Organophosphorus-catalyzed relay oxidation of H-Bpin: electrophilic C–H borylation of heteroarenes†

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A nontrigonal phosphorus triamide (1, P(N(o-NMe-C6H4)2)) is shown to catalyze C–H borylation of electron-rich heteroarenes with pinacolborane (HBpin) in the presence of a mild chloroalkane reagent. C–H borylation proceeds for a range of electron-rich heterocycles including pyrroles, indoles, and thiophenes of varied substitution. Mechanistic studies implicate an initial P–N cooperative activation of HBpin by 1 to give P-hydrido diazaphospholene 2, which is diverted by Atherton–Todd oxidation with chloroalkane to generate P-chloro diazaphospholene 3. DFT calculations suggest subsequent oxidation of pinacolborane by 3 generates chloropinacolborane (ClBpin) as a transient electrophilic borylating species, consistent with observed substituent effects and regiochemical outcomes. These results illustrate the targeted diversion of established reaction pathways in organophosphorus catalysis to enable a new mode of main group-catalyzed C–H borylation.

Introduction

Recent innovations in synthetic organophosphorus chemistry are fueling new opportunities for catalysis. As a complement to well-known nucleophilic (Lewis basic) reactivity, new structural design principles are emerging that now enable organophosphorus catalysis to comprise Lewis acidic, dehydrative, redox O-atom transfer, and reductive activation modes for catalysis. Within this vein, nontrigonal phosphorus triamide 1 (ref. 7) was reported to catalyze the activation and transfer of H–Bpin to imines in a ligand cooperative fashion via the intermediacy of P-hydrido diazaphospholene 2 (Scheme 1, top). The pronounced hydricity of related P-hydrido diazaphospholenes—studied extensively by Gudat—has been advanced by Kinjo,11 Speed,12 Cramer,13 and Melen14 within the context of hydroboration catalysis to effect either 1,2- or 1,4-addition of H–Bpin to π-electrophiles (e.g. imines, carbonyls, and pyridines).

With a view toward enabling new reactivity, we considered that catalytic hydriboration by 1 might be interrupted by the inclusion of an exogenous sacrificial electrophile to scavenge the activated hydride of 2, achieving catalytic oxidative crossover to P-chloro diazaphospholene 3. Doing so would present the possibility that the established reductive manifold, i.e. hydroboration with H–Bpin, of diazaphospholene catalysis might be diverted via sequential oxidative transfers, or relay oxidation, to access electrophilic “pinB+” synths for delivery.

Scheme 1. Previous work: imine hydriboration catalyzed by nontrigonal phosphorus triamide 1. Guiding hypothesis: diversion of reactivity via relay oxidation can be accomplished by Atherton–Todd crossover of P–H in 2 for P–Cl in 3. Present work: direct heteroarene C–H borylation with HBpin catalyzed by 1 in presence of chloroalkane electrophile.
to suitable nucleophilic substrates for C–H borylation (Scheme 1, bottom). Herein, we realize this vision and achieve a C–H borylation of electron-rich heteroarenes with H–Bpin as the boron donor under the catalytic action of phosphorus triamide and a mild chloroalkane oxidant, establishing a new organophosphorus catalyzed platform for C–H borylation.

Results and discussion

The success of the proposed catalytic platform is predicated upon the compatibility and interplay of both reducing (HBpin) and oxidizing (sacrificial electrophile) reagents with the organophosphorus catalyst 1. Inspired by an observed Atherton–Todd-like chlorination of P-hydrido diazaphospholene, we considered the possibility that even a weak electrophilic reagent such as chloroform might efficiently serve to capture the P–H hydride of 2 and thus divert H–Bpin activation toward electrophilic borylation via relay oxidation. As an initial probe of this hypothesis, the reaction of N-Me-pyrrole (4a) with HBpin (1 equiv.) and NEt₃ under the action of catalytic phosphorus triamide 1 and a mild chloroalkane oxidant, establishing a new organophosphorus catalyzed platform for C–H borylation.

Table 1  Discovery and optimization of organophosphorus-catalyzed C–H borylation of electron-rich heterocycles

| Entry | 1 (mol%) | HBpin (equiv.) | Base (equiv.) | [C]–Cl (equiv.) | Temp (°C) | 5a (%) |
|-------|----------|----------------|--------------|----------------|-----------|--------|
| 1     | 10       | 1              | NEt₃ (1)     | CHCl₃          | 80        | 8      |
| 2     | 10       | 1              | NEt₃ (1)     | CHCl₃          | 80        | 8      |
| 3     | 10       | 1              | NEt₃ (1)     | CHCl₃ (2)      | 100       | 29     |
| 4     | 10       | 1              | NEt₃ (1)     | CHBr₃ (2)      | 100       | 0      |
| 5     | 10       | 1              | NEt₃ (1)     | CHCl₃ (2)      | 100       | 28     |
| 6     | 10       | 1              | Et₄NPr₂ (1)  | CHCl₃ (2)      | 100       | 35     |
| 7     | 20       | 2              | Et₄NPr₂ (2)  | CHCl₃ (2)      | 100       | 50     |
| 8     | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (2)    | 100       | 60     |
| 9     | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (2)    | 100       | 60     |
| 10    | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (1)    | 100       | 60     |
| 11    | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (1)    | 100       | 60     |
| 12    | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (1)    | 100       | 0      |
| 13    | 20       | 2              | Et₄NPr₂ (2)  | PhCHCl₃ (1)    | 100       | 0      |
| 14    | 20       | 2              | Et₄NPr₂ (2)  | None           | 100       | 0      |

a Reactions conducted on 0.125 mmol scale, 0.25 M in MeCN. b H NMR yields compared to internal standard. c CHCl₃ used as solvent in place of MeCN. d Reactions conducted at 25, 50, and 80 °C also yielded 0% 5a. e Et₄NBr (0.1 equiv.) additive. f HBcat (2 equiv.) used in place of HBpin. HBpin = pinacolborane. HBcat = catecholborane.
relative to steric effects. Substitution at all positions of the benzenoid ring could be similarly tolerated, as methyl substitution at the C4-position had no effect on the efficiency with respect to unsubstituted indole substrate, yielding 5e in 74% yield. Substitution at each of the C5-, C6-, and C7-positions with a methoxy groupboosted efficiency, delivering C3-borylated product in excellent yield (5f–5h, 83–87% yields). While N-H and N-silyl indoles did not deliver synthetically useful yield of borylation products, N-Bn-indole could be borylated in good efficiency (5i, 45% yield, >99% yield based on recovered starting material). Also, tricyclic indole alkaloid lilolidine could be borylated in near-quantitative efficiency to deliver 5j (98% yield). Other electron-rich heterocycles are subject to borylation, as demonstrated by the formation of 5k from 2-OMe-thiophene. However, π-rich benzenes are unreactive, as exemplified by no formation of 5l from N,N-dimethylaniline. 21

A systematic variation of substituents on the benzenoid ring of indole substrates revealed a reactivity pattern which is gated by heteroarene nucleophilicity (Scheme 3), indicative of a borylation event proceeding via an electrophilic aromatic substitution reaction (S_{EAr}) pathway. In the case of C4-substituted indoles (Scheme 3A), the formation of borylation products 5 correlates with Hammett substituent constant \( \sigma_{meta} \); specifically, inclusion of a 4-methoxy substituent (\( \sigma_{meta} = 0.1 \)) leads to lower yield (33%) than the parent 5-unsubstituted substrate (75%). Relatedly, C5-substitution of indoles trend with substituent constant \( \sigma_{para} \) (Scheme 3B), such that 5-methoxy substitution (\( \sigma_{para} = -0.3 \)) gives higher yield (90%) than the parent 4-unsubstituted substrate. 24 While strongly electron-withdrawing substituents such as CN completely suppressed borylation independent of C4/C5 position on the indole, weakly withdrawing 5-F substitution on 1-methylindole provided synthetically useful levels of efficiency upon conducting the reaction at 100 °C for 24 hours (5m, 60% yield).

In situ NMR analysis of a representative catalytic reaction is consistent with the evolution of compounds 1, 2, and 3 as envisioned (Scheme 4). Specifically, \(^{31}P\{(\text{H})\}\) NMR spectral monitoring of the catalytic borylation of 1,2-dimethylindole (4d) with HBpin and CHCl\(_3\) by catalyst 1 shows initial conversion of 1 (\( \delta \) 159.7 ppm) to \( \text{P}-\text{hydrido diazaphospholene} \) (P by reaction with HBpin. Compound 2 is further converted to \( \text{P}-\text{chloro diazaphospholene} \) (\( \delta \) 147.0 ppm) within ca. 2 h, ultimately reaching a steady state ratio of 3 : 2 (ca. 4 : 1) that persists for the duration of the borylation reaction (96% yield of 5d after 16 h). Complementary monitoring in the \( ^1H \) and \(^{11}B \) NMR channels indicates a delay in formation of borylation product 5d until a significant concentration of 3 is accrued (2%...
yield of 5d at 2 h). Evidently, P-chloro diazaphospholene 3 is necessary for product formation; indeed, when 3 is employed directly as a catalyst under otherwise identical conditions, formation of product 5d was observed without an induction period. Moreover, $^{13}$P NMR spectra confirm the formation of 2 under these catalytic reaction conditions with catalyst 3, converging on a 4:1 steady-state ratio of 3:2 as was observed by reaction with catalyst 1. Taken together, these spectroscopic results are consistent with sequential activation of HBpin by 1 and of CHCl$_3$ by 2, followed by turnover-limiting reaction of 3, presumably to effect C–H borylation of 4d.

A single turnover experiment reacting 3 with 4d under conditions that lack exogenous chloroalkane reagent but otherwise approximate the catalytic reaction (i.e., containing HBpin and EtN$_2$P$_2$) resulted in formation of borylated product 5d in 87% yield with respect to 3 (Scheme 5A, bottom). In this reaction, P-chloro diazaphospholene 3 is converted cleanly into P-hydrido diazaphospholene 2 with no observable intermediates along the reaction pathway (see ESI† for in situ $^1$H and $^{31}$P NMR reaction profile). However, an analogous stoichiometric reaction of 3 with 4d omitting the additional HBpin did not lead to C–H borylation (Scheme 5A, top); moreover, $^{31}$P NMR spectra demonstrate the conversion of P-chloro diazaphospholene 3 to the nontrigonal phosphorus triamide 1 in this experiment.

Evidently, P-chloro diazaphospholene 3 is, in itself, necessary but insufficient to effect the C–H borylation of 4d under these single turnover conditions. Although a downstream borylating species arising from the interaction of 3 and HBpin might be presumed, the simple mixture of 3 and HBpin at 60 °C does not yield any spectroscopic changes. Regrettably, then, the identity of the active borylating species cannot be unambiguously assigned at this time via experimental means.

Density functional theory (DFT) calculations were performed to investigate the reactivity of 3 as the active borylating species or precursor. Consistent with the aforementioned experimental results, direct S$_2$Ar borylation of 4d with the pendant Bpin moiety of 3 (TS1, $\Delta G^\ddagger = 57.6$ kcal mol$^{-1}$) requires an insurmountably high activation energy (Scheme 5B, top). Further, unimolecular decomposition of 3 to generate 1 and electrophilic Cl–Bpin was found to be substantially uphill (Scheme 5B,

Scheme 5  (A) Stoichiometric borylation of 4d occurs from 3 only in the presence of additional HBpin. EtN$_2$P$_2$ (1 equiv.), MeCN, 60 °C, 3 h. $^1$H NMR yields compared to internal standard. (B) DFT calculations indicate (top) direct borylation from 3 is kinetically inaccessible, while (bottom) release of electrophilic Cl–Bpin from 3 is substantially thermodynamically uphill. DFT calculations were performed at the M06-2X/6-311+G(d,p), SMD(MeCN)/M06-2X/6-31G(d), SMD(MeCN) level of theory. All energies are in kcal mol$^{-1}$.

Scheme 6  (A) DFT calculations indicate (top) a kinetically accessible, minimally uphill stepwise metathesis reaction between 3 and H–Bpin to generate Cl–Bpin, with a contraction of d(P–O) in TS2 and TS3, and (bottom) facile S$_2$Ar borylation of 4d with Cl–Bpin. DFT calculations were performed at the M06-2X/6-311+G(d,p), SMD(MeCN)/M06-2X/6-31G(d), SMD(MeCN) level of theory. Bond distances are in angstroms. All energies are in kcal mol$^{-1}$. Hydrogen atoms in 3D structures are omitted for clarity. (B) Stoichiometric borylation of 4d with 7, lacking the N(OMe)Bpin moiety, is significantly diminished relative to 3.

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bottom, $\Delta G = 15.9 \text{ kcal mol}^{-1}$, indicating that, while 1 is observed as a decay product of 3 in the presence of 4d and EtNPF$_3$ (see Scheme 5A, top), it is likely not generating Cl-Bpin in this process due to the energetic penalty.

Given the evident requirement of H-Bpin in addition to 3 to achieve C–H borylation, DFT calculations were performed on higher-order reaction pathways (see ESI for full details). These calculations suggest that highly electrophilic chloropinacolborane (Cl-Bpin)$^{22}$ can be generated via a stepwise, formal o-bond metathesis between H-Bpin and the P–Cl bond of 3 with kinetically accessible barriers of $\Delta G^\ddagger = 19.2$ and 21.9 kcal mol$^{-1}$ for P–Cl cleavage (TS2) and P–H formation (TS3), respectively, via the intermediacy of 6 (Scheme 6A). Although the conversion of H–Bpin to Cl–Bpin is endergonic by 3.7 kcal mol$^{-1}$, the subsequent borylation of 4d with Cl–Bpin proceeds with a low relative barrier of 16.7 kcal mol$^{-1}$ (TS4) and is highly exergonic upon deprotonation and rearomatization.

Although such an endergonic exchange reaction between HBpin and 3 was not observed experimentally (via in situ NMR of the full reaction mixture or isolated reaction of the two species), insights can be drawn from analysis of the stepwise metathesis pathway. In the course of the reaction of 3 and HBpin to form 2, the distance between an O-atom of the Bpin moiety of 3 and the electropositive P-atom shortsens in the rate-limiting TS ($d$($\text{P-O}$) = 2.95 Å and 2.90 Å in 3 and TS3, respectively), indicating the formation of Cl–Bpin is possibly promoted by a stabilizing P–O interaction in the transition state. To probe this hypothesis, diazaphospholene 7, which lacks the pendant N(Me)Bpin moiety, was synthesized and exposed to the single turnover conditions (Scheme 6B). Consistent with the delineated hypothesis, product 3d was formed in substantially diminished yield of 12%. Thus, this unexpected Lewis base-stabilization effect provides a potential guiding principle for future development.

In accordance with the preceding experimental and computational results, the mechanism in Scheme 7 is proposed. First, during the induction period phosphorus triamide 1 activates HBpin to generate P-hydrido diazaphospholene 2. Then, catalytic relay oxidation occurs in which 2 reacts with chloroalkane to generate $P$-chloro diazaphospholene 3, followed by stepwise metathesis with H-Bpin to provide Cl-Bpin and regenerate 2. In effect, the facile oxidation of the P–H bond of 2 enables the downstream oxidation of the B–H bond of H–Bpin. Subsequently, the catalytically generated, substoichiometric electrophile Cl–Bpin can undergo $S_p$Ar borylation with substrate to provide borylated product. Notably, Cl–Bpin is known to be extremely unstable and difficult to prepare,$^23$ and its reactivity in $S_p$Ar borylation has therefore not been previously reported. Thus, a catalytic platform for the in situ substoichiometric generation of Cl–Bpin from H–Bpin is a novel approach to borylative chemistry via relay oxidation, as proposed in Scheme 1.

Conclusions

To summarize, nontrigonal phosphorus triamide 1 represents the first organophosphorus catalyst to enable C–H borylation of electron-rich heteroarenes. In this transformation, a novel mode of catalysis is realized by targeted diversion of an established hydroboration pathway of 2 with a sacrificial chloroalkane electrophile via Atherton–Todd oxidation, diverting the reactivity towards electrophilic borylation from 3. Computational studies support the in situ generation of the highly electrophilic Cl–Bpin, which serves as a fleeting intermediate for $S_p$Ar borylation, avoiding the difficulties inherent to working with stoichiometrically-generated Cl–Bpin. This novel phosphacatalytic system is poised for further study of the impact of catalyst structure on this mode of catalysis in borylative transformations.

Conflicts of interest

There are no conflicts to declare.

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