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Monomeric (dialkylamino)boranes: a new and efficient boron source in palladium catalyzed C–B bond formation with aryl halides

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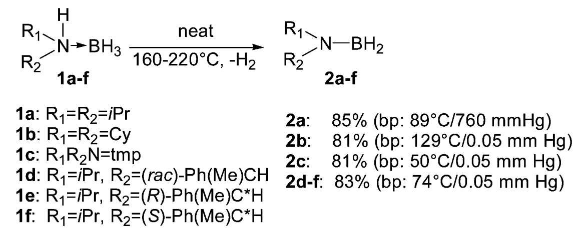
Thermal decomposition of hindered amine-borane adducts leads in high yields to monomeric (dialkylamino)boranes $R_1R_2N–BH_2$ (R_1 and R_2 = alkyl) that are new and efficient boron-sources in the Pd^0 catalyzed borylation reaction affording monomeric aryl(dialkylamino)boranes $R_1R_2N–BHR_3$ (R_3 = aryl).

Aminoboranes ($R_1R_2N–BR_3R_4$) are well known in material science as precursors of BN-based ceramics.[1] Among them and since discovery of the hydroboration reaction in 1956, (amino)-dihydridoboranes ($R_1R_2N–BH_2$) were scarcely studied as useful tools for organic synthesis probably because of their lack of reactivity as hydroborating agents.[2]

One would expect (amino)dihydridoboranes to offer a moderate synthetic attraction and the usual borane reductive properties *via* hydride transfer. Interestingly, their potential is greatly broadened with the present description of their unprecedented boron transfer ability in palladium-catalyzed Csp^2–B bond formation.

(Amino)dihydroboranes readily form mixtures of cyclic and linear oligomers[3] that often prevent any purification. Provided that the nitrogen atom is hindered enough, they can be obtained in their monomeric form by tedious reduction of corresponding (amino)dihaloboranes[4] or *via* the under-used thermally-induced dehydrogenation[5] of chosen secondary amine-borane adducts. We then revisited this thermal decomposition considering the incidence of steric hindrance on the physical properties of the final product in order to define the best monomeric candidates, including a chiral version[6] for further synthetic purposes. Monomeric aminoboranes **2a–f** were easily isolated in more than 80% yield in a multigram scale as distillable and non-pyrophoric liquids (Scheme 1). ^{11}B NMR spectroscopy revealed in all cases a deshielded triplet in the range of 35–36 ppm ($122 < {}^1J_{BH} < 137$ Hz) which is in agreement with the expected monomeric aminoboranes **2** structures and excluded *ipso facto* the cyclic patterns.[3]

The potential of (dialkylamino)boranes **2** was then evaluated through their ability to react in a palladium-catalysed coupling process, in dioxane at 80 °C for 15 h in the presence of 4-iodoanisole (**3a-I**), triethylamine as the base and a catalytic amount (5 mol%) of $(Ph_3P)_2PdCl_2$. Interestingly, (dialkylamino)boranes **2a–d** led to the corresponding aryl(dialkylamino)-monohydridoborane **4a–7a** (Scheme 2) in good to high yields. The outcome of the borylation of 4-iodoanisole (**3a(I)**) appeared to be dependent on the steric bulk of the amino moiety in **2**. Borylation was performed in 99% yield with less hindered **2a** *vs*. 51% with the overcrowded **2c**; satisfactory conversion being obtained with **2d** and **2b**.

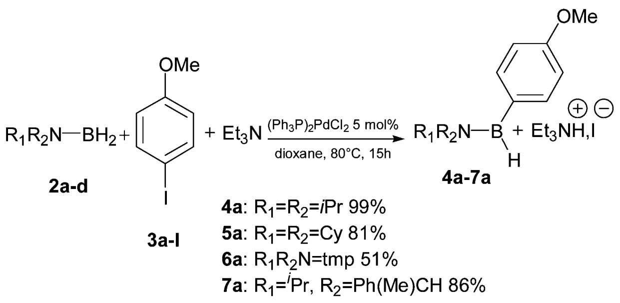


Scheme 1 Thermal decomposition of secondary amine-borane adducts **1**.

It was also of interest to investigate the scope of the reactivity of aminoboranes **2** toward different haloarenes. Selected results with **2a** and representative aryl halides **3** are listed in Table 1.

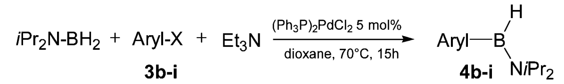
2a displays an H : B ratio of 2 as compared to 1 in pinacolborane. Nevertheless, hydrogenolysis of the carbon–halogen bond was barely observed with aryliodides and limited to some extent with arylbromides except in the case of bromonaphthalene (Table 1-entry 11). Best results were obtained with electron-rich aryl halides compare to electron poor haloarenes (Table 1-entries 12, 13).

We have also tried to get some insights into the mechanism of catalyzed borylation reactions[7,8] with organoboranes. In Masuda borylation,[9] authors had inconclusive evidences for a mechanism involving an aryl-Pd^{II}-X intermediate resulting from the oxidative addition of **3** to the $[(Ph_3P)_2Pd^0]$ active intermediate. However, they did not exclude the formation of aryl–Pd–B(OR)$_2$ *via* a σ-bond metathetic pathway between the aryl halide and a H–Pd–B(OR)$_2$ intermediate resulting from a first addition of the organoborane to palladium. In our case with **2a**, two experimental features are different from Masuda's observations. Starting from iodobenzene and **2a** in the presence



Scheme 2 Catalyzed borylation of 4-iodoanisole with (dialkylamino)boranes **2**.

Table 1 Borylation of representative aryl halides **3** with **2a**



Entry	3	Yield (%)^a	
1	**3b-I**: C_6H_5–I	**4b**	99%
2	**3b-Br**: C_6H_5–Br	**4b**	79%
3	**3c-I**: 4-Me–C_6H_4–I	**4c**	85%
4	**3c-Br**: 4-Me–C_6H_4–Br	**4c**	80%
5	**3d-I**: 3-Me–C_6H_4–I	**4d**	91%
6	**3d-Br**: 3-Me–C_6H_4–Br	**4d**	73%
7	**3e-I**: 2-Me–C_6H_4–I	**4e**	94%
8	**3e-Br**: 2-Me–C_6H_4–Br	**4e**	50%
9	**3f-I**: 4-Me$_2$N–C_6H_4–I	**4f**	99%
10	**3g-I**: 1-$C_{10}H_7$–I	**4g**	80%^{b}
11	**3g-Br**: 1-$C_{10}H_7$–Br	**4g**	20%^{c}
12	**3h-Br**: 4-F–C_6H_4–Br	**4h**	70%
13	**3i-Br**: 4-NC–C_6H_4–Br	**4i**	34%^{d}

[a] Isolated yields. 20%. [b] 60%. [c] And 40%. [d] Hydrogenolysis.

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of 5 mol% of authentically isolated [PhPd(I)(PPh_3)$_2$], phenyl-(diisopropylamino)borane **4b** was isolated in 85% yield in the same reaction conditions. Moreover, starting from **2a** and 4-fluorobromobenzene (Table 1-entry 12), coupling product **4h** was contaminated by about 10% of **4b** (PhBHN*i*Pr_2) resulting from aryl exchanges of [4-F–C_6H_4–Pd(Br)(PPh_3)$_2$] giving [PhPd(Br)(PPh_3)(PPh_2(4-F–C_6H_4))].[10] Accordingly, with (diisopropylamino)borane **2a** as the boron-donor, the likely oxidative addition step of **3** is clearly confirmed. Also of interest is the impact of electronic effects in the organic electrophiles for the outcome of the borylation reaction.

It is known that the oxidative addition is favoured with electron poor aryl halides. This fact takes much importance in the Suzuki–Miyaura coupling in which oxidative addition is the rate-determining step of the catalytic cycle.[11] In our case with aminoborane **2a**, the results suggest that rate-limitation in this catalytic process could be attributed to a slow transmetalation that allow the phosphine-bound aryl side coupling to take place in enhanced ratio. However, the transmetalation step is a debatable question. To rationalize this point, Masuda *et al.* proposed an intriguing triethylamine/pinacol- or catecholborane interaction mode. Lewis acid–base adduct is the most common interaction mode that one would normally expect between an amine and a B^{III}-containing organoborane.[12] Authors however suggested, by analogy with trichlorosilane reactivity, this interaction would lead to an ammonium/boride ion pair of type $Et_3NH^+.^-B(OR)_2$ with the boride as the active transmetalating anion.[13] With pinacol- or catecholborane acting as a proton provider able to protonate triethylamine into triethylammonium, this process is difficult to conceive outside the coordination sphere of a transition-metal.[14] In order to check the proposed hypothesis, various amounts of triethylamine were added to **2a** and pinacolborane respectively. Monitoring the reactions by variable temperature ^{11}B NMR and ^{14}N NMR spectroscopy did not allow us to detected either ionic nor Lewis acid–base interaction between the reagents even with triethylamine as the solvent.[15] Aminoborane **2a** and (Ph_3P)$_4$Pd in stoichiometric amounts did neither afford any detectable entity exhibiting the H–Pd–B sequence. From PhPd(I)(PPh_3)$_2$ and a two fold excess of aminoborane **2a**, triethylamine and heat appeared both necessary to give **4b**. These results are not in favour of Masuda's hypothesis even if they do not completely clarify the role of triethylamine in the post oxidative-addition mechanism. The involvement of a Pd^{IV}-transient species resulting of the oxidative addition of the borane to the X-Pd^{II}-aryl intermediate would be an elegant way out but without extra evidences the mechanism keeps open.

In conclusion, monomeric aminoboranes **2** are easily and cleanly obtained from secondary amine-borane adducts **1** in a multigram scale. They are excellent and new boron transferring agents that tolerate a wide range of aryl halides **3**. Experimental evidence now clearly confirm a mechanism involving aryl-Pd-X species *via* the oxidative addition of **3** to the [(Ph_3P)$_2$Pd] active catalyst in a first non rate-determining elementary step. The role of the amine in the transmetallation step is not understood and the mechanism is currently under investigation.†

Notes and references

† *Selected spectroscopic data*: for **2a**: ^1H NMR (300 MHz, $CDCl_3$): δ 1.17 (d, CH_3), 3.38 and 3.41 (hept, CH). $^{13}C\{1H\}$ NMR (75 MHz, $CDCl_3$): δ 25.1 (s, CH_3), 52.3 (s, CH). ^{11}B NMR (96 MHz, $CDCl_3$): 35.0 (d, $^1J_{BH}$ 126.2, BH). ^{14}N NMR (21.7 MHz, $CDCl_3$) −209 (s, br, NB). For **5a** ^1H NMR (300 MHz, $CDCl_3$): δ 1.21 and 1.34 (d, CH_3), 3.42 and 4.34 (hept, CH), 3.87 (s, OCH_3), 6.96 and 7.47 (d, CH aryl). $^{13}C\{1H\}$ NMR (75 MHz, $CDCl_3$): δ 22.6 and 27.4 (s, CH_3 ^{i}Pr), 44.9 and 49.4 (s, CH ^{i}Pr), 55.2 (s, OCH_3), 113.5 and 135.5 (s, CH aryl), 159.8 (s, C^{IV}–OMe). ^{11}B NMR (96 MHz, $CDCl_3$): 37.6 (d, $^1J_{BH}$ 90, BH). HRMS [$M^{+\cdot}$] calcd. for $C_{13}H_{22}NOB$: *m*/*z* 219.1794. Found 219.1794 (0 ppm).

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