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Catalytic Synthesis of N-Heterocycles via Direct C(sp³)–H Amination Using an Air-Stable Iron(III) Species with a Redox-Active Ligand

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Supporting Information

ABSTRACT: Coordination of FeCl₃ to the redox-active pyridine–aminophenol ligand NNOO₃² in the presence of base and under aerobic conditions generates FeCl₃(NNOOISQ) (1), featuring high-spin Fe⁺ and an NNOOISQ radical ligand. The complex has an overall S = 2 spin state, as deduced from experimental and computational data. The ligand-centered radical couples antiferromagnetically with the Fe center. Readily available, well-defined, and air-stable 1 catalyzes the challenging intramolecular direct C(sp³)–H amination of unactivated organic azides to generate a range of saturated N-heterocycles with the highest turnover number (TON) (1 mol% of 1, 12 h, TON = 62; 0.1 mol% of 1, 7 days, TON = 620) reported to date. The catalyst is easily recycled without noticeable loss of catalytic activity. A detailed kinetic study for C(sp³)–H amination of 1-azido-4-phenylbutane (S₁) revealed zero order in the azide substrate and first order in both the catalyst and Boc₂O. A cationic iron complex, generated from the neutral precatalyst upon reaction with Boc₂O, is proposed as the catalytically active species.

INTRODUCTION

The development of efficient methods for the formation of carbon–nitrogen (C–N) bonds is one of the most crucial tasks in chemical synthesis. The installment of C–N bonds by direct functionalization of C(sp³)–H bonds is a powerful and atom-efficient transformation for chemical synthesis. Although the direct installation of nitrogen into a C(sp³)–H bond is extremely challenging due to the thermodynamic and kinetic stability of the C(sp³)–H bond, intra- and intermolecular C(sp³)–H amination has seen much progress in the past decade.¹ Particularly, intramolecular C(sp³)–H amination as an atom-economical strategy has found extensive applications for the construction of varieties of important N-heterocycles.² Four main strategies have been developed for the construction of C(sp³)–H bonds by direct, intramolecular amination of either activated or unactivated C(sp³)–H bonds. A crucial advance in intramolecular C(sp³)–H amination can be traced back to the Hofmann–Löffler–Fretoy (HLF) reaction, developed in the early 1880s with the initial discovery by Hofmann.³ The N-halogenated amines are utilized as starting materials in HLF reactions, and the generally accepted mechanism involves a free radical pathway (Scheme 1a).⁴ Another effective method involves the oxidation of C,N-dianions generated by successive deprotonation of an N–H and a C–H bond, followed by oxidative coupling under strongly basic conditions (Scheme 1b).⁵ Recently, transition-metal-catalyzed (predominantly palladium) amination has emerged for the activation of aliphatic C–H bonds, which typically requires an electron-withdrawing directing group (Scheme 1c).⁶ Lastly, nitrene (in situ generated) insertion into a C(sp³)–H bond is an efficient and perhaps the best studied approach for C(sp³)–N bond formation.

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formation (Scheme 1d). Nitrenes can be generated either from amines by utilizing a combination of Ph(1)Cl, and MgO or from activated, nonaliphatic organic azides (e.g., sulfonyl azide, aryl azide) or iminoiodinanes in the presence of transition metal catalysts.7

Unfortunately, most of the existing C–H amination strategies involve directing groups, preoxidation of substrates, or external chemical oxidants, leading to poor atom economy and waste generation. In contrast, in situ generation of a metal-bound nitrone species from readily available aliphatic organoazides, releasing only molecular nitrogen as the side product, followed by selective insertion into a C(sp3)–H bond would constitute an efficient approach for catalytic C–H amination. Synthesis of N-heterocycles via direct C(sp3)–H amination using aliphatic azide substrates is an appealing strategy, given that N-heterocycles are prevailing building blocks in natural products, pharmaceuticals, and functional materials (Figure 1a).8 Recently, two reports appeared on air-sensitive FeII.

The ligand NNOH2 is readily accessible following a literature procedure. Coordination of the neutral ligand NNOH2 to FeCl3 in MeOH at −80 °C followed by the addition of NEt3 in air resulted in the paramagnetic dark green solid 1 in good yield (Scheme 2). UV–vis spectroscopy supports the imino-semiquinonato (ISQ) ligand oxidation state (λmax = 740 nm, ε = 8.37 × 103 M−1 cm−1).13–16 Magnetic susceptibility measurements of 1 at 298 K using Evans’ method revealed an effective magnetic moment (μeff) of 4.86 μB, thus indicating an S = 2 ground state, which is consistent with a high-spin Fe center (d5) that is strongly antiferromagnetically coupled with a ligand-centered NNO radical. Temperature-dependent solid-state SQUID measurement and zero-field 57Fe Mössbauer spectroscopy confirmed the total S = 2 ground state (Q = 0.85 mm/s), respectively (Figure 2).17

The formulation of 1 as FeIICl3(NNOOII) was further confirmed by single-crystal X-ray structure determination (Figure 3a). The geometry around iron (r of 0.52) is intermediate between trigonal bipyramidal and square pyramidal. The iron–ligand bond lengths (Fe–O 1.9572(10); Fe–N 2.0136 (12) Å) as well as ligand-based interatomic distances (O1–C1 1.2809(17); N1–C6 1.3390(17) Å) are characteristic of the ISQ ligand oxidation state.14,18–20 A metrical oxidation state value of FeIII was determined for the NNOISQ ligand of 1 by DFT. The spin-density plot for 1 shows a total spin equivalent to four unpaired electrons. Temperature-dependent solid-state SQUID magnetometry and zero-field 57Fe Mössbauer spectroscopy confirmed the total S = 2 ground state (Q = 0.85 mm/s), respectively (Figure 2).17
Cyclic voltammetry of 1 in CH2Cl2 solution revealed quasi-reversible one-electron oxidation and reduction events at +0.51 V and −0.74 V vs FeC/Fe⁺, respectively (Figure 4a). Chemical oxidation of 2 with AgBF₄ resulted in the formation of [FeIII(NNOISQ)₂]Cl (3b), which was accessible directly by heating a mixture of FeCl₃ and NNOOH (2 molar equiv) at reflux in the presence of NEt₃ under aerobic conditions.

We set out to investigate the activity of well-defined air-stable 1 for catalytic C(sp³)–H amination of aliphatic azide S₁ to P₁₄ and P₁₆. Amination of Aliphatic Azide S₁ to P₁₄ and P₁₆

### Table 1. Performance of 1 in Intramolecular C(sp³)–H Amination of Aliphatic Azide S₁ to P₁₄ and P₁₆

<table>
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<th>Entry</th>
<th>1 (mol%)</th>
<th>Boc₂O (equiv)</th>
<th>Temp. (°C)</th>
<th>Time (h)</th>
<th>P₁₄ (%)</th>
<th>P₁₆ (%)</th>
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aConditions: [S₁] 20 mM, [Boc₂O] 20 mM, 1 (10/5/2/1 mol%), C₆H₆ (5 mL). 1H NMR yields of P₁₄ and P₁₆ are reported using 1,3,5-trimethoxybenzene as a standard. bIsolated yields. cRecycled catalyst. d[Boc₂O] 50 mM, [Boc₂O] 100 mM. eConditions: [S₁] 20 mM, [Boc₂O] 20 mM, 1 (0.1 mol%), C₆H₆ (25 mL). fConditions: [S₁] 20 mM, [Boc₂O] 20 mM, 1 (10 and 5 mol%), toluene (5 mL). gKey parameters for each entry are indicated in red.
an equimolar mixture of both reagents (100 μmol) at 100 °C in benzene for 24 h in the presence of 10 mol% of 1 as catalyst in a pressure tube resulted in complete conversion of S₄ to the desired Boc-protected pyrrolidine P₁a (70%) and Boc-protected amine P₁b (30%) as the side product (entry 1). Lowering the catalyst loading to 5 mol% led to a slightly different product ratio of 63:37 for P₁a/P₁b (entry 2).

Catalyst 1 was successfully recovered by precipitation (dark green precipitate) from the crude reaction mixture upon addition of pentane, allowing recycling without any loss of catalytic activity (entry 3). Analysis of the recovered dark green solid by UV−vis spectroscopy (λmax: 740 nm) and mass spectrometry (M⁺: m/z 464.1084) confirmed the structural integrity of complex 1 after catalysis. Based on these observations, we exclude involvement of homoletic FeII species 2 as the catalytically active species, as this complex cannot regenerate complex 1. Further reduction of the catalyst loading to 2 or 1 mol% gave full conversion with virtually the same ratio of P₁a/P₁b (entries 4 and 5). Using excess Boc₂O at 100 °C did not lead to any change in the product distribution (entries 6 and 7). Monitoring the reaction progress with 5 mol% of catalyst loading showed complete conversion after 3 h (entry 9) and also for recovered catalyst (entry 10). Upon reducing the catalyst loading to 2 mol%, we observed approximately 50% conversion of substrate in 3 h (entry 12) and full conversion in 6 h (entry 13). Also in this case, the catalyst was recovered and reused without significant loss of catalytic activity (entry 14). The ratio of P₁a/P₁b (∼1.6:1) remained constant (entries 12–14). Hence, the catalyst can be recovered and reused without significant loss of catalytic activity, using either 5 mol% (entries 3 and 10) or 2 mol% (entry 14) of catalyst loading. Complete conversion of substrate to products was also obtained with 1 mol% of catalyst loading after 12 h (entry 15). Heating an equimolar mixture of both reagents (500 μmol) at 100 °C in benzene (25 mL) for 12 h in the presence of 1 mol% of 1 (5 μmol, entry 16) also allowed for facile catalyst recovery by precipitating into pentane. In this case, the reaction did not go to completion in 12 h using the recycled catalyst (entry 17). Besides the two products (P₁a/P₁b ≈ 1.6:1), roughly 16% unreacted azide (S₄) was recovered. Hence, a slight loss of catalytic activity was observed with this recycling at 1 mol% of catalyst loading. However, this diminished catalytic activity might be due to partial loss of catalyst during recovery. Thereafter, the catalyst loading was further reduced to 0.1 mol%. We performed the runs with 500 μmol of S₄ and Boc₂O in 25 mL of solvent, keeping the effective concentration constant (entries 18–20). Lowering the catalyst loading to 0.1 mol% resulted in 17 and 36% conversion of substrate in 24 h (entry 18) and 48 h (entry 19), respectively, with a product ratio of ∼1.6:1 (P₁a/P₁b). The highest TON of 620 was obtained with 0.1 mol% of catalyst loading after a week of heating (entry 20). Changing from benzene to toluene did not have a significant influence on the outcome (entries 21 and 22), and only minor differences in product ratio were observed. A large-scale reaction (500 μmol S₄, 500 μmol Boc₂O, 5 mol% of catalyst) resulted in an isolated yield for P₁a of 62% (see Supporting Information). Therefore, catalyst 1 allows turnover numbers significantly higher than those in previously reported homogeneous Fe-based systems (maximum TON of ∼6) for the direct intramolecular C(sp³)−H amination of unactivated organic azide.

We explored several additional substrates for the intramolecular C(sp³)−H amination catalyzed by complex 1 (Table 2 and Supporting Information). Complete conversion of substrates S₂ to S₁₀ to the corresponding N-heterocycles and linear amines was observed in 24 h at 100 °C using 5 mol% of catalyst loading.

Utilizing 1-azido-5-hexene (S₅) as substrate, allylic C−H amination occurs cleanly to give five-membered N-heterocycle (P₃a, 96% isolated yield), and no linear amine byproduct was detected. Both homoallylic and allylic C−H amination occur using 1-azido-6-heptene (S₆), generating five- (P₃b, 57%) and six-membered (P₃c, 38%) N-heterocycles with traces of undesired amine (P₃d). The products P₃b and P₃c are obtained by homoallylic and allylic C−H bond activation, respectively, with a ratio of 1:5.1:0 (P₃b/P₃c). This observation can be considered as support for direct nitrene insertion into the C(sp³)−H bond, generating both an N−H and C−N bond simultaneously. Combined with the formation of a favorable five-membered ring, the somewhat stronger homoallylic C−H bond is preferentially activated over the weaker allylic C−H bond. A similar observation (but without explanation) was made by Betley et al. for the C−H amination of 1-azido-5-methylhexane, with five-membered pyrrolidine (from secondary C−H bond activation) being the major and six-membered piperidine (from weaker tertiary C−H bond activation) the minor product in a ratio of 1:5.1:0. Substrates S₇ and S₉, containing secondary C−H bonds adjacent to an electron-
withdrawing ester group were transformed to the corresponding pyrrolidines \( \text{P}_a \) (51%) and \( \text{P}_b \) (39%). Azide substrate \( \text{S}_6 \), containing an ether linkage in the aliphatic chain, gave the oxazolidine product \( \text{P}_{na} \) gave the oxazolidine product \( \text{P}_{a} \) in high yield (90% isolated yield). Apart from monocyclic products, bicyclic N-heterocycles also proved accessible via this approach. Starting from 1-azidomethyl-2-ethylbenzene (\( \text{S}_a \)), containing secondary benzyl C–H bonds, or 1-azidomethyl-2-methylbenzene (\( \text{S}_b \)) and 1-(2-azidomethyl)-2-methylbenzene (\( \text{S}_c \)) with primary C–H bonds, yielded the desired N-heterocycles (\( \text{P}_{2a} \) 53%; \( \text{P}_{3a} \) 46%; \( \text{P}_{4a} \) 44%).

The scope of the intramolecular C(sp\(^3\))–H amination catalyzed by complex \( \text{I} \) was also extended to include 1-azido-1-phenyl-5-hexene (\( \text{S}_{10} \)) as secondary azide, selectively yielding the desired N-heterocycle \( \text{P}_{10a} \) (mixture of rotamers and diastereomers) (95% isolated yield). Furthermore, organozaines containing a vinyl functionality (\( \text{S}_d \), \( \text{S}_e \), and \( \text{S}_{10} \)) provide the desired N-heterocycles (\( \text{P}_{2a} \), \( \text{P}_{3a} \), \( \text{P}_{4a} \), and \( \text{P}_{10a} \)) with very little or no undesired linear amine or aziridine. We could not find a clear correlation between the bond dissociation energy of all types of C–H bonds involved and the outcome of the catalytic reactions.

To exclude that the observed catalytic C–H amination activity was due to an impurity originating from the FeCl\(_3\) precursor, we tested the FeCl\(_3\) used for the synthesis of complex \( \text{I} \) as a catalyst for the conversion of \( \text{S}_1 \). No conversion to N-heterocycle (\( \text{P}_{n1} \)) or linear amine (\( \text{P}_{n2} \)) was observed with either 5 or 10 mol% of catalyst loading in the presence of 1 equiv of Boc\(_2\)O (in benzene or toluene) at 100 °C for 24 h. When using homoleptic Fe\(^{III}\) complex \( \text{S}_b \), [Fe\(^{III}\)(NNO\(_2\))\(_2\)]Cl (5 or 10 mol%), prepared directly from FeCl\(_3\) and NNO\(_2\), no product formation was detected. Partial poisoning tests using tetramethylthiourea \(^{24}\) (±0.3 molar equiv relative to 1) and elemental mercury gave identical conversion and product ratio compared to the standard reaction without these additives. On the basis of these results, we rule out the active participation of (ligand-stabilized) trace metal impurities present in the FeCl\(_3\) precursor.\(^{25}\) Thereafter, we performed kinetic analysis for the intramolecular C(sp\(^3\))–H amination of \( \text{S}_1 \) catalyzed by complex \( \text{I} \) (see Tables S4–S6 in the Supporting Information). Monitoring the reaction progress using 2 mol% of catalyst loading (entries 1–5), we observed in a linear decrease in \( \text{S}_1 \) with time, suggestive of saturation kinetics or zero-order kinetics in \( \text{S}_1 \) (rate constant = 3.5 μM h\(^{-1}\)) (Figure 5a). A constant rate of substrate consumption (17.5 μmol h\(^{-1}\)) was observed (Figure 5b). The rate of substrate consumption (μmol h\(^{-1}\)) against the concentration of \( \text{I} \) (mM) varied between 1 and 7 mol% (entries 6–12) showed first-order kinetics in \( \text{I} \) (Figure 5c). Performing the C(sp\(^3\))–H amination of \( \text{S}_1 \) with different concentrations of Boc\(_2\)O (20–60 mM; entries 13–17) led to a linear increase in the rate of reaction (μmol h\(^{-1}\)) (Figure 5d), indicating first-order kinetics in Boc\(_2\)O. An intramolecular kinetic isotope effect (KIE) of 3.4 was obtained using 1-azido-4-deutero-4-(deuterophenyl)butane as a substrate (Scheme 3). This value is identical to the KIE value (3.4) obtained for the C(sp\(^3\))–H amination of 1-azido-4-deutero-4-phenylbutane catalyzed by the Pd catalyst recently published by our group.\(^{12,24}\)

For both Beley’s iron catalyst\(^{9a}\) and the palladium catalyst reported by us,\(^{12,24}\) C(sp\(^3\))–H amination of unactivated azides was proposed to occur via rate-limiting azide activation (release of \( \text{N}_2 \)) and a subsequent radical pathway involving metal- ligand-based single-electron transfer, resulting in the formation of a metal–nitrene radical species. Similar “nitrene radical” intermediates have recently been spectroscopically characterized for cobalt porphyrins and other systems.\(^{26–28}\) Formation of the saturated N-heterocycle proceeds via either H atom abstraction followed by radical rebound or direct insertion of the nitrene moiety into the benzyl C–H bond and then forms a pyrrolidine complex. Finally, reaction with Boc\(_2\)O releases the Boc-protected N-heterocycle and regenerates the catalyst (see the Supporting Information for hypothetical scheme based on 1).

However, this mechanism, as postulated for other systems, is not in agreement with the observed kinetic data when employing catalyst \( \text{I} \). The zero order in substrate (\( \text{S}_1 \)) implies that (binding and) activation of the azide substrate is not rate-limiting. Reaction of complex \( \text{I} \) with either a stoichiometric amount or excess (5 and 10 times) \( \text{S}_1 \) in the absence of Boc\(_2\)O at room temperature (or high temperature) did not yield intermediate \( \text{A} \) (or \( \text{B} \) or \( \text{C} \); see Supporting Information), and only starting materials were recovered. The first-order kinetics in Boc\(_2\)O suggests that a reaction with Boc\(_2\)O is the rate-determining step in the overall C(sp\(^3\))–H amination reaction of \( \text{S}_1 \). The active involvement of Boc\(_2\)O for catalytic turnover is also suggested by the lack of any product (\( \text{P}_{1a}/\text{P}_{1b} \)) formation from \( \text{S}_1 \) in the absence of Boc\(_2\)O. However, pyrrolidine adduct \( \text{C} \) proved inaccessible by reaction of \( \text{I} \) with (excess) 2-phenylpyrrolidine, which argues against product inhibition in this case. Therefore, we propose an alternative mechanism to explain the kinetic data (Scheme 4). Initial activation of complex \( \text{I} \) by Boc\(_2\)O (present in slight excess relative to substrate) at elevated temperature (rate-determining step) leads to the activated Fe\(^{III}\) catalyst with a higher affinity for the

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Figure 5. Kinetic analysis for C(sp\(^3\))–H amination of \( \text{S}_1 \) in the presence of Boc\(_2\)O catalyzed by \( \text{I} \): (a) rate of substrate consumption vs time, (b) rate of substrate consumption vs substrate concentration, (c) rate of substrate consumption vs concentration of catalyst, and (d) rate of substrate consumption vs concentration of Boc\(_2\)O.

Scheme 3. Intramolecular Kinetic Isotope Effect in Catalytic C–H Amination of 1-Azido-4-deutero-4-(deuterophenyl)butane as Substrate

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substrate. Two potential ways for Boc₂O to interact with 1 are depicted in Scheme 5: either chloride abstraction or reaction with the phenolate fragment of the redox-active NNO ligand can (pseudo)reversibly generate a cationic FeIII species 1⁺.²⁹ Thereafter, facile coordination of the azide substrate to the metal center gives adduct A′ and subsequent N₂ elimination generates iron(III)-nitrenoid species B′. Either direct nitrene insertion (preferred for (homo)allylic substrates) or H atom abstraction and radical rebound forms the FeIII(pyrrolidine) adduct C′. Finally, reaction with a Boc-containing species (denoted “Boc” in Scheme 4) — either the in situ generated tert-butylcarbonyl chloride or the carbonate derivative of the NNO ligand; see Scheme 5 — releases Boc-protected N-heterocycle (P₁a) and tert-butanol with regeneration of complex 1.

It is reasonable to assume that chloride dissociation from complex 1 generates a four-coordinated cationic complex [FeIII(Cl(NNO)SO₄)]⁺ (1’a) or FeIII(Cl(NNO)SO₄-Boc)⁺ (1’b), which can easily bind an organoazide to generate A’. Release of dinitrogen forms an Fe−NR intermediate B’, which may exist in various spin states. This eventually forms cationic pyrrolidine adduct [FeIII(Cl(NNO)SO₄)(2-phenylpyrrolidine)]⁺ (C’). Upon reaction of 1 with 1 equiv of TIPF₆ as redox-inert halide-abducting agent in the presence of a small excess of S₁ (2.5 equiv) in THF, a color change from green to blue-green was observed, concomitant with formation of a white precipitate. Mass spectrometric analysis of the filtrate (m/z 614.3342) is in line with formation of the cationic complex [Fe(NNO)(2-phenylpyrrolidine)(THF)]⁺.³⁰ This cationic complex was further reacted with Boc₂O (1 equiv) to cleanly form Boc-protected pyrrolidine P₁a, supporting its possible involvement in the proposed catalytic pathway for the C−H amination of S₁.³¹

Performing the C(sp³)−H amination of S₁ in the presence of excess tBuOH, which is generated after coupling of the heterocycle with Boc₂O led to the same P₁a/P₁b ratio of 63:37 as observed under standard reaction conditions, excluding any role of the alcohol in the formation of the side product. No nitrile or imine byproduct was observed under these conditions, which argues against the substrate acting as the H atom donor. When the catalysis was carried out at 10-fold higher absolute concentrations of all components (S₁, Boc₂O and 1) — to reduce any harmful effects of impurities in the solvent — the P₁a/P₁b ratio increased significantly (P₁a/P₁b = 79:21; see Supporting Information for details). Additional distillation of the solvent or switching from C₆H₆ to C₆D₆ did not affect the product ratio determined by ¹H NMR spectroscopy, which speaks against the solvent acting as a hydrogen source and suggests the involvement of an unknown impurity at low concentration in the side reactions producing the linear Boc-protected amines.

### SUMMARY AND CONCLUSIONS

In summary, straightforward synthesis of complex 1 [FeIII(Cl₂(NNO)SO₄)] gives access to an air-stable and recoverable Fe catalyst for the efficient direct C(sp³)−H amination of unactivated organic azides to N-heterocycles, providing TONs significantly higher than those previously reported with any homogeneous catalyst for this type of transformation. Experimental and computational data suggest that 1 is best described as an FeIII center that is antiferromagnetically coupled to a ligand-centered NNO radical. In addition to the standard azide substrate S₁, the scope of C−H amination was extended to eight other primary azides (S₉−S₉) and a secondary azide (S₁₀). Based on the experimental evidence, we propose a mechanism for the C−H amination of organoazides involving catalyst activation by Boc₂O to form an activated cationic species, followed by a cationic azide activation pathway. In addition to the desired N-heterocycles, unwanted linear amines form in most of the cases. However, organoazides containing a vinyl functionality were converted almost exclusively to the preferred N-heterocycles. The origin of the hydrogen required for the formation of linear amine is unclear to date. The exact mechanism of the C−H amination is currently unknown, and various redox states as well as spin states are possible for the combination of iron, NNO ligand, and a metal-bound nitrene moiety, all of which are potentially redox-active and make for a complex overall system. However, the observed preference for homoalyllic versus allylic C−H amination suggests direct nitrene insertion without radical character induced by metal or ligand electron transfer as the most competent pathway. The catalyst integrity as a heteroleptic species, enabling turnover at relatively low catalyst loading as well as catalyst recycling, and the versatile coordination chemistry and the potential proclivity to allow various redox spin states are considered key factors that contribute to the overall performance of this system. Detailed...
computational investigations are ongoing to unravel the mechanism and to determine the metal, ligand, and substrate redox states of the key intermediates. Additionally, we are exploring the catalytic activity of complex 1 for intermolecular C–H amination and other types of reactions.

**REFERENCES**


(23) (a) Blanksby, S. J.; Ellison, G. B. Acc. Chem. Res. 2003, 36, 255–263. (b) For substrates S1–S8, the substrate with the weaker C–H bond is more easily converted. The bond dissociation energy (BDE) at 298 K of the C–H bond in toluene is 89.8 kcal mol−1. The BDE (ΔH98) of benzylic C–H bond of ethylbenzene (77.6 kcal mol−1) is ca. 12 kcal mol−1 lower than that of toluene. Therefore, C–H bond activation of S1 (α-substituted ethylbenzene) is easier than S8 and S9 (α-substituted toluene), and this is reflected in higher yield of Pα1 (53%) compared to that of Pαa (46%) or Pαb (44%). Substrates S1a and S9a with similar allylic C–H bonds gave similar yields of products (Pαa, 96%, Pα9a, 95%). The BDEs (ΔH98) of allylic C–H bonds are very similar to those of benzylic C–H bonds: propene (88.8 kcal mol−1) vs toluene (89.8 kcal mol−1), 1-buten e (76.5 kcal mol−1) vs ethylbenzene (77.6 kcal mol−1), 1-pentene (75.4 kcal mol−1) vs α-ethylbenzene (76.4 kcal mol−1). However, S9 with an allylic C–H bond gave Pα9 in high yield (96%), while S1 with a benzyl C–H bond resulted in only 65% of Pα1. The BDE (ΔH98) of a benzyl C–H bond adjacent to an alkyl group is comparable to the BDE (ΔH98) of a benzyl C–H bond adjacent to an allyl group. However, S9 gave 92% of Pα9a whereas S1 gave only 65% of Pα1. So, no clear correlation between C–H bond strength of substrates and yields of products can be found for S1, S2, and S9.


(25) ICP-AAS analysis confirmed <10 ppm levels for Co, Rh, Ir, Ni, Pd, and Cu; see the Supporting Information for details.


(29) Stoichiometric reactions between complex 1 and Boc3O resulted in 1:1 recovery of 1. This suggests that the catalyst activation process by Boc3O is most likely an energetically uphill process generating the active form of the catalyst as a short-lived species in rather low concentrations.

(30) Slow diffusion of pentane into the blue-green solution led to almost quantitative precipitation of a microcrystalline blue solid, but attempts to analyze this species by single-crystal X-ray structure determination were unsuccessful to date.

(31) The C(sp3)-H amination of S1 in the presence of Boc3O with 1 and TiP=O (both 5 mol%) led to the formation of P1a and P1b in the same ratio of ≈1:6:1 as observed under the standard conditions.