The adduct [MeO → Bpin–Bpin]− efficiently mediates the β-boration of α,β-unsaturated imines formed in situ. The use of chiral phosphines as additives, and in particular the chiral phosphine (S)-MeBoPhoz, enables the catalytic asymmetric reaction to proceed with higher enantioselectivity than the analogue copper(I) mediated reaction.

Metal-free activation of diboron reagents has gained significant momentum, particularly to generate C–B bonds in an organocatalytic context.1–3 However, the development of a general, highly efficient asymmetric version of this reaction is still an important goal4 with only limited successful examples.5,6 Therefore, Cu(I) catalysts have become the most widely used for inducing asymmetry in β-boration, since Yun et al.5 discovered that copper catalysts modified with chiral phosphines can activate diboron reagents, such as bis(pinacolato)diboron (B2pin2), and catalyze the borylation of α,β-unsaturated carbonyl compounds with high levels of enantioselectivity, in the presence of MeOH.6 In this context, we have found that this approach might enable efficient access to γ-aminoalcohols from the corresponding α,β-unsaturated imines.7 The optimal combination of an amine (for imine formation), a copper source and a chiral ligand, followed by careful selection of a reducing reagent has provided a convenient methodology to obtain γ-aminoalcohols in a highly diastereo- and enantioselective manner (Scheme 1, pathways A and B).7 The unique attempt to perform the β-boration of (E)-1-phenyl-N-(4-phenylbutan-2-ylidene)methanamine, in the absence of Cu(I) salts as precatalysts, required the substrate preactivation by Lewis acidic Fe(II) and Fe(III) salts (Scheme 1, pathway C).8

Here, we have developed an asymmetric organocatalytic approach to generate C–B bonds at the β-position of an unsaturated imine, i.e. Scheme 1, pathway D, as an alternative strategy to synthesize γ-aminoalcohols. Towards this end, we focus our efforts on the in situ generation of a model α,β-unsaturated imine, i.e. (E)-1-phenyl-N-(4-phenylbutan-2-ylidene)methanamine, from 4-phenyl-3-buten-2-one (1) and benzylamine in THF with the dehydrating reagent, MK10.7a,d After 6 hours, the
isolated yields were obtained for the corresponding γ-amino alcohols by reduction with NaBH₄ in methanol and oxidation with H₂O₂ in NaOH.

With these preliminary results in hand, we extended this observation to other ketone and amine combinations, to develop a general organocatalytic methodology for the β-boration of α,β-unsaturated imines. Interestingly, nBuNH₂ was also a versatile amine for the imine formation with 1, and was compatible with the organocatalytic β-boration to produce quantitatively the β-borated imine 2b (Table 1, entry 5). Electron accepting and electron releasing substituents at the para-position of the phenyl group of the ketone substrates 3 and 5, respectively, did not change the reaction outcome (Table 1, entries 6–8). Hence, it can be seen that the organocatalytic β-boration of in situ formed α,β-unsaturated imines is a general and indeed new methodology for the formation of β-borylated imines in a one-pot reaction.

In the next step we considered the possibility of inducing asymmetry into the formation of the new C–B bond using this organocatalytic approach. Hence, we proposed that chiral phosphine additives might interact with the substrate and provide an asymmetric environment for the β-boration with the Lewis acid–base adduct [i.e. MeO⁻ → Bpin–Bpin]. This concept had already been successfully demonstrated in the β-boration of α,β-unsaturated ketones with B₂pin₂ or BpinBdan (dan = 1,8-diaminonaphthalene) (see Scheme 2).2e and the hypothesis of the role of the phosphine in the asymmetric induction has also been postulated from both an experimental and theoretical point of view.9

However, since imine functionality is more sterically hindered and less polarized than the carbonyl group, we were interested to ascertain whether asymmetric induction would be more or less efficient. Hence, we initiated our studies with substrate 1 and conducted the imine formation with benzylamine, followed by β-boration with the Lewis acid–base [MeO⁻ → Bpin–Bpin] adduct in the presence of a series of chiral diphosphines. Preliminary results using chiral Josiphos-type of diphosphines did not provide any significant asymmetric induction, which contrasts with the efficient trends observed with the corresponding ketones.2d Relatively, however, when the [MeO⁻ → Bpin–Bpin] adduct was used with the diphasphines (Scheme 2).

![Scheme 2 β-Boration of α,β-unsaturated ketones with B₂pin₂ and BpinBdan (dan = 1,8-diaminonaphthalene), assisted by chiral diphosphines.](image)
sphine (S)-MeBoPhoz (P1), total conversion was observed together with moderate enantioselectivity of the β-borated product (54% ee, Table 2, entry 1). When subtle changes were made to the reaction conditions, such as a lower base loading or a different reaction temperature, conversions and enantioselectivities remained essentially unchanged. However, when the β-boration was carried out in the presence of CuCl (3 mol%), conversions from 1 to 2a were high but lower ees were observed (32% ee, Table 2, entry 2). Note that the isolated yields of the product are given for the final syn-γ-aminoalcohol after a highly stereoselective reduction protocol with NaBH₄ in MeOH, as reported previously, followed by oxidation with H₂O₂ in NaOH.

Table 2 Asymmetric organocatalytic versus asymmetric Cu(I) catalyzed β-boration of in situ formed α,β-unsaturated imines with (S)-MeBoPhoz

<table>
<thead>
<tr>
<th>Entry</th>
<th>β-Borated imine</th>
<th>Method</th>
<th>% Conv.</th>
<th>% ee</th>
<th>% I.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bpin NBu</td>
<td>A</td>
<td>90</td>
<td>54</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>Bpin NBu</td>
<td>B</td>
<td>99</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>Bpin NBu</td>
<td>A</td>
<td>94</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>Bpin NBu</td>
<td>B</td>
<td>80</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>Bpin NBu</td>
<td>A</td>
<td>98</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>6</td>
<td>Bpin NBu</td>
<td>B</td>
<td>95</td>
<td>45</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>Bpin NBu</td>
<td>A</td>
<td>96</td>
<td>70</td>
<td>61</td>
</tr>
<tr>
<td>8</td>
<td>Bpin NBu</td>
<td>B</td>
<td>88</td>
<td>61</td>
<td>57</td>
</tr>
<tr>
<td>9</td>
<td>Bpin NBu</td>
<td>A</td>
<td>99</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>Bpin NBu</td>
<td>B</td>
<td>92</td>
<td>33</td>
<td>57</td>
</tr>
<tr>
<td>11</td>
<td>Bpin NBu</td>
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<td>99</td>
<td>57</td>
<td>73</td>
</tr>
<tr>
<td>12</td>
<td>Bpin NBu</td>
<td>B</td>
<td>95</td>
<td>29</td>
<td>52</td>
</tr>
</tbody>
</table>

*a Conditions for method A: ketone or aldehyde (0.5 mmol), amine (0.5 mmol), THF (2 mL), MK-10 (140 mg), B₂pin₂ (1.1 eq.), Cs₂CO₃ (15 mol%), MeOH (2.5 eq.), (S)-MeBoPhoz (10 mol%), 70 °C; for method B: same as method A + CuCl (3 mol%), 25 °C. Conversion determined by ¹H NMR spectroscopy. Enantioselectivity determined from HPLC-MS. Isolated yield for the corresponding syn γ-aminoalcohol (see ESI for reaction conditions). ee calculated on the 4-(N-benzhydrylamidobutyl-2-y) acetate derivative.

Fig. 1 Comparison of the chiral phosphine additives P2–P4 for asymmetric β-boration of α,β-unsaturated imines 4, 6 and 8.

Since (S)-MeBoPhoz has been shown to be the most active and enantioselective additive for accessing β-boryl imines, in this metal free context, we extended this study to other similar chiral phosphines, i.e. P2–P4. We concluded that (R)-PhEt-(R)-BoPhoz (P4) provides comparable asymmetric induction than the close phosphine P1, and higher than the enantioselectivities provided by the other analogues, i.e. P2 and P3, in which the amine is either mono- or di-substituted (Fig. 1).

To gain a deeper insight into the reaction mechanism and compare with other substrates that we reported previously, we conducted DFT-based theoretical studies (Scheme 3).

Initially, we postulated that the methoxide ion can quaternize a boron atom of the B₂pin₂ molecule forming the activated adduct \([\text{MeO} \rightarrow \text{Bpin} – \text{Bpin}]^-\) (chosen as the origin of the

Scheme 3 Mechanistic proposal on the organocatalytic β-boration of imines. Electronic energies and Gibbs free energies (in parentheses) of the involved species in relation to the \([\text{MeO} \rightarrow \text{Bpin–Bpin}]^-\) adduct are shown. All energies are in kcal mol⁻¹.
energies). This adduct can then react with the model α,β-unsaturated imine through a transition state TS, which corresponds to the nucleophilic attack of the sp² boron atom on the β-carbon of the α,β-unsaturated imine. The structural features of the TS show the cleavage of the B–B bond (Δd_{B–B} = 0.257 Å) and the formation of the new B–C bond (d_{B–C} = 2.078 Å). After this transition state (TS), a negatively charged intermediate I is formed. Also in this step, a molecule of (pin)B–OME is released as the by-product. The anionic intermediate I is then protonated in the presence of an excess of B₂pin₂ and MeOH, regenerating again the active species [MeO → Bpin–Bpin⁺] and hence the β-borated product. At this point, it is interesting to compare energy values computed herein, with those obtained for the metal-free β-boration of ketones, esters and aldehydes.\(^1\) For the model imine (E)-1-phenyl-N-(4-phenylbutan-2-ylidene)methanamine, (2a), the transition state TS is higher (ΔG* = 32.3 kcal mol\(^{-1}\)) than that found for acrolein (ΔG* = 16.7 kcal mol\(^{-1}\)), 3-buten-2-one (ΔG* = 18.7 kcal mol\(^{-1}\)), methyl acrylate (ΔG* = 21.5 kcal mol\(^{-1}\)) and styrene (ΔG* = 25.1 kcal mol\(^{-1}\)), but lower in energy than propylene (ΔG* = 35.9 kcal mol\(^{-1}\)). This fact can be explained by the lower electrophilicity of the C\(_β\) of the α,β-unsaturated imine which makes it less reactive towards the nucleophilic attack. Moreover, the intermediate I for the imine (ΔG = −17.2 kcal mol\(^{-1}\)) is energetically more stable than the reactants, as expected, but less stable than the corresponding analogues for the activated alkenes.\(^1\) This can be also rationalized by the fact that the negative charge that is generated is more stabilized by the oxygen atom than the nitrogen due to their different electronegative characters. It is worth mentioning that the reaction energies computed for this model α,β-unsaturated imine substrate are in a similar range to those previously computed for ketones, aldehydes and esters, thus justifying the similarity in the reaction conditions (T = 70 °C) as described above.

Finally, we addressed the role of the chiral phosphine in not only mediating the catalytic reaction but importantly, guiding the asymmetric C–B bond formation. A possible interaction between a model phosphine of reduced steric congestion PMe\(_3\), and the α,β-unsaturated imine 2a, is to form a phosphonium enolate intermediate (Fig. 2).\(^10\)--\(^12\) We compared this with the corresponding α,β-unsaturated ketone-derived enolate species (Fig. 2). Interestingly, the imine-derived phosphonium enamide formed from PMe\(_3\) and 2a is higher in energy than the corresponding ketone-derived phosphonium enolate intermediate, which explains why that reaction has to be carried out at 70 °C, and does not proceed readily at lower temperature. Hence, the origin of the asymmetric induction when using (S)-MeBoPhoz may result from the protonation of the zwitterionic phosphonium enamide with MeOH, and formation of a tight ion-pair between the resulting [B₂Pin₂·MeO⁻]⁻ adduct and the chiral phosphonium imine, i.e. as in 15 (Scheme 4), as we have postulated before.\(^9\)

Conclusions

In conclusion, we have developed the first example of metal-free β-boration of in situ formed α,β-unsaturated imines, highlighting the compatibility of the organocatalytic Bpin addition with the imine formation in the presence of both ketone and amine. The reaction shows little dependence upon substrate electronics and shows consistently high conversion. Importantly, the use of chiral phosphines, such as the diphosphine (S)-MeBoPhoz, enables the catalytic asymmetric version to be realized with moderate asymmetric induction. Interestingly, the enantioselectivity is higher than that induced by the same chiral phosphines when modified using the corresponding Cu(II)-based catalytic system. The mechanism of the organocatalytic β-boration of these α,β-unsaturated imines has been postulated from a theoretical point of view, and seems to necessarily involve quaternization of the diboron reagent with methoxide. The role of the phosphine has been regarded to the ion pair formation and further work to elucidate this issue will be reported in due course.

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Notes and references


