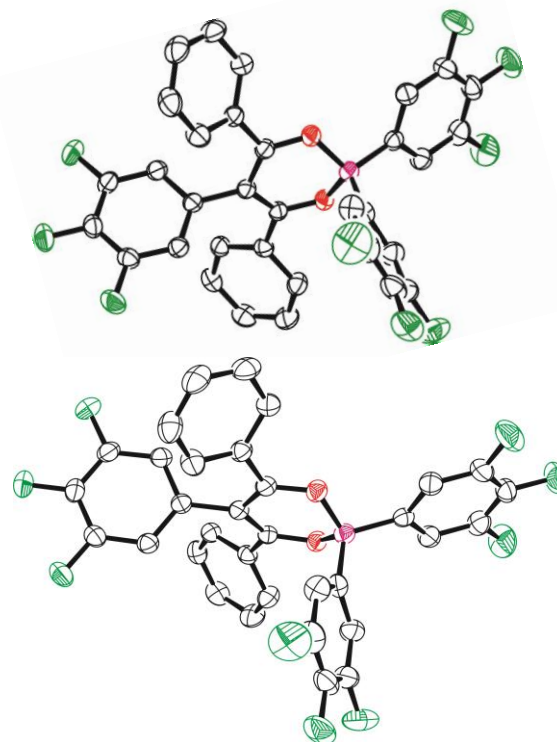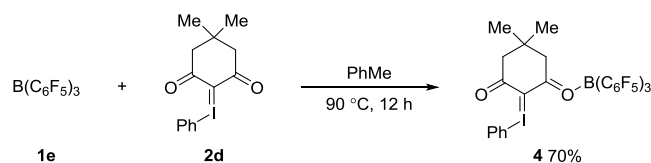
Having established the feasibility of transferring fluorophenyl rings to symmetrical bis-ester stabilised ylides, we turned our attention to less stable iodonium ylides bearing an ester and a ketone (**2b**), as well as a diketone (**2c**) (Scheme 3). As before, reaction of **2b** and **2c** with tris(3,4,5-trifluorophenyl)borane (**1a**) showed similar reactivity to that with **2a** resulting in the formation of **3f** and **3g** respectively. The ^{11}B{^{1}H} NMR spectrum showed a broad resonance at δ = 7.7 ppm for **3f** and δ = 7.3 ppm for **3g** consistent with a four-coordinate boron centre with diminished Lewis acidity.

^{1}H and ^{19}F NMR spectroscopic data were also consistent with the formation of **3f** and **3g**. X-ray crystallography unambiguously confirmed the structures of both products (Figure 2). Compound **3f** crystallised in the *P2$_1$/c* space group and has similar metrics to that of **3a**, with a distorted tetrahedral four-coordinate boron and B–O bond lengths 1.488(3) Å and 1.540(3) Å. It was noted that the degree of resonance appeared less in **3g** than **3a**, with C–O bond lengths of 1.278(3) Å and 1.316(3) Å and C–C bond lengths of 1.366(4) Å and 1.419(4) Å. Compound **3g**, like **3a,** crystallised in *P-1* the space group and again has similar metrics to **3a** (see ESI for further details). Repeated attempts were made to cleave the boron moiety from compounds **3a-g** to yield organic products in which an aryl functionality had been incorporated. However, these compounds proved remarkably stable and resistant to hydrolysis in both acidic and aqueous media,[19] e.g. deprotection using a variety of reagents all proved unsuccessful including: (i) NaOH/H$_2$O$_2$; (ii) Ag$_2$O/BnBr in MeCN; (iii) N$_2$H$_4$·H$_2$O/AcOH in

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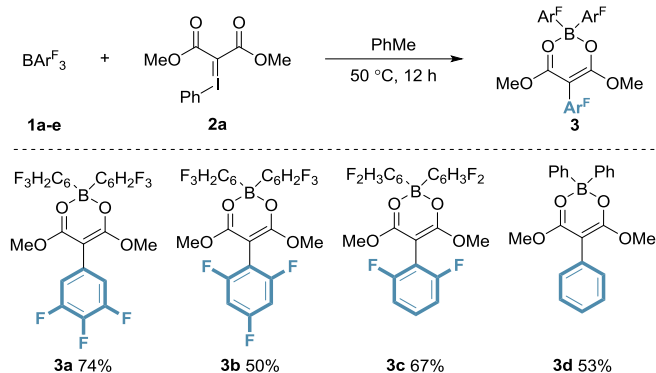
**Scheme 2** Reaction of **2a** with boranes **1a-d**.

Scheme 3 Reaction of iodonium ylides 2b and 2c with B(3,4,5-F$_3$C$_6$H$_2$)$_3$ 1a..

Figure 2 Solid-state structure of **3f** and **3g.** C: black, B: pink, O: red, F: green. Thermal ellipsoids drawn at 50% probability. H atoms omitted for clarity.

EtOH (to form the equivalent pyrazole); (iv) Na$_2$CO$_3$ in EtOH, H$_2$O then HCl. It was postulated that removing the ylide's ability to form stable intramolecular chelates would facilitate such a cleavage. To test this, iodonium ylide **2d** bearing a dimedone motif was synthesised. Due to its conformational rigidity it was envisaged that only a single oxygen atom would be available to yield a B-O linkage thus facilitating hydrolysis. Yet, when **2d** was reacted with all boranes, unlike the acyclic iodonium ylides, a complex mixture of products was formed in most cases. With B(C$_6$F$_5$)$_3$ (**1e**) however adduct **4** was isolated and crystallised (see ESI). This adduct proved to be resistant to elevated temperatures (100 °C), precluding the carboboration reaction. This indicates that a single B–O connection is not sufficient to activate the boron and effect the transfer. However secondary effects should not be discounted. It is reported that cyclic iodonium ylides are more stable compared to their open chain counterparts. This effect is imparted by secondary C-I----O bonding.[23] However, this is a weak interaction that should be readily disrupted at elevated temperatures. It is likely these two factors work in a synergistic fashion preventing the aryl transfer. Adduct **4** shows short intermolecular O···I contacts in the solid-state at 2.916 Å and 3.105 Å, slightly longer than those reported for similar compounds in the absence of the B(C$_6$F$_5$)$_3$ adduct.[23]

Scheme 4 Reaction of **2d** with B(C$_6$F$_5$)$_3$ **1e**.

In order to probe the reactivity of the Lewis acidic borane with the iodonium ylide, a series of computational studies on the formation of **3c** were undertaken with the M06-2X functional and LACVP+ basis set (see ESI for details). Initial calculations probed adduct formation between the borane and the iodonium ylide using the carbonyl O atom as a hard donor. Adduct formation was computed to be strongly favourable (ΔE = -115 kJ·mol^{-1}) and an analysis of the two conformers revealed that the less sterically hindered conformation was more favoured by just 11 kJ·mol^{-1} (Scheme 5). Reaction profiles for migration of the aryl group to the ylidic carbon commencing form both exo and endo adducts were explored and the migration commencing from the more stable exo adduct passed through a lower energy transition state. These studies reveal a four-coordinate transition state with limited C-I bond weakening (d$_{C···I}$ = 2.10 Å) reflecting an early transition state in

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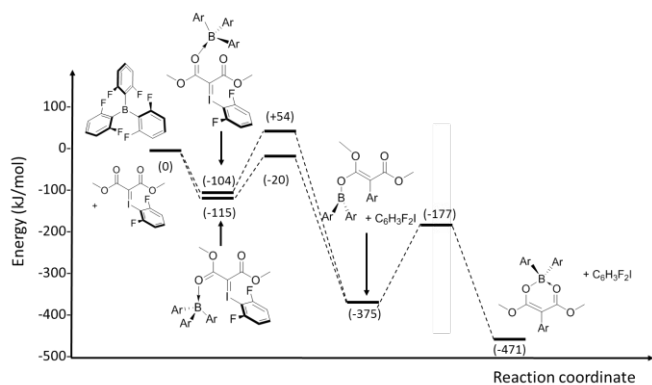
Scheme 5. Reaction profile for the formation of **3c** from $B(C_6H_3F_2)_3$ and $C_6H_3F_2I=C(COOMe)_2$.

agreement with Hammond's postulate.[24] After elimination of the aryl iodide leaving group, cyclization exhibits a low activation energy and led to the observed ring-closed product as the most stable species on the potential energy surface.

Conclusions

In summary, we have showcased an innovative route to boron dienolates utilising iodonium ylides. This study revealed that acyclic symmetrical iodonium ylides were successful substrates. Unsymmetrical ylides were also amenable to this transformation, whereas conformationally restricted cyclic variants led to adduct formation. The products from this reaction were unequivocally identified by X-ray crystallography. Through the use of DFT computational studies, the net 1,3-carboboration was shown to proceed *via* initial adduct formation followed by an aryl migration coupled with elimination of aryl iodide and finally, cyclisation. The generation of these aryl-substituted products in a metal-free fashion provides a facile route to boron containing heterocycles.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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