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Iron-mediated intermolecular N-group transfer chemistry with olefinic substrates†

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The dipyrinato iron catalyst reacts with organic azides to generate a reactive, high-spin imido radical intermediate, distinct from nitrenoid or imido species commonly observed with low-spin transition metal complexes. The unique electronic structure of the putative group-transfer intermediate dictates the chemoselectivity for intermolecular nitrene transfer. The mechanism of nitrene group transfer was probed *via* amination and aziridination of *para*-substituted toluene and styrene substrates, respectively. The Hammett analysis of both catalytic amination and aziridination reactions indicate the rate of nitrene transfer is enhanced with functional groups capable of delocalizing spin. Intermolecular amination reactions with olefinic substrates bearing allylic C–H bonds give rise to exclusive allylic amination with no apparent aziridination products. Amination of substrates containing terminal olefins give rise exclusively to allylic C–H bond abstraction, C–N recombination occurring at the terminal C with transposition of the double bond. A similar reaction is observed with *cis*- β -methylstyrene where exclusive amination of the allylic position is observed with isomerization of the olefin to the *trans*-configuration. The high levels of chemoselectivity are attributed to the high-spin electronic configuration of the reactive imido radical intermediate, while the steric demands of the ligand enforce regioselective amination at the terminal position of linear α -olefins.

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Introduction

The prevalence of nitrogen functionalities in bioactive molecules and materials has inspired the development of numerous techniques for direct C–H bond amination. Transition-metal catalyzed approaches^{1,2} offer a unique opportunity to control the reactivity and selectivity of nitrene transfer. Careful modulation of metal identity and ligand design can drastically dictate the degree of bonding and electronic structure of the metal-bound nitrene intermediates, ranging from simple oxidant-metal adducts, to singlet and triplet stabilized nitrenoids, to closed- and open-shell metal imidos (Fig. 1). In particular, metal stabilized nitrene transfer using noble metal catalysts, specifically dirhodium,³ have been successfully applied in the context of complex molecule synthesis. These well-behaved catalysts have been extensively studied and are believed to transfer functionality to both olefins and C–H bonds *via* a singlet nitrenoid intermediate (Fig. 1b) in a concerted asynchronous mechanism.⁴

Despite the success of the dirhodium class of catalysts, a renewed interest in late, first-row transition metal nitrenoid

catalysts, composed of copper,^{5–9} cobalt,^{10,11} manganese,^{12–15} nickel,^{16,17} and iron^{12,18,19} has emerged. Their high d-electron count and compressed ligand fields create a unique opportunity for ancillary ligands to strongly influence the bonding interactions between the nitrene moiety and the metal center. For instance, the binding of strong field ligands destabilizes metal–ligand antibonding orbitals and promotes low-spin electronic configurations. Similar to their second- and third-row congeners, closed-shell first-row transition metals will interact with nitrene precursors to generate either a metal-bound singlet nitrenoid (Fig. 1b) or a covalently-bound metal imido (Fig. 1c). Alternatively, weak field ligand environments favor population of metal–ligand antibonding orbitals and high-spin electronic configurations. Communication between highly paramagnetic metal centers and N-group transfer reagents has the potential to translate radical character directly to the N-atom or along the metal–nitrogen bond vector (Fig. 1d or e).

Given the range of accessible metal–nitrene electronic configurations, it is not surprising that the established catalysts exhibit dramatically different reactivity, particularly when considering the functionalization of olefinic substrates (Fig. 1). For instance, exposure of a macrocyclic tetracarbene-ligated Fe-complex exclusively catalyzes the aziridination of aliphatic olefins,¹⁹ while a phthalocyaninato Fe-complex facilitates preferential intramolecular allylic C–H amination,¹⁸ and an Fe-porphyrin complex generates mixtures of both aziridine and

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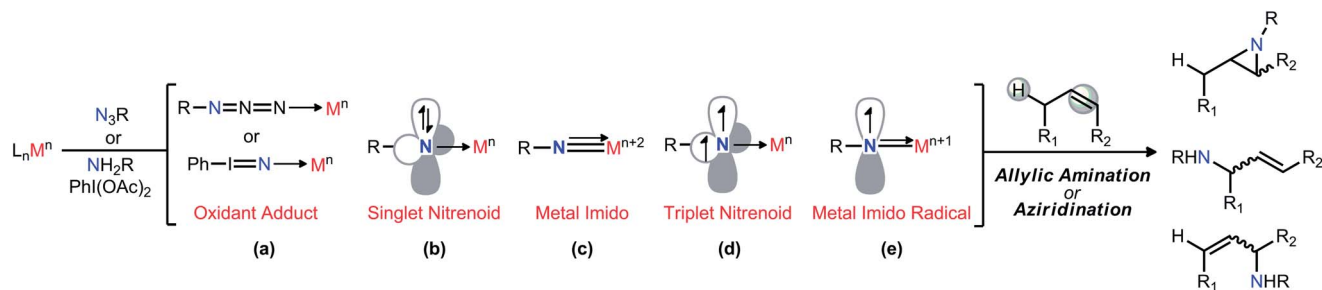


Fig. 1 Available reactive intermediates and product distributions for transition metal-based nitrogen group transfer chemistry with olefinic substrates.

allylic amine products.¹² While each of these complexes is confined to a tetragonal field by tetra-chelating macrocyclic ligands, the ligand field strength, metal oxidation state, and nitrene source vary and are likely responsible for the changes in chemoselectivity. However, in each of these examples, the structure and electronic configuration of the reactive intermediate are only posited, as is the case for nearly all C–H amination catalysts.

Ideally, one would like to probe the influence a given metal, ligand, and nitrene unit bears on reactivity and selectivity through the isolation of the reactive metal–nitrenoid intermediate. We previously reported²⁰ intermolecular amination and aziridination with aryl and alkyl azides using ferrous dipyrriato complexes (^RL)FeCl(Et₂O) [R = 2,4,6-Ph₃C₆H₂ (Ar), 1-adamantyl (1), ^tBu (2)] (Fig. 2). Isolation and characterization of the radical imido complex (^{Ar}L)FeCl(N(*p*-^tBuC₆H₄)), wherein a high-spin Fe(III) (*S* = 5/2) is antiferromagnetically coupled to the imido radical (*S* = −1/2) to give an overall high-spin ground state (*S* = 2), suggests a similar electronic structure for the proposed iron-bound imido radical 3. Such an electronic structure places significant radical character on both the Fe–N σ and π bond vectors, facilitating both H-atom abstraction and radical recombination pathways. In this report, we have explored the implications of the reactive intermediate's unique electronic structure on both the reaction mechanism and chemoselectivity of intermolecular N-group transfer. We have established the catalyst's strong preference for allylic amination over aziridination with aliphatic olefin substrates. Additionally, we report on the functionalization of α -olefins to linear allylic amines with outstanding regioselectivity.

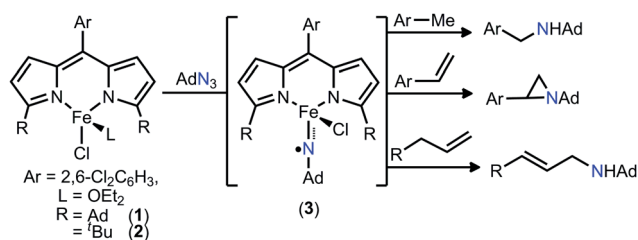


Fig. 2 Ferrous dipyrriato complexes 1 and 2 are competent catalysts for benzylic and allylic amination and styrene aziridination, operating through the proposed reactive imido radical intermediate 3.

Results and discussion

A. Benzylic amination and aziridination

We previously reported²⁰ that **1** catalyzes nitrogen group transfer to styrene and toluene with 1-azidoadamantane, resulting in the formation of 1-adamantyl-2-phenylaziridine (85% yield) and benzyladamantylamine (60% yield) respectively. In attempts to expand the substrate scope, a series of *para*-substituted toluenes and styrenes were subjected to **1** (5–10 mol%) and 1-azidoadamantane (Table 1). All substrates successfully underwent the desired intermolecular nitrogen group transfer, demonstrating that catalysis is amenable to substrates with both electron withdrawing and donating groups and etheral C–H bonds (Table 1, entries 4 and 8). The yields for aziridination at room temperature are overall higher than that for amination (75–85% vs. 46–60%); this trend correlates with the lower propensity for the aziridine product to bind to the catalyst and retard the rate of catalysis. Amination yields can be improved upon heating to 60 °C (entry 1) to encourage product dissociation from the electrophilic Fe center.

Styrene aziridination is amenable to a variety of organoazides. Exposure of **1** and styrene to 5 equivalents of *tert*-butyl azide (Table 1, entry 10) resulted in the corresponding aziridine in good yield (86%). The yield for 1-azidobutane drops significantly (entry 11, 53%), likely due to imide decomposition pathways. In general, primary and secondary alkyl azides rapidly react with **1** to generate the imide intermediate, but are then prone to undergo either intramolecular C–H amination to yield N-heterocycles or α -hydrogen abstraction to yield linear imines²¹ rather than intermolecular group transfer chemistry. Copper⁹ and iridium²² complexes also generate imines upon exposure to primary and secondary azides through nitrenoid intermediates. Aryl azides are also compatible with the aziridination reaction. *Para*-substitution of the aryl ring eliminates a bimolecular imido decomposition pathway, and noticeably improves the yield of aziridination (entry 12 vs. entry 13). Unfortunately application of either sulfonyl (entry 14) or silyl (entry 15) azides does not result in productive N-group transfer but rather catalyst decomposition through unproductive H-atom abstraction or ligand amination pathways, respectively.

Table 1 Scope of N-group transfer^a

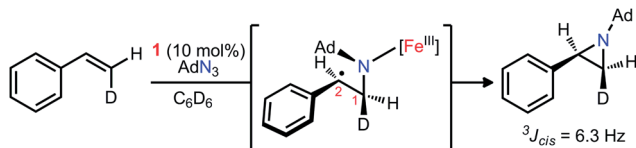
$\text{Ar-Me} \xrightarrow[23\text{ }^\circ\text{C}]{\text{AdN}_3, \text{1 (10 mol\%)}} \text{Ar-CH}_2\text{-NHAd}$				$\text{Ar-CH=CH}_2 \xrightarrow[23\text{ }^\circ\text{C}]{\text{RN}_3, \text{1 (10-20 mol\%)}} \text{Ar-CH}_2\text{-NR}$				$\text{R}_1\text{-CH=CH-R}_2 \xrightarrow[23\text{ or }60\text{ }^\circ\text{C}]{\text{AdN}_3, \text{2 (20-100 mol\%)}} \text{R}_1\text{-CH}_2\text{-CH=CH-NHAd}$			
Benzyllic amination				Aziridination				Allylic amination			
Entry	Substrate	Yield ^b (%)	k_x/k_H ^c	Entry	Substrate	Yield ^b (%)	k_x/k_H ^c	Entry	Substrate	Product	Yield ^d (%)
1		60 ^d	1.00	6		85 ^e	1.00	10			38 ^j
2		46	1.10	7		80	1.11	11			12 ^h , 7(9) ⁱ , 17(19) ^j
3		52	1.14	8		75	1.20	12			18 ^j
4		47	1.08	9		80	1.09	13			77 ^h , 29 ⁱ , 43 ^j
5		47	1.18					14			52 ^h , 15(15) ⁱ , (38) ^j
								15			0

^a All reactions run with substrate as solvent. ^b Reaction with specified substrate and 1 (10 mol%) and AdN₃ at 23 °C for 12 h. Yields determined by ¹H NMR, using ferrocene as an internal standard. ^c Ratio determined by ¹H NMR from single turnover competition experiment run with 1 and AdN₃ (1 equiv.) in 1 : 1 substituted : parent toluene or styrene. ^d Reaction run at 60 °C. ^e Reaction run with 5 mol% 1. ^f Reaction with styrene and 1 (20 mol%) and specified azide at 23 °C for 12 h. Yields determined by ¹H NMR, using ferrocene as an internal standard. ^g Yields were determined by GC/MS (¹H NMR). ^h Reaction with specified substrate and 2 (100 mol%) and AdN₃ at 23 °C for 12 h. ⁱ Reaction with specified substrate and 2 (20 mol%) and AdN₃ at 23 °C for 12 h. ^j Reaction with specified substrate and 2 (20 mol%) and AdN₃ at 60 °C for 12 h.

B. Mechanism of benzylic amination and aziridination reactions

We previously reported that the mechanism of catalytic toluene amination and styrene aziridination proceeds *via* one-electron pathways, largely based on the non-classical KIE value (12.8) for toluene amination and the high-spin electronic structure of the putative intermediate **3**. Following this initial report, we have conducted a series of labelling and Hammett studies to further corroborate a mechanistic proposal in which short-lived carboradical intermediates are formed en route to the functionalized products.

Exposure of **1** and 1-azidoadamantane to excess *cis*- β -deuterostyrene resulted in the isolation of *cis*-1-adamantyl-2-deutero-3-phenylaziridine, with no evidence of the *trans* isomer (Scheme 1). While isomerization of the *cis*-olefin to a mixture of *cis*- and *trans*-aziridines is suggestive of a stepwise mechanism, lack of isomerization is less definitive. Either the reaction is occurring *via* a concerted mechanism or a two-step mechanism with radical recombination out-competing C–C bond rotation. The adamantyl units on both the dipyrin and imido generate a very narrow cleft in which the substrate can orient itself. The crowded environment likely impedes C–C bond rotation and renders radical recombination more facile. However, we cannot rule out a concerted aziridination mechanism with this experiment alone.



Scheme 1 Aziridination of *cis*- β -deuterostyrene occurs without rotation about the C1–C2 bond, generating only *cis*-1-adamantyl-2-deutero-3-phenylaziridine. The coupling constant (6.3 Hz) between the vicinal hydrogens is indicative of a *cis* orientation.

The electronic nature of the transition state was further studied by conducting a Hammett analysis of both the aziridination and amination reactions. The relative rates of catalytic aziridination and amination of a series of *para*-substituted styrenes and toluenes using **1** with one equivalent of 1-azidoadamantane were determined through pairwise competition experiments. Equimolar mixtures of styrene or toluene and a *para*-substituted styrene or toluene derivative, respectively, were treated with 1-azidoadamantane in the presence of a stoichiometric amount of the Fe complex **1**. The ratios of the resulting aziridines and benzylamines were determined by GC/MS analysis and by ^1H NMR integration of the spectra taken on unpurified material. The results are summarized in Table 1.

In all cases, $k_{\text{R}}(k_{\text{X}}/k_{\text{H}})$ slightly exceeds one, suggesting that the rate of amination and aziridination is marginally enhanced with substitution by both electron donating and electron withdrawing groups. Plotting $\log k_{\text{R}}$ versus σ^+ parameters (Fig. 3a) results in a non-linear correlation between reaction rate and electron-donating ability of the *para*-substituent. Linear correlations are consistent with cationic charge stabilization in the transition state and typically observed in concerted amination chemistry with Rh_2 -carboxylate catalysts.⁴ The lack of correlation with our catalyst led us to consider the incorporation of a spin delocalization parameter, $\sigma_{\text{JJ}}^{\cdot}$, developed by Jiang and co-workers.²³ The $\log k_{\text{R}}$ vs. $(\sigma_{\text{mb}}, \sigma_{\text{JJ}}^{\cdot})$ plot (Fig. 3b) gave rise to an appreciably more linear relationship ($R^2 = 0.99, 0.93$ for amination and aziridination respectively). Multiple coefficient linear regression for the dual-parameter equation

$$\log k_{\text{R}} = \rho_{\text{mb}}\sigma_{\text{mb}} + \rho_{\text{JJ}}\sigma_{\text{JJ}}^{\cdot} \quad (1)$$

provided $\rho_{\text{mb}} = 0.086$ and $\rho_{\text{JJ}} = 0.24$ for amination and $\rho_{\text{mb}} = -0.0073$ and $\rho_{\text{JJ}} = 0.18$ for aziridination. The positive ρ_{JJ} values reveal that the *para*-substituents delocalize spin in the transition state. In addition, the large $|\rho_{\text{JJ}}/\rho_{\text{mb}}|$ values (2.8 amination, 24.7 aziridination) indicate that the spin delocalization effect is dominant in the N-group transfer reactions.

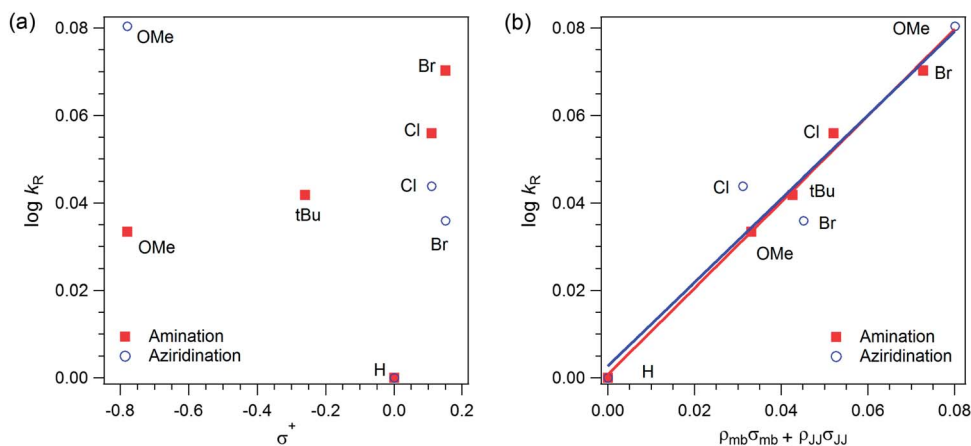


Fig. 3 (a) Linear-free-energy correlation of $\log k_{\text{R}}$ vs. σ^+ for the reactions of **1** with AdN_3 (1 equiv.) and a series of *para*-substituted toluenes (red) and styrenes (blue). (b) Linear-free-energy correlation of $\log k_{\text{R}}$ vs. $(\sigma_{\text{mb}}, \sigma_{\text{JJ}}^{\cdot})$ for the reactions of **1** with AdN_3 (1 equiv.) and a series of *para*-substituted toluenes (red) and styrenes (blue). For the amination reaction, $\rho_{\text{mb}}, \rho_{\text{JJ}} = 0.086, 0.24$. For the aziridination reaction, $\rho_{\text{mb}}, \rho_{\text{JJ}} = -0.0073, 0.18$.

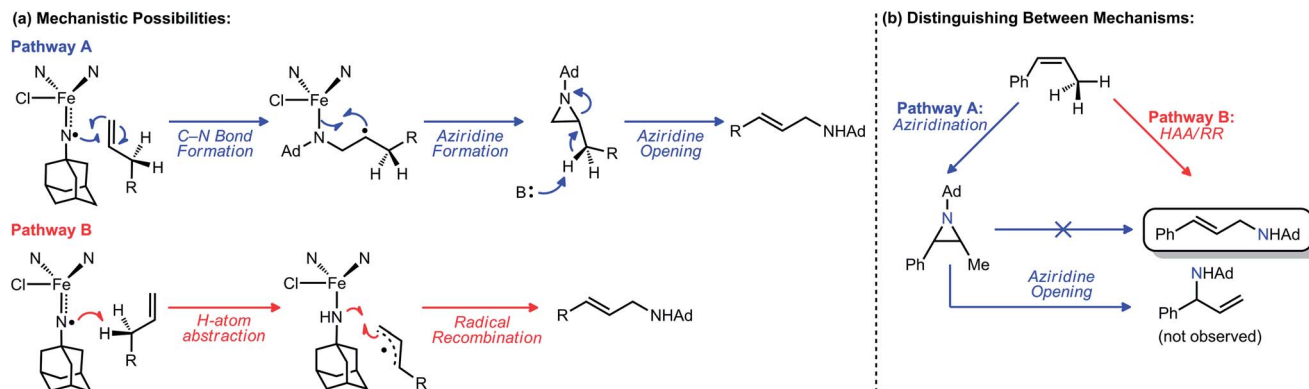


Fig. 4 (a) Possible mechanisms of allylic amination. (b) Product analysis of reaction with *cis*- β -methylstyrene elucidates reaction mechanism proceeding through H-atom abstraction (HAA)/radical rebound (RR).

Octahedral (porphyrinato)Ru- ($|\rho_{jj}/\rho_{mb}|_{\text{aziridination}} = 0.5$)²⁴ and tetrahedral (trispyrazolylborate)Cu-based ($|\rho_{jj}/\rho_{mb}|_{\text{aziridination}} = 1.2$)²⁵ aziridination and amination catalysts behave similarly; the relative reaction rates were relatively insensitive to substituent effects. Such behaviour is indicative of a two-step reaction mechanism involving radical intermediates.

C. Allylic amination

Next, the reactivity of a series of olefins with **2** and 1-azidoadamantane was investigated (Table 1, entries 16–20) in order to determine the preference for aziridination over allylic C–H bond amination. Reaction of **2** with *cis*- β -methylstyrene (Table 1, entry 16) resulted in the exclusive formation of *N*-cinnamyladamantan-1-amine with complete isomerization to the *trans* olefin. Cyclic alkenes cyclohexene and cyclooctene similarly resulted in allylic amination products in comparatively poorer yields (17% and 18%, respectively). In fact, the stoichiometric reaction of **2** with 1 equivalent of 1-azidoadamantane in cyclohexene resulted in only 12% of the allylic amine. While some azide remained unconsumed, a significant amount of radically coupled bi-cyclohexenyl product was formed (as determined by GC/MS).

Exposure of **2** and 1-azidoadamantane to linear, non-styrenyl terminal olefins resulted in exclusive formation of the linear allylic amine products (Table 1, entry 19 and 20) as a mixture of *cis* and *trans* isomers. Stoichiometric application of **2** to 1-azidoadamantane at room temperature in excess 1-hexene resulted in the formation of the allylic amine *N*-adamantyl-*N*-hex-2-enylamine in 77% yield, with the remaining mass balance belonging to 1-aminoadamantane and 1,2-diadamantyl diazene. Lowering the catalyst loading (20 mol%) and extending the reaction time to 24 hours resulted in only a slight increase in product formation (29%) and a significant portion of unreacted azide remains (64%). As the reaction temperature is increased, product dissociation from the Fe center is encouraged, allowing for catalyst turnover and increased yields (29% at 25 °C *versus* 43% at 60 °C) but without reaching full conversion. At elevated temperatures (100 °C), the azide is completely consumed, yet the yield of the desired *N*-adamantyl-*N*-hex-2-enylamine is

diminished. We suspect that free nitrene forms *via* thermal decomposition of 1-azidoadamantane under these conditions, generating significant amounts of diazene and 1-aminoadamantane. Additionally, several new products corresponding to N-group transfer to 1-hexene appear in the GC/MS trace at this temperature. Importantly, the linear allylic amine is not formed to any extent in the absence of catalyst **2**, regardless of the reaction temperature.

Recently developed C–H amination protocols have highlighted the ability to run intermolecular reactions with limiting amounts of the C–H bond substrate.^{26–28} As such, we were interested in determining the effect of diluting the olefin substrate with a chemically inert solvent. As expected, the highest yields (46%) occurred when the reaction was conducted in 1-hexene without dilution (300 equivalents substrate). Addition of benzene to the reaction mixture (aryl C–H bonds are unreactive) significantly hampered catalysis [yield % (equiv. substrate, % v/v 1-hexene/benzene)]: 26% (150, 50%); 18% (75, 25%), 12% (30, 10%); 6% (15, 5%). This trend can be attributed to increasingly competitive diazene and 1-aminoadamantane formation as the substrate is diluted with benzene.

Under optimized conditions, we explored the reactivity of a terminal, linear diene (entry 20). Again, primary amination products were obtained in moderate yield favoring the *trans* olefin isomer. Diamine formation was not observed due to the large excess of diene substrate. No reaction is observed with substrates lacking allylic C–H bonds (*e.g.* *tert*-butylethylene).

While the method has synthetic limitations, the interesting chemo- and regioselectivity of linear allylic amination inspired us to investigate the mechanism of this transformation. Typically, intermolecular transition metal-catalyzed allylic amination does not proceed with exclusive olefin transposition.²⁹ However, precedence for this transformation has been demonstrated previously using simple Fe^{II} and Fe^{III} halide salts³⁰ and Fe phthalocyanine complexes in the presence of phenylhydroxylamine.³¹ Recently, a hetero-bimetallic Pd and Cr catalytic protocol has also been developed to affect a similar amination reaction.²⁷

We have proposed two possible mechanistic pathways (Fig. 4). Both mechanisms begin with formation of the reactive

imido radical intermediate **3**, consisting of three bulky adamantyl units (two on the dipyrinato ligand, one on the imido *N*). The olefin then approaches the sterically crowded reaction centre *trans* to the Cl ligand. As such, heightened reactivity is observed with the least bulky, mono-substituted olefin substrates (Table 1, entries 19 and 20). In pathway A (Fig. 4a), approach of the olefin induces C–N bond formation at the primary carbon with homolytic cleavage of the π -bond. Next, the carboradical rapidly recombines with the Fe-bound amide to generate an aziridine product. Finally, under the reaction conditions, the aziridine is ring opened to the primary allylamine through either a heterolytic (as drawn) or homolytic pathway. In pathway B, the Fe-imido intermediate abstracts an H-atom from the olefin substrate to generate an allylic radical, followed by radical recombination at the terminal carbon.

Analysis of the reaction with *cis*- β -methylstyrene was used to distinguish between pathways A and B (Fig. 4b). If pathway A were operative, initial aziridination would generate 1-adamantyl-2-methyl-3-phenylaziridine. *In situ* aziridine ring opening would then install the amino group at the benzylic carbon. If pathway B were operative, radical recombination would occur regioselectively at the less-hindered terminal position of the unsymmetrical allylic radical to generate *N*-cinnamyladamantan-1-amine. As discussed earlier, the linear allylic amine is the only product of the reaction, suggesting that pathway B is operative.³² This is an appealing mechanistic possibility, as it correlates well with our proposed mechanism for the benzylic amination of toluenes.

Conclusions

In line with previous studies of this system, we have determined that one-electron reaction pathways dominate intermolecular N-group transfer chemistry when mediated by the dipyrinato ferrous complexes. As such, an innate preference for amination over aziridination has been established for a range of allylic C–H bond containing substrates. We attribute the extremely high levels of chemoselectivity to the high-spin electronic configuration of the reactive imido radical intermediate **3**. Further, the steric demands of our ligand coupled with the bulky adamantyl imido fragment enforce regioselective amination at the terminal position of linear α -olefins. The preservation of unsaturation following imido transfer furnishes products that are amenable to subsequent functionalization.

Acknowledgements

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