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A doubly electrophilic pyrazabole derivative (pyrazabole =  $[H_2B(\mu-C_3N_2H_3)]_2$ ), activated with  $I_2$ , was found to effect the ortho-borylation of *N*-alkyl-anilines in the presence of  $Et_3N$ . This methodology represents a metal free transiently directed C-H borylation approach to form *N*-alkyl-2-BPin-aniline derivatives. In addition, this work includes mechanistic studies of doubly electrophilic pyrazabole systems that led us to use the aforementioned.

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## Borylation directed borylation of *N*-alkyl anilines using iodine activated pyrazaboles†

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Doubly electrophilic pyrazabole derivatives (pyrazabole =  $[H_2B(\mu-C_3N_2H_3)]_2$ ) combined with one equiv. of base effect the *ortho*-borylation of *N*-alkyl anilines. Initial studies found that the bis(trifluoromethane) sulfonimide ( $[NTf_2]^-$ ) pyrazabole derivative,  $[H(NTf_2)B(\mu-C_3N_2H_3)]_2$ , is highly effective for *ortho*-borylation, with this process proceeding through N–H borylation and then *ortho* C–H borylation. The activation of pyrazabole by  $I_2$  was developed as a cheaper and simpler alternative to using  $HNTf_2$  as the activator. The addition of  $I_2$  forms mono or ditopic pyrazabole electrophiles dependent on stoichiometry. The ditopic electrophile  $[H(I)B(\mu-C_3N_2H_3)]_2$  was also effective for the *ortho*-borylation of *N*-alkyl-anilines, with the primary C–H borylation products readily transformed into pinacol boronate esters (BPin) derivatives. Comparison of borylation reactions using the di- $NTf_2$ - and the diiodo-pyrazabole congeners revealed that more forcing conditions are required with the latter. Furthermore, the presence of iodide leads to competitive formation of side products, including  $[HB(\mu-C_3N_2H_3)_3BH]^+$ , which are not active for C–H borylation. Using  $[H(I)B(\mu-C_3N_2H_3)]_2$  and 0.2 equiv. of  $[Et_3NH][NTf_2]$  combines the higher yields of the  $NTf_2$  system with the ease of handling and lower cost of the iodide system generating an attractive process applicable to a range of *N*-alkyl-anilines. This methodology represents a metal free and transiently directed C–H borylation approach to form *N*-alkyl-2-BPin-aniline derivatives.

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## Introduction

C–H borylation is a powerful methodology for generating synthetically ubiquitous organoboranes in an efficient manner.<sup>1</sup> The use of directing groups (DGs) in C–H borylation reactions enables access to organoboranes with a distinct regiochemistry to that formed from non-directed transformations.<sup>2</sup> One specific example of this is in the synthesis of *ortho*-borylated anilines, which are useful for accessing *ortho* substituted anilines prevalent in pharmaceuticals, agrochemicals and organic materials.<sup>3</sup> Directing groups generally are required for this *ortho* C–H borylation as in the absence of DGs the electrophilic C–H borylation of anilines leads to *para*-functionalisation,<sup>4</sup> while iridium and cobalt catalysed C–H borylations generally lead to mixtures of *meta*- and *para*-borylated products.<sup>1b,5</sup> To date, the *ortho* C–H borylation of anilines has been dominated by approaches requiring the separate installation and removal of a directing group (resulting in “multiple pot” processes).<sup>6,7</sup> For example, the electrophilic *ortho* C–H borylation of aniline derivatives using *N*-pivaloyl DGs and  $BBr_3$

(Fig. 1a, top)<sup>8</sup> requires the installation and removal of pivaloyl in separate processes, the latter under forcing conditions.<sup>9</sup> The use of transient DGs is preferable as these are installed, direct the C–H borylation and then are removed all in one pot.<sup>10</sup> In notable work, the *ortho*-borylation of anilines using transient DGs has been reported using iridium catalysts and  $B_2Eg_2$  ( $Eg$  = ethylene glycolato).<sup>11</sup> This proceeds *via in situ* formation of an  $AryN(H)BEg$  species (Fig. 1b, inset) that then directs the *ortho* C–H borylation. The N-BEg unit is then readily cleaved during work-up. While this methodology is highly effective for  $AryN(H)NH_2$  species, much lower yields (<30%) are obtained with *N*-alkyl-anilines.<sup>11,12</sup> Given the prevalence of *ortho*-functionalised *N*-alkyl-anilines in pharmaceuticals (*e.g.* Flutemetamol, Entrectinib and Agratroban), the development of a higher yielding, transient DG approach for the *ortho*-borylation of *N*-alkyl-anilines is desirable, particularly if the process is precious metal-free.<sup>13</sup>

Recently, we reported the borylation directed borylation (BDB) of indoles using pyrazabole electrophile **A** (Fig. 1c) as a method to install boron units at the C7 position.<sup>14,15</sup> In this process reduction of indole to indoline occurs first, with the spectroscopic data indicating that this led to an *N*-borylated indoline intermediate (*e.g.* **B**). The N–B bond and the pyrazabole structure in compound **B** positions the second boron centre appropriately to borylate the proximal  $sp^2C-H$  leading to **C**, a C7

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Fig. 1 a = pivaloyl directed electrophilic borylation. b = a transient directing group in iridium catalysed *ortho*-borylation of anilines. c = previous work on indole reduction/C7 borylation via BDB. Inset bottom, this work.

borylated indoline. Protection of the C–B unit and cleavage of the N–B bonds in C during work up formed indolines containing the useful pinacol boronate ester (BPin) group at C7. Therefore, pyrazabole is acting as a transient DG in this BDB process, with transient DGs underexplored in electrophilic C–H borylation.<sup>2a,16</sup> Our initial BDB study utilised stoichiometric amounts of bistriflimidic acid ( $\text{HNTf}_2 = \text{HN}(\text{SO}_2\text{CF}_3)_2$ ) to form the reactive electrophile A. However,  $\text{HNTf}_2$  is relatively expensive,<sup>17</sup> and it, and  $\text{NTf}_2$ -pyrazabole electrophiles (e.g. A), have to be handled within a glovebox. Therefore, extending the BDB of *N*-alkyl-aniline derivatives beyond indoline while using an inexpensive and more readily handled activator would be attractive. Herein we report our studies addressing this challenge. This led to the development of iodine as a cheap and easy to handle activator for pyrazaboles that forms ditopic electrophiles that are effective in the transient DG mediated *ortho*-borylation of *N*-alkyl-anilines.

## Results and discussion

Our first focus was identifying electrophilic pyrazabole – base combinations that achieved the *ortho*-borylation of our model substrate, *N*-Me-aniline. Initially, the previously reported **1** (Scheme 1) was added to *N*-Me-aniline in the presence of 2,6-di-

*tert*-butyl-4-methylpyridine (DBP) as base. At room temperature this led to slow BDB, but on heating to  $\geq 70^\circ\text{C}$  the BDB product **[2]NTf<sub>2</sub>** was formed as the major product within 18 h. **[2]NTf<sub>2</sub>** was fully characterised, which revealed protonation of the aniline nitrogen occurs during this BDB. A modified (shorter reaction time)<sup>14</sup> N–B cleavage/pinacol installation process then led to formation of **3a**.

DBP is an expensive Brønsted base that was used to simplify initial studies as it does not coordinate to boron electrophiles. In contrast, other Lewis bases (e.g. MeCN) can displace  $\text{NTf}_2^-$  anions from **1**, and base coordination to boron could retard the BDB reaction.<sup>14</sup> Given the aniline substrate also functions as a Brønsted base during BDB (as indicated by the formation of **[2]NTf<sub>2</sub>**) only one equivalent of exogenous base is required. Therefore, one equivalent of the inexpensive bases  $\text{Et}_3\text{N}$  and Hünigs base were trialled in place of DBP in the BDB of *N*-Me-aniline using **1**. On heating both of these reactions led to the formation of **[2]NTf<sub>2</sub>** and **[baseH][NTf<sub>2</sub>]** as a by-product. Pinacol installation/work-up enabled **3a** to be isolated in 62 and 65% yield using  $\text{Et}_3\text{N}$  and Hünigs base, respectively. Thus cheaper (than DBP) bases can be used in the BDB of *N*-alkyl-anilines. Our attention turned next to replacing  $\text{HNTf}_2$  with a simpler to handle and cheaper activator.

Based on the established reactivity of  $\text{L} \rightarrow \text{BH}_3$  with iodine, which forms reactive boron electrophiles of general formula  $\text{L} \rightarrow \text{BH}_2\text{I}$ ,<sup>18</sup> diiodo-pyrazabole was targeted as an alternative to **1**. While dibromo- and dichloro-pyrazaboles are known,<sup>19</sup> to our knowledge no B–I containing pyrazaboles have been reported to date. The latter are desirable as iodine is inexpensive, easy to handle and is less coordinating to boron than the lighter halides. Furthermore,  $\text{L} \rightarrow \text{BH}_2\text{I}$  species have been demonstrated to react with  $\pi$  nucleophiles to form C–B bonds in a related manner to  $\text{L} \rightarrow \text{BH}_2(\text{NTf}_2)$  species.<sup>20</sup> Therefore, one equivalent of iodine, pyrazabole and  $\text{Et}_3\text{N}$  were combined and found to be viable for the BDB of *N*-Me-aniline (Scheme 2), albeit requiring heating to  $100^\circ\text{C}$  for significant BDB to occur. In contrast, attempts using dibromo-pyrazabole under identical conditions led to no BDB reaction (Scheme 2), indicating that the less coordinating nature of iodide towards boron is vital for this transformation. Despite extensive optimisation studies using iodine activated pyrazabole (see Table S2†) the isolated yield of **3a** remained  $<50\%$  (based on *N*-Me-aniline) – with  $\text{Et}_3\text{N}$  providing the best outcome from the bases explored. Notable points from this optimisation study included: use of  $>1$  equiv. of  $\text{Et}_3\text{N}$  retarding the BDB reaction, while using two equiv. of *N*-Me-aniline and no other base gave only trace amounts of **3a**. Given the lower yields of **3a** using iodine activated pyrazabole



Scheme 1 BDB of *N*-Me-aniline using **1** and an amine base.







**Scheme 4** Left, formation of mono- (**6**) and diiodo-pyrazabole (**7**). Inset right, the solid state structure of *cis*-**7**, ellipsoids at 50% probability. Blue = nitrogen, pink = boron, purple = iodine, grey = carbon, white = hydrogen.

$L \rightarrow BH_2I$  compounds ( $L = N$ -heterocyclic carbenes or  $PR_3$ ).<sup>26</sup> Notably, combining equimolar **7** and pyrazabole in chlorobenzene led to formation of the mono-iodo pyrazabole **6** at ambient temperature (by *in situ* NMR spectroscopy - Fig. S48†), indicating that intermolecular H/I exchange occurs in iodo-pyrazaboles. Finally, it should be noted that **7** has appreciable thermal stability: heating **7** at 100 °C in PhCl for 3 days led to minimal decomposition (<5% by multinuclear NMR spectroscopy), with the only observable new <sup>11</sup>B NMR resonance consistent with formation of an  $L-BI_3$  compound (based on the  $\delta_{11B} = -34.6$ , see Fig. S46 and S47†).

With an understanding of the products formed from combining iodine and pyrazabole in hand the reactivity of **7** towards  $Et_3N$  was explored,  $Et_3N$  was selected as it gave the best outcome in our initial optimisation study (see Table S2†). The addition of one equivalent of  $Et_3N$  to **7** led to formation of the mono-cation **8** (Scheme 5). The identity of **8** was confirmed by single crystal X-ray diffraction analysis (inset, Scheme 5). The solid-state structure of **8** also has a flattened boat conformation for the  $B_2N_4$  core with the iodide and  $Et_3N$  moieties being *cis* in the flagpole positions. The steric demand of  $Et_3N$  in **8** causes a distortion in the geometry with an increase of the  $Y-B$ -Centroid angles ( $Y = I$  or  $N_{Et_3}$ ; centroid = calculated centroid of the  $B_2N_4$  ring) observed on comparing **7** ( $I-B$ -centroid = 113.3(3)° and 112.6(3)°) and **8** ( $I-B$ -centroid = 118.6(12)°;  $Et_3N-B$ -centroid = 122.1(14)°). Compound **8** also has a longer B-I bond of 2.36(2) Å vs. the B-I bonds in **7** (2.290(6) and 2.302(6) Å), consistent with greater steric crowding in **8** relative to **7**. However, the B- $N_{Et_3}$  bond length in **8** (1.62(2) Å) is in the range of previously reported  $Et_3N-BR_3$  adducts (1.60–1.69 Å).<sup>27</sup>



**Scheme 5** Top, the reaction of **7** towards  $Et_3N$ . Inset bottom, the solid-state structure of the cationic portion of **8**, ellipsoids at 30% probability. Blue = nitrogen, pink = boron, purple = iodine, grey = carbon, white = hydrogen.

In contrast to the di- $N Tf_2$  analogue **1** (where both  $N Tf_2$  anions are displaced by Lewis bases to form dicationic products),<sup>14</sup> the addition of further  $Et_3N$  to **8** did not displace the second iodide (Fig. S49†). This is consistent with the more coordinating nature of iodide relative to  $[NTf_2]^-$ . However, the addition of both *N*-Me aniline and  $Et_3N$  (in either order of addition) to **7** led to substitution of both iodides to form the dianilide product **5** as the major boron containing species. This indicates that  $Et_3N$  coordination to boron in **8** does not irreversibly block *N*-Me-aniline from reacting with boron. Next, diiodo-pyrazabole **7** and dianilide-pyrazabole **5** were combined to determine if the iodide analogue of the dimer **4** forms. This led to slow and complex reactivity at room temperature with no iodide analogue of **4** observed. In contrast, the di- $N Tf_2$  pyrazabole **1** and compound **5** are completely consumed within minutes of mixing to form **4** cleanly. In the *in situ* monitored BDB reactions using diiodo-pyrazabole **7**, **5** is the only major new pyrazabole product observed, again there is no evidence for the iodide analogue of **4** (by NMR spectroscopy). From the *in situ* monitoring experiments [**2**]**I** forms as one of the major products on heating, but this occurs along with the formation of two other major products. The first of these was assigned as  $(Me(Ph)N)_2BH$  ( $\delta_{11B} = 29.0$   $^1J_{B-H} = 126$  Hz) by comparison to the previous report.<sup>28</sup> The second was identified as compound **9** (Scheme 6), which precipitated from the BDB reactions mixtures (along with some  $[Et_3NH][I]$  precipitating). Compound **9** was independently synthesised and crystallised with X-ray diffraction studies confirming its formulation (inset Scheme 6). These results combined indicate that heating diiodo-pyrazabole **7** in the presence of  $Et_3N$ /*N*-Me-aniline leads to competitive (to BDB) break-up of the pyrazabole core and the formation of species that are non-productive for BDB (e.g.





Scheme 6 Left, the reactivity of **7** towards  $\text{Et}_3\text{N}/N$ -Me-aniline at raised temperatures. Inset, the solid-state structure of compound **9**, ellipsoids at 30% probability. Blue = nitrogen, pink = boron, grey = carbon, white = hydrogen.

compound **9**). This contrasts with BDB using the  $\text{NTf}_2$  derivative **1** (which are much cleaner by *in situ* NMR spectroscopy with <5% formation of other pyrazole containing products by NMR spectroscopy), indicating that the more coordinating iodide anion plays a crucial role in the cleavage of the pyrazabole core under these conditions. This is presumably the origin of the lower conversions to  $[\mathbf{2}]\text{I}$  (and thus **3a**) observed using **7** compared to conversions to  $[\mathbf{2}]\text{NTf}_2$  using the  $\text{NTf}_2$  analogue **1**.

Given the lower conversion to **3a** using **7** relative to that using stoichiometric **1**, attempts were made to use sub-stoichiometric  $\text{HNTf}_2$  (or sub-stoichiometric **1**) and stoichiometric pyrazabole in the BDB of *N*-Me aniline. However, these reactions all led to low yields of **3a**, this is consistent with the observation that  $[\text{Et}_3\text{NH}][\text{NTf}_2]$  (the by-product from BDB) and pyrazabole do not react on heating to 100 °C. Therefore alternative approaches were sought to achieve a high yielding, operationally simple and cheaper BDB protocol.

### Optimisation of the BDB of *N*-alkyl-anilines using iodo-pyrazaboles

To combine the best of the  $\text{NTf}_2$  (higher yields) and iodide (cheaper/easier to handle) systems we considered an *in situ* anion exchange process that could convert iodo-pyrazaboles into more reactive  $\text{NTf}_2$ -pyrazaboles. The feasibility of iodide/ $\text{NTf}_2$  exchange initially was explored computationally which indicated that the displacement of iodide from pyrazabole by triflimide is endergonic (by +7.5 kcal mol<sup>-1</sup> for the mono-pyrazabole, Scheme 7). This is consistent with the addition of 5 equiv. of  $[\text{Et}_3\text{NH}][\text{NTf}_2]$  to **7** resulting in no observable anion exchange (by NMR spectroscopy). Nevertheless, as the BDB process has a significantly lower overall barrier for the  $\text{NTf}_2$  system relative to the iodide analogue (**1** performs BDB at room



Scheme 7 Free energy change for iodide/ $[\text{NTf}_2]^-$  exchange.

temperature, albeit slowly, while **7** requires heating to  $\geq 70$  °C for BDB) anion exchange may still lead to an enhanced BDB outcome. Note, a related anion exchange process facilitating an electrophilic C–H borylation with B-trypticenes has been reported recently using stoichiometric  $\text{Na}[\text{B}(\text{C}_6\text{F}_5)_4]$ .<sup>29</sup>

An initial experiment to assess for any anion exchange derived enhancement in yield used a 0.9 : 0.1 mix of **7** : **1** in the BDB of *N*-Me-aniline with one equiv. of  $\text{Et}_3\text{N}$  as base. Notably, this led to comparable yields for the formation of **3a** (Scheme 8) to that using 1 equiv. of **1**. A significant yield enhancement was also observed using a 0.9 : 0.1 mix of **7** and **1** in the BDB of tetrahydroquinoline to form **3b** post pinacol installation/work-up (Scheme 8). The significant yield enhancement observed using 0.9 : 0.1 mixtures of **7** and **1** indicates it is not just due to compounds **7** and **1** reacting separately in the BDB process. We tentatively attribute this enhancement to a degree of metathesis of an iodo-pyrazabole with  $[\text{Et}_3\text{NH}][\text{NTf}_2]$  (formed during BDB) leading to a more reactive  $\text{NTf}_2$ -pyrazabole electrophile. Note, during these reactions in chlorobenzene solid precipitates, which on analysis was found to be  $[\text{Et}_3\text{NH}][\text{I}]$ . Thus the lower solubility of  $[\text{Et}_3\text{NH}][\text{I}]$  relative to the  $\text{NTf}_2$  salt under these conditions may be assisting anion exchange. The precipitation of  $[\text{Et}_3\text{NH}][\text{I}]$  also will reduce the iodide concentration in solution, potentially slowing the formation of decomposition species. This is consistent with the observation that compound **9** is not observed during the reactions using 0.9 : 0.1 of **7** and **1**.

Overall, these observations suggested that combining **7** with sub-stoichiometric  $[\text{cation}][\text{NTf}_2]$  could result in a similar enhancement in yield. This hypothesis was confirmed by the use of one equiv. of **7** and 0.2 equiv. of  $[\text{Et}_3\text{NH}][\text{NTf}_2]$  in the BDB process leading to a 60% yield of **3a** and a 78% yield of **3b** (comparable to outcomes from conditions B and C in Scheme 8). This is a notable improvement over the yields reported using iridium catalysed transient DG approaches to form *ortho*-BPin-



Scheme 8 Outcomes from using **1**, **7** or **1/7** in the BDB reaction.



*N*-alkyl-anilines.<sup>11,12,30</sup> Note, the use of 0.2 equiv. of LiNTf<sub>2</sub> with 7 gave lower yields relative to using [Et<sub>3</sub>NH][NTf<sub>2</sub>] under otherwise identical conditions, therefore the latter salt is used hereon. With conditions identified that avoided expensive bases and stoichiometric amounts of anhydrous HNTf<sub>2</sub> ([Et<sub>3</sub>NH][NTf<sub>2</sub>] can be stored on the bench and is readily accessible from commercial LiNTf<sub>2</sub> and [Et<sub>3</sub>NH][Cl]) a substrate scope exploration was performed (Scheme 9). The scoping study revealed that in addition to **3a** and **3b** the conditions were amenable to larger alkyl substituents on nitrogen, with the *N*-<sup>i</sup>Pr derivative, **3c**, isolated in 52% yield. Alongside **3b**, the seven (**3d**) and five (**3e**) membered analogues were also amenable to BDB, indicating the change in positioning of the *N*-bound pyrazabole unit enforced by the different ring sizes does not significantly influence this BDB reaction. Notably, neither **3d** nor any other C9 borylated benzo[*b*]azepines have been reported previously to

our knowledge. This is despite the significant importance of substituted benzo[*b*]azepines in pharmaceuticals and agrochemicals, including C9-substituted derivatives (*e.g.* zilpaterol).<sup>31</sup> In contrast, the *ortho*-methyl derivative, 2,*N*-Me<sub>2</sub>-aniline, was not amenable to this process. We attribute this to the *ortho* methyl forcing an orientation that disrupts conjugation between the aniline phenyl ring and the nitrogen lone pair. This was supported by calculations on analogues of **5** containing 2,*N*-Me<sub>2</sub>-aniline (twisted away from co-planarity by 44°) and indoline and tetrahydroquinoline (see Table S4†) – with the latter two compounds and **5** having close to co-planar *N* and phenyl units that maximise conjugation and thus increase the nucleophilicity of the π system (thereby favouring S<sub>E</sub>Ar).

Moving to other substituents, as this is an electrophilic borylation using borenium cation equivalents and forcing conditions, functional group tolerance will be limited (as indicated by the *p*-MeO derivative not being amenable to this process),<sup>23</sup> but halides and NR<sub>2</sub> groups are tolerated (*vide infra*). Furthermore, while the *ortho* methyl aniline derivative was not amenable substituents at the *meta* (**3f** and **3i**) and *para* (**3g** and **3h**) positions of *N*-Me-aniline were tolerated. This BDB process was found to be sensitive to arene electronics, with electron withdrawing groups significantly retarding BDB, requiring longer reaction times for **3h** and **3i**. Consistent with this observation, an *N*-Me-aniline substrate substituted with an electron donating group, specifically a *para*-piperidine unit, performed much better in this BDB process, with **3j** isolated in 62% yield. *Ortho*-substituted anilines containing a *para*-piperidine unit are important as these motifs are found in approved and developmental bioactives, *e.g.* Brigatinib and ASP3026.<sup>32</sup> Next, we attempted to extend this BDB process to aniline and diphenylamine. However, in both cases no *ortho* borylated products (**3k** and **3l**) were isolated. While diphenylamine is presumably insufficiently nucleophilic for this BDB reaction (consistent with an S<sub>E</sub>Ar type process), the origin of the incompatibility of aniline with this BDB reaction is currently unclear. Finally, we assessed the amenability of this methodology to scaling and glovebox free conditions: compound **3a** was isolated in 62% yield when the BDB process was scaled up ten-fold, while **3a** was isolated in 45% yield under glovebox free conditions (making **7** *in situ* from bench stable pyrazabole and iodine, note pyrazabole itself is readily accessed from pyrazole and L → BH<sub>3</sub>).<sup>19</sup>



Scheme 9 Substrate scope and isolated yields (unless otherwise stated) for the BDB of aniline derivatives using **7**/Et<sub>3</sub>NH[NTf<sub>2</sub>]. <sup>a</sup> = conversion *versus* an internal standard.

## Conclusions

Iodine is an inexpensive activator for pyrazaboles that forms mono- and di-topic pyrazabole electrophiles, with the latter effective in the borylation directed borylation (BDB) of *N*-alkyl anilines. However, when using diiodo-pyrazabole **7** competitive formation of inactive (for BDB) species occurs that arise from break-up of the B<sub>2</sub>N<sub>4</sub> pyrazabole core. This leads to lower BDB conversions using **7** than when using the di-NTf<sub>2</sub> pyrazabole analogue **1** (which reacts with <5% of unwanted side products by NMR spectroscopy). The attractive features of both systems (iodine = cheaper and easy to handle activator, while NTf<sub>2</sub>-pyrazaboles = higher conversions in BDB) can be combined by



using the diiodo-pyrazabole **7** in combination with 0.2 equiv. of  $[\text{Et}_3\text{NH}][\text{NTf}_2]$ . This BDB methodology is operationally simple (no glovebox required) and is applicable to a range of *N*-alkyl anilines. The primary BDB products can be readily transformed into synthetically ubiquitous pinacol boronates esters, thus this process represents a metal-free transient directed C–H borylation methodology to form desirable *N*-alkyl-2-BPin-anilines.

## Data availability

The data supporting this article has been uploaded as part of the ESI,† this includes NMR spectra for all new compounds, *in situ* NMR spectra for catalytic and mechanistic reactions and Cartesian coordinates for all calculated structures.

## Author contributions

MI, and CM conceived the research concept and aims and analysed all data. CM performed the majority of the synthetic work and the majority of the analytical components of this project. EN, AS, and JP also performed the synthesis and characterisation of a number of compounds reported in this manuscript. GN and JP collected and solved all the crystal structures. JL performed a number of the calculations. Combined, MI, CM and EN drafted, reviewed and edited the manuscript.

## Conflicts of interest

There are no conflicts to declare.

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