



Article

High spin iron imido complexes competent for C-H bond amination

Matthew J.T. Wilding, Diana A. Iovan, and Theodore A. Betley

J. Am. Chem. Soc., Just Accepted Manuscript • DOI: 10.1021/jacs.7b06682 • Publication Date (Web): 04 Aug 2017

Downloaded from http://pubs.acs.org on August 4, 2017

Just Accepted

"Just Accepted" manuscripts have been peer-reviewed and accepted for publication. They are posted online prior to technical editing, formatting for publication and author proofing. The American Chemical Society provides "Just Accepted" as a free service to the research community to expedite the dissemination of scientific material as soon as possible after acceptance. "Just Accepted" manuscripts appear in full in PDF format accompanied by an HTML abstract. "Just Accepted" manuscripts have been fully peer reviewed, but should not be considered the official version of record. They are accessible to all readers and citable by the Digital Object Identifier (DOI®). "Just Accepted" is an optional service offered to authors. Therefore, the "Just Accepted" Web site may not include all articles that will be published in the journal. After a manuscript is technically edited and formatted, it will be removed from the "Just Accepted" Web site and published as an ASAP article. Note that technical editing may introduce minor changes to the manuscript text and/or graphics which could affect content, and all legal disclaimers and ethical guidelines that apply to the journal pertain. ACS cannot be held responsible for errors or consequences arising from the use of information contained in these "Just Accepted" manuscripts.



Journal of the American Chemical Society is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036 Published by American Chemical Society. Copyright © American Chemical Society. However, no copyright claim is made to original U.S. Government works, or works produced by employees of any Commonwealth realm Crown government in the course of their duties.

High spin iron imido complexes competent for C-H bond amination

Matthew J. T. Wilding, Diana A. Iovan, and Theodore A. Betley[†]*

[†]Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, Massachusetts 02138, United States

KEYWORDS (Word Style "BG_Keywords"). If you are submitting your paper to a journal that requires keywords, provide significant keywords to aid the reader in literature retrieval.

ABSTRACT: Reduction of previously reported (^{Ar}L)FeCl with potassium graphite furnished a low-spin ($S = \frac{1}{2}$) iron complex (^{Ar}L) Fe which features an intramolecular η^6 -arene interaction and can be utilized as an Fe¹ synthon ($^{Ar}L = 5$ -mesityl-1,9-(2,4,6- $Ph_3C_6H_2$)dipyrrin). Treatment of (^{Ar}L)Fe with adamantyl azide or mesityl azide led to the formation of the high-spin ($S = \frac{5}{2}$), threecoordinate imidos (^{Ar}L)Fe(NAd) and (^{Ar}L)Fe(NMes), respectively, as determined by EPR, zero-field ⁵⁷Fe Mössbauer, magnetometry, and single crystal X-ray diffraction. The high-spin iron imidos are reactive with a variety of substrates: (^{Ar}L)Fe(NAd) reacts with azide yielding a ferrous tetrazido (^{Ar}L)Fe(κ^2 -AdN₄Ad); undergoes intermolecular nitrene transfer to phosphine; abstracts Hatoms from weak C-H bonds (1,4-cyclohexadiene, 2,4,6-¹Bu₃C₆H₂OH) to afford ferrous amido product (^{Ar}L)Fe(NHAd); and can mediate intermolecular C–H amination of toluene [PhCH₃/PhCD₃ $k_{\rm H}/k_{\rm D}$: 15.5(3); PhCH₂D $k_{\rm H}/k_{\rm D}$: 11(1)]. The C–H bond functionalization reactivity is rationalized from a two-step mechanism wherein each step occurs via maximal energy and orbital overlap between the imido fragment and the C-H bond containing substrate.

1. INTRODUCTION

Coordination complexes featuring metal ligand multiple bonds (MLMBs) are implicated as intermediates in a variety of catalytic transformations both biologically¹⁻² and abiologically.³⁻⁵ The pursuit of MLMBs is driven by their capacity to facilitate atom- and group-transfer catalysis to unreactive C-H bond and olefinic functionalities, key to biological metabolism. Factors that govern MLMB reactivity and, conversely, stability include metal oxidation state, molecular oxidation level, and electronic structure.^{1, 5-20} Efficacy for group transfer reactivity is often reliant on accessing high molecular oxidation²¹ levels to provide the driving force for substrate functionalization (e.g., cytochrome P450), though the direct impact of differing electronic structures has not yet been fully explored. We hypothesized that targeting high-spin configurations could provide a similar driving force: electronic population of MLMB antibonding orbitals limits the MLMB covalency, enhancing its electrophilicity and reactivity group transfer processes.²²⁻²⁶ We have demonstrated enhanced reactivity for group transfer from cobalt imido²⁷ and iron iminyl complexes^{22, 24, 26} capable of activating and functionalizing C-H bonds, respectively. The dipyrrin's weak ligand field strength engenders the high-spin electronic structure despite the inherent strong field MLMB component. Ferric imido complexes have been isolated in $S = \frac{1}{2}$ and $\frac{3}{2}$ configurations, ²⁸⁻³⁴ but the putative high-spin $\frac{5}{2}$ configuration has thus far eluded isolation. Thus, we sought to prepare and evaluate the reaction chemistry of a high-spin iron(III) imido complex against the

literature examples and determine the impact of the electronic structure for group transfer processes.

2. EXPERIMENTAL SECTION

General experimental considerations, reaction assays, characterization and physical measurements, data and spectra, and Xray diffraction techniques are all provided in the Supplementary Information.

(^{Ar}L)FeCl (1): The preparation of this complex has been modified from the previously reported method²²: To a 50 mL pressure vessel was added (^{Ar}L)Li (0.500 g, 0.57 mmol, 1 equiv.), FeCl₂ (0.078 mg, 0.61 mmol, 1.07 equiv.), and 20 mL toluene. The vessel was equipped with a magnetic stir bar, capped, removed from the glovebox, and placed in an oil bath at 150 °C for 14 h. The dark purple mixture was cooled to room temperature, returned to the glovebox, and filtered through a coarse glass frit with Celite to remove lithium chloride and excess iron. The Celite was washed with benzene until the filtrate was nearly colorless. The solvent was removed in vac*uo* and the resulting purple material recrystallized overnight at -40 °C from 18 mL of 2:1 ratio of hexanes to benzene. The mother liquor was decanted and the crystals washed with 4 mL cold (-40 °C) hexanes and dried in vacuo to afford (^{Ar}L)FeCl as purple crystals (0.400 g, 73%). Characterization data (Figure S1-S3) for this compound matches that previously reported.²² $\mu_{\rm eff}$ (295 K, SQUID, Figure S3) = 5.3 $\mu_{\rm B}$.

58 59 60

 $(^{Ar}L)Fe$ (2): In a 20 mL vial, potassium graphite (KC₈, 0.055) g, 0.41 mmol, 1.2 equiv.) was slurried in 1 mL benzene and frozen. A thawing solution of 1 (0.322 g, 0.33 mmol, 1.0 equiv.) in benzene was pipetted on top of the frozen slurry and the reaction allowed to stir while warming to room temperature, during which time the color changed from pink to bright purple. After 3 hours, the reaction was filtered through Celite and the filter cake eluted with excess benzene until the filtrate was nearly colorless. The solvent was removed in vacuo and the solids were dissolved in benzene and again filtered through Celite. The solvent was removed in vacuo and the resulting material dissolved in minimal benzene and transferred to a 20 mL vial. The solution was frozen and the solvent removed via sublimation *in vacuo* to afford **2** as a purple powder (0.191 g, 62%). Crystals suitable for X-ray diffraction were grown from a 2:1 *n*-hexane/benzene mixture at -38 °C. ¹H NMR (400 MHz, 295 K, C₆D₆): no observable peaks. μ_{eff} (150 K, SQUID, Figure S4): 1.7 μ_B . EPR (toluene, 77 K): $g_{eff} = 2.24$, 2.04, 1.98 (Figure 1b). Zero-field ⁵⁷Fe Mössbauer (90 K) (δ, $|\Delta E_{O}|$ (^{mm/}_s)): 0.64, 0.86 ($\gamma = 0.22$ ^{mm/}_s) (Figure 1a). %CHN Calc. for C₆₆H₄₉FeN₂: C 85.61, H 5.33, N 3.03; Found: C 85.38, H 5.13, N 2.89. HRMS (ESI⁺) m/z calcd C₆₆H₄₉FeN₂⁺ [M⁺]: 925.3240, found: 925.3219.

 $(^{Ar}L)Fe(\kappa^2-N_4Ad_2)$ (3): In a 20 mL vial 2 (80 mg, 0.09 mmol, 1 equiv.) was dissolved in 10 mL of benzene. A solution of adamantyl azide in benzene (3.21 g, 1% w/w, 0.18 mmol, 2 equiv) was added resulting in an immediate color change from dark purple to dark red. After stirring for 30 min the solvent was removed in vacuo, and the residue washed with n-hexane to give the tetrazene complex **3** as a dark red powder (98.3 mg, 91%). Crystals suitable for X-ray diffraction were grown from a concentrated toluene solution layered with pentane at -38 °C. ¹H NMR (400 MHz, C₆D₆) δ 31.05, 20.84, 15.40, 15.05 (br s), 14.64, 13.63, 8.76 (br s), 6.73 (d, *J* = 27.2 Hz), 5.67 (t, *J* = 7.0 Hz), 5.40 (t, J = 7.2 Hz), 5.30, 4.79, 3.56 (d, J = 7.3 Hz), 1.76, 1.60, 1.55, 1.32 (q, J = 11.4 Hz), -3.49, -5.40, -5.96 (br s), -7.08, -8.68, -9.52, -18.01 (br s), -27.70, -30.73. μ_{eff} (295 K, SQUID, Figure S7) 4.1 μ_B . EPR (toluene, 4 K): $g_{eff} = 6.25$, 2.07. Zero-field ⁵⁷Fe Mössbauer (90 K) (δ , $|\Delta E_{O}|$ (^{mm/}_s)): 0.70, 2.74 ($\gamma = 0.27 \text{ mm/}_{s}$) (Figure S6). %CHN Calc. for C₈₆H₇₉FeN₆: C 82.47, H 6.36, N 6.71; Found: C 82.30, H 6.21, N 6.57. HRMS (ESI⁺) m/z calcd $C_{86}H_{80}FeN_6^+$ [M⁺]: 1252.5791 found: 1252.5780.

(^{Ar}L)Fe(NAd) (4): A solution of 2 (101 mg, 94 µmol, 1 equiv.) in 50 mL benzene was transferred to an oven-dried 100 mL round bottom flask. A solution of adamantyl azide in benzene (7.90 g, 0.2% w/w, 89 µmol, 0.95 equiv) was added dropwise over the course of 1.5 hours, during which time the color changed from purple to pink. The solvent was removed in vacuo and the resulting solid washed extensively with hexanes to remove unreacted azide and (^{Ar}L)Fe, yielding 4 as a pink/purple solid (81 mg, 85 %). To remove trace tetrazido 3, 4 was recrystallized from a concentration toluene solution layered with pentane at -40 °C to afford purple microcrystals suitable for X-ray diffraction analysis. ¹H NMR (500 MHz, C_6D_6) δ 136.50 (br s), 56.28 (br s), 51.87, 41.60, 37.00, 32.96, 17.89, 10.60, 9.85, 9.43, 2.12, -4.19 (br s), -6.81, -11.79, -26.25, -82.68 (br s). μ_{eff} (295 K,SQUID) 6.20 μ_{B} . EPR (toluene, 4 K): $g_{eff} = 8.62$, 5.35, 3.10. Zero-field ⁵⁷Fe Mössbauer (200 K) (δ , $|\Delta E_0|$ (mm/s)): 0.37, 0.00 ($\gamma = 0.50$ mm/s). %CHN Calc. for C₇₆H₆₄FeN₃: C 84.90, H 6.00, N 3.91; Found: C

84.73, H 5.89, N 4.09. HRMS (ESI⁺) m/z calcd $C_{66}H_{49}FeN_2^+$ [M⁺]: 1074.4444, found: 1074.4421.

(^{Ar}L)Fe(NMes) (5): A solution of mesityl azide (15 mg, 0.09 mmol, 1.05 equiv) in 1 mL benzene was added all at once to a solution of 2 (83 mg, 0.089 mmol, 1 equiv.) in 5 mL benzene, causing an immediate color change from purple to pink. The solvent was removed in vacuo and the resulting material recrystallized from a concentrated solution of toluene layered with pentane at -35 °C. The mother liquor was decanted the resulting crystals washed with pentane to yield 5 as purple crystals (70 mg, 74 %). Crystals were suitable for X-ray diffraction prior to pentane washing. ¹H NMR (400 MHz, C₆D₆) δ 60.95, 50.58, 38.18, 32.24, 17.51, 14.66, 12.57, 11.13, 5.61, -16.90, -22.01, -49.31. Zero-field ⁵⁷Fe Mössbauer (200 K) (δ, $|\Delta E_0|$ (^{mm}/_s)): 0.47, 0.00 ($\gamma = 0.82$ ^{mm}/_s) (Figure S10). %CHN Calc. for C₇₅H₆₀FeN₃•C₇H₈: C 85.55, H 5.95, N 3.65; Found: C 85.46, H 6.28, N 3.73 (one molecule of toluene comes from crystal unit cell).

(^{Ar}L)Fe(HNAd) (6): A solution of 1 (25.8 mg, 26.8 µmol, 1.0 eq) in 5 mL benzene was added to a stirring slurry of lithium adamantyl amide (4.3 mg, 27.4 µmol, 1.02 eq) in 1 mL benzene. After stirring at room temperature for 8 hours, the reaction was filtered through Celite and the filter cake washed with excess benzene until the eluent was nearly colorless. The solvent was frozen and removed *in vacuo* to yield **6** as a purple powder (22.2 mg, 77 %). Crystals suitable for X-ray diffraction were grown from a concentrated solution of toluene layered with pentane at -40 °C. ¹H NMR (400 MHz, C₆D₆) δ 71.27, 50.96, 49.63 (br), 47.26, 36.07, 25.61, 25.36, 17.53, 13.63, 11.69, 10.97, 9.96, 7.76, 2.26, -12.30, -22.49, -54.93 (br). Zero-field ⁵⁷Fe Mössbauer (200 K) (δ , $|\Delta E_o|$ (mm/_s)): 0.61, 0.83 ($\gamma = 0.17$ ^{mm}/_s) (Figure S19). %CHN Calc. for C₇₆H₆₅FeN₃: C 84.82, H 6.09, N 3.90; Found: C 84.68, H 5.96, N 3.76. HRMS (ESI⁺) m/z calcd $C_{66}H_{49}FeN_2^+$ [M+THF+MeOH+H]⁺: 1180.54435, found: 1180.5554. (Note: ionization of this molecule was very poor, which contributed to the 9.3 ppm error.)

(^{Ar}L)Fe(HNMes) (7): A solution of (^{Ar}L)FeCl (100 mg, 0.089 mmol, 1.0 eq) in 5 mL benzene was added to a stirring slurry of lithium mesityl amide (14.7 mg, 0.1 mmol, 1.16 eq) in 1 mL benzene. After stirring at room temperature for 8 hours, the reaction was filtered through Celite and the filter cake washed with excess benzene until the eluent was nearly colorless. The solvent was frozen and removed *in vacuo* to yield 7 as a purple powder (105 mg, 95 %) ¹H NMR (400 MHz, C₆D₆) δ 114.03, 93.91, 86.90, 79.20, 49.81, 38.01, 26.62, 14.47, 12.69, 11.62, 10.17, -18.90, -20.26, -34.42. Zero-field ⁵⁷Fe Mössbauer (90 K) (δ , $|\Delta E_Q|$ (^{mm}/_s)): 0.66, 0.46 (Figure S11). %CHN Anal. Calc. for C₇₅H₆₁FeN₃: C 84.97, H 5.80, N 3.96; Found: C 83.78, H 5.93, N 3.96.

3. RESULTS AND DISCUSSION

Scheme 1

2

3

4

5

6 7

8 9

10

11

12

13 14

15 16

17

18 19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54



3.1 Synthesis and Structural Characterization. The synthesis of metal imido complexes typically utilize oxidative group transfer from organic azides or hypervalent iodine reagents to a reactive coordination complex capable of nitrene capture.⁵ Thus, we prepared a suitable iron(I) reagent following chemical reduction of the three coordinate ferrous dipyrrin (^{Ar}L: (^{Ar}L)FeCl (1) complex 5-mesityl-1,9-(2,4,6- $Ph_3C_6H_2$)dipyrrin).²² Cyclic voltammetry on 1 in dichloromethane revealed a reversible $Fe^{II/III}$ couple at -460 mV and an irreversible reduction event at -1.80 V (both versus $[Cp_2Fe]^{0/+}$, Figure S1) which was attributed to an iron-centered reduction. Accordingly, treatment of 1 with a slight excess (1.05 equiv) of potassium graphite in thawing benzene cleanly afforded the reduced complex (^{Ar}L)Fe (2) (Scheme 1), as evidenced by the single quadrupole doublet (δ : 0.62 ^{mm}/s, $|\Delta E_Q|$: 0.86 ^{mm}/_s) in the ⁵⁷Fe Mössbauer spectrum (Figure 1a). Structural elucidation of 2 reveals an η^6 -interaction between the iron and an orthophenyl substituent of the dipyrrin 2,4,6-Ph₃C₆H₂ aryl flanking unit (Figure 2a). The arene binding interaction is inert to displacement by coordinating ligands (THF, diethyl ether, pyridine, trimethylphosphine, primary amines).

Although the ¹H NMR displays no observable resonances (295 K), the frozen toluene EPR spectrum of **2** at 77 K consists of a rhombic signal ($g_{eff} = 2.24, 2.04, 1.98$), consistent for an $S = \frac{1}{2}$ spin state (Figure 1b). SQUID magnetometry corroborates this assignment with $\mu_{eff} = 1.7 \mu_B$ at 75 K, complete overlay of the isofield curves by reduced magnetization, and good fit of the field-dependence of low-temperature magnetization to the $S = \frac{1}{2}$ Brillouin function (Figure S4). A single-point DFT calculation¹⁶ on a truncated structural model of **2** suggests a high degree of covalency between the iron and η^6 -bound arene (Figure S5), although the predominance of spin density (75 % based on Mulliken spin population analysis) is localized on the metal center and no broken-symmetry solution was found (e.g., $S_{Fe} = 1$, $S_{arene} = -\frac{1}{2}$). The VT magnetic susceptibility data for **2** does not plateau at higher temperature,

instead it manifests a gradual increase at ca. 250 K that continues to the temperature limit of the magnetometer. Thus, we assign the ground state of **2** as a low-spin ($S = \frac{1}{2}$) Fe^I that may thermally populate higher spin states.



Figure 1. 90 K Zero-field ⁵⁷Fe Mössbauer (a) and frozen toluene X-band EPR (b) at 77 K of **2** (red lines provide fits to data with the parameters indicated; EPR fit represents simulation with Easyspin³⁵ using labeled g_{eff} values and $S = \frac{1}{2}$).

Dropwise addition of a dilute (0.03 % w/w) solution of adamantyl azide to $({}^{Ar}L)Fe^{I}$ was sufficient to suppress the formation of the iron-tetrazinato complex $({}^{Ar}L)Fe(\kappa^2-N_4Ad_2)$ (3), and provide the targeted iron-imido complex $({}^{Ar}L)Fe(NAd)$ (4) in good yield (85%). Treatment of 2 with mesitylazide cleanly affords the arylimido complex $({}^{Ar}L)Fe(NMes)$ (5, 74%) without the competing tetrazinato formation, presumably due to the steric protection of the imido aryl *ortho* substituents. The molecular structures of 4 and 5 were obtained by single crystal X-ray diffraction studies on single crystals grown from a concentrated toluene solution layered with pentane at -35 °C (Figure 2b and c, respectively).



Figure 2. Solid-state structure of (a) (^{Ar}L)Fe (2), (b) (^{Ar}L)Fe(NAd) (4) at 100 K with 20% probability ellipsoids and (c) (^{Ar}L)Fe(NMes) (5) and (d) (^{Ar}L)Fe(NHAd) (6) at 100 K with 35 % probability ellipsoids. H atoms and solvent molecules have been omitted for clarity. Colors: Fe, orange; C, gray; H, white; N, blue.



Figure 3. (a) Zero-field ⁵⁷Fe Mössbauer of 4 (red) and 5 (blue) (δ , $|\Delta E_Q|$, Γ (^{mm/}_s): 4, 0.37, 0.00, 0.50; 5, 0.47, 0.00, 0.82), collected at 200 K. (b) X-band EPR of 4 (fit parameters: $S = \frac{5}{2}$, g = 2.0, |E/D| = 0.145), collected at 4 K. (c) VT dc magnetic susceptibility for 4 collected at 0.5 T over the temperature range 5 – 300 K (blue circles). Inset: VTVH magnetization data collected on increasing temperature from 1.8 to 10 K at increasing field for 1, 4, and 7 T with the fit parameters as described in the text.

The molecular structures for imidos 4 and 5 feature distorted trigonal planar iron(III) centers supported by the dipyrrin ligand and single imido moieties. The Fe–N3 distance of 1.674(11) Å in 4 and 1.708(2) Å in 5 are consistent with the reported range for three- and four-coordinate iron-alkylimido species [1.622 – 1.700(5) Å] with established multiple bond character.^{22, 28-31, 33-34, 36-44} In addition, the \angle Fe–N3–C_{*imido*} angle of 174.7° in 4 and 172.3(2)° in 5 suggest biaxial π contributions, supporting the view of 4 and 5 as iron(III) complexes featuring doubly-bonded imidos.

3.2 Spectroscopic Characterization. The Mössbauer spectra of **4** and **5** feature single broad transitions (δ , $|\Delta E_Q|$, Γ (^{mm}/_s): **4**, 0.37, 0.00, 0.50; **5**, 0.47, 0.00, 0.82) at 200 K (Figure 3a). The isomer shift values are close to those previously reported for iminyl radicals (^{Ar}L)Fe^{III}Cl('NAr) (δ , $|\Delta E_Q|$ (^{mm}/_s): 0.29, 2.29),²² (^{IBu}L)Fe^{III}Cl('NAr) (δ , $|\Delta E_Q|$ (^{mm}/_s): 0.37, 2.17),²⁴ and the bimolecularly-coupled [(^{Ar}L)Fe^{III}Cl]₂(κ^2 -N(Ph)(C₆H₅)N) (δ , $|\Delta E_Q|$ (^{mm}/_s): 0.33, 2.15)²² suggesting a common iron oxidation state assignment among these molecules and **4**, whereas the parameters for **5** are presumably affected by the conjugation to the imido mesityl functionality. Spectra obtained below ca. 150 K suffer from significant

broadening and low signal-to-noise ratio, likely due to incomplete resolution of hyperfine splitting at 90 K or more complex relaxation broadening phenomena⁴⁵ often observed in high-spin Fe^{III} compounds.

In accordance with the observed temperature dependent phenomena (vide supra). 4 and 5 do not exhibit an EPR signal above ca. 50 K. The frozen toluene EPR spectrum of 4 (Figure 3b) obtained at 4 K displays a rhombic signal ($g_{eff} = 8.62, 5.35$, 3.10), well reproduced by an $S = \frac{5}{2}$ simulation treating each intra-doublet transition as an effective $S = \frac{1}{2}$ system (in accordance with the weak-field limit) and including the effects of both rhombicity $(^{E}/_{D})$ and *D*-strain (simulation parameters: g = 2.0, |E/D| = 0.145, linewidth = 15 G). The inclusion of Dstrain is necessary to account for the randomness in spatial confirmation of the frozen solution and provide an effective powder pattern for a given S and $^{\rm E}/_{\rm D}$.⁴⁸ No satisfactory agreement with experiment was found for simulations employing the $S = \frac{3}{2}$ assignment. Accordingly, solid-state magnetometry of 4 is consistent with a high spin state as evidenced by a μ_{eff} of 5.3 $\mu_{\rm B}$ ($\chi_{\rm M}T$ = 4.76 cm³ K/mol) at 295 K (Figure 3c). The value of $\chi_{\rm M}T$ over the temperature range surveyed is consistent with an $S = \frac{5}{2}$ configuration (spin-only value anticipated is

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55 56

57

58

59 60 4.38 cm³ K/mol). The spin state suggested by the magnetic susceptibility data is further corroborated by variable-temperature, variable-field magnetization data collected on heating from 1.8 to 10 K and at increasing fields of 1–7 T (Figure 3c inset). Magnetization saturation occurs at 4.86 $\mu_{\rm B}$ at 1.8 K and 7 T. The lower than expected saturation (5.92 $\mu_{\rm B}$ for an ideal $S = \frac{5}{2}$ with g = 2) and the observation of non-superimposable isofield curves indicates the presence of zero-field splitting, which was quantified by fitting the data to the spin Hamiltonian $\hat{H} = D\hat{S}_z^2 + E(\hat{S}_x^2 - \hat{S}_y^2) + g_{\rm iso}\mu_{\rm B}$ **S**•**H**. The fitt parameters considering an $S = \frac{5}{2}$ that best reproduce the data are g = 2.02, D = 1.0 cm⁻¹, $|^{\rm E}/_{\rm D}| = 0.01$ (Figure 3c inset, continuous black traces).

A single-point DFT calculation⁴⁹ on 4 corroborates the $S = \frac{5}{2}$ ground state assignment and the calculated Mössbauer parameters match well with those observed for 4 (calculated δ (mm/s): 0.35). The calculated spin density plot ($\alpha - \beta$) for 4, shown in Figure 4a, illustrates the contributions to the total spin contributed by iron (78%) and the imide nitrogen atom (16%). The molecular orbital ordering indicated in Figure 4b is governed by the type of bonding and overlap between the metal center, the dipyrrin ligand, and the imido fragment, each singly populated in the high-spin configuration: 286a (dx2: σ^* to dipyrrin; π^* to imido Npx), 285a (dx2: π^* to imido Npy), 280a (dz2: σ^* to imido Npz). 273 α -274 α (dz2: σ^* , dxy: nominally nonbonding) (Figure S20). The density functional modeling and magnetic data acquired for imido complexes 4 and, by extension, 5 are assigned as the first high-spin ($S = \frac{5}{2}$) complexes thus far observed on iron.

3.3 Reactivity Assessment. With the isolated high-spin imidos 4 and 5 in hand, we were thus interested in assessing whether the reactivity of these two complexes diverge from that reported for the low- and intermediate spin analogues. Low-spin $(S = \frac{1}{2})$ complexes have been shown to exhibit nitrene transfer to tertiary phosphines and CO,²⁸ whereas the intermediate spin imido complexes have displayed this reactivity in addition to facilitating H-atom abstraction from weak C–H bonds.^{37, 50-52} A reaction between 4 and excess PMe_2Ph (100 equivalents) proceeded instantaneously at room temperature to produce the phosphinimide Me2PhP(NAd) and regenerate 2. Heating a mixture of 4 and 1,4-cyclohexadiene at 45 °C resulted in slow consumption of 4 and formation of a new paramagnetic complex as evidenced by ¹H NMR (Figure S13), to afford the amido product of H-atom abstraction (^{Ar}L)Fe(NHAd). This assignment was verified by comparison of the reaction mixture ¹H NMR spectrum (Figure S13) with an authentic sample of (ArL)Fe(NHAd) (6) afforded by the direct metathesis of 1 with LiNHAd in benzene. The amide is not stable to prolonged heating, preventing the full consumption of 4 prior to decomposition. Nevertheless, a significant amount of product can be observed after 7 days incubating at 45 °C. In a similar fashion, 5 partially (ca. 50% completion) converts to the amide (ArL)Fe(NHMes) following treatment with 2,4,6-^tBu₃C₆H₂OH (BDE O-H: 81 kcal/mol)⁵³ at 60 °C for 6 h, as shown in the ¹H NMR overlay with authentic (^{Ar}L)Fe(NHMes) (7) (Figure S14). While production of the amide 7 is evident, further reaction between 7 and the aryloxide radical is also apparent (Figure S14).



Figure 4. The calculated spin density population $(\alpha - \beta)$ for 4 $(S = {}^{5}/{}_{2})$ (a), the qualitative orbital energetic ordering (b), and the highest singly occupied orbitals for $(Fe_{yz} - NR_{py}, 285\alpha)$ and $(Fe_{xz} - NR_{px}, 286\alpha)$ (c) as suggested by DFT (B3LYP/6-31g(d); Gaussian 09).⁴⁹

The reactivity of three coordinate **4** and **5** should be contrasted with the quartet imido reported by Holland that does not undergo intermolecular HAT reactivity except in the presence of a Lewis base (e.g. pyridine, lutidine).³⁴ The authors propose the intermediacy of an $S = \frac{5}{2}$ pyridine adduct that possesses sufficient potency to engender reactivity towards C– H bonds. While imide variants that do not necessitate pyridine coordination prior to HAT have since been prepared ($S = \frac{3}{2}$), their rate of reaction with 1,4-cyclohexadiene, for example, is between one and four orders of magnitude slower than the postulated $S = \frac{5}{2}$ adduct complex.³²

While 4 is stable in toluene solutions below or at room temperature, heating toluene solutions of 4 to 80 °C resulted in amination of the solvent benzylic C-H bond. Analysis of the reaction mixture by LC-MS revealed intermolecular C-H amination and formation of N-adamantyl-benzylamine (14%), N-adamantyl-benzylimine (3%), and significant amounts of 1,2-diphenylethane. Kinetic isotope effects $(k_{\rm H}/k_{\rm D})$ of 15.5(3) and 11(1) were determined for intermolecular (C_7H_8 vs. C_7D_8) and intramolecular (d_1 -toluene C₆H₅CH₂D activation) competition experiments, respectively, based on analysis of the resulting insertion products by LC-MS (see Supporting Information). These data are reminiscent of the intermolecular C-H amination chemistry with (AdL)FeCl(OEt2) reported previously (KIE: 12.8(5), presence of 1,2-diphenylethane at elevated temperatures as a result of solvent cage breakdown and coupling of two benzylic radicals), and are similarly consistent with a stepwise abstraction/recombination mechanism. Although 4 does not possess radical density on the imido fragment as proposed for (^{Ar}L)FeCl('NAr),²² C-H functionalization chemistry is still possible with 4.

3.4 Molecular Orbital Considerations. The large KIE observed in the reaction of **4** with toluene suggests that the C–H bond breaking event contributes significantly to the rate limiting step of the reaction sequence illustrated in Figure 5a. A

consideration of the frontier molecular orbitals (FMOs) that complete this process includes the two iron imido π interactions and the toluene C–H σ bond (see Figure 5). The two $N\pi$ FMOs consist of the non-degenerate π interactions: $\pi_x \left[\sigma^*_{(dxz)} \right]$ $L_{\sigma} \pm Np_x$ which includes a Fe-L_{dipyrrin} σ^* component, and the orthogonal π_v (Fe d_{vz} ± Np_v). We propose the π_v^* FMO dictates the primary orbital interaction with the incoming toluene C-H substrate given its steric accessibility and more favorable energetic overlap. The H-atom abstraction step is highlighted in Figure 5b, where the homolyzed C-H orbital (yielding PhC'H₂ and H 1s) combine with π_y/π_y^* to yield four orbital combinations: $(\sigma_{N-H})^2$ (Fe $3d_{yz}$)² (PhC H₂)¹ $(\sigma_{N-H}^*)^0$, constituting a one-electron reduction at the iron center to Fe^{II}. The H-atom abstraction step conserves total spin-angular momentum as the resulting radical pair complex remains in a sextet spin configuration. The recombination step (Figure 5c) should proceed combining the benzylic radical with the remaining $\pi_x \left[\sigma_{(dxz - c)} \right]$ $L_{\sigma} \pm Np_x$ pair yielding three product orbitals: $(\sigma_{N-C})^2$ (Fe $(3d_{xz})^2 (\sigma^*_{N-C})^0$, requiring a spin inversion to avoid population of σ^*_{N-C} , and thus constituting a net reduction of the iron center to Fe¹.

While **4** is operative for C–H bond amination, the (β -diketiminate)Fe^{III}(NAd) ($S = {}^{3}/_{2}$) congener described by Holland was reported to be active for the H-atom abstraction reaction but not for the radical rebound mechanism.^{32, 34} The principal difference between the two nearly isostructural materials is the spin ground states resulting from the ligand field strengths of the two ancillary ligand sets. From an orbital perspective, the π_y components are largely the same between the β -diketiminate and dipyrrin complexes, thus the HAA step is

largely unchanged and could proceed by similar mechanisms. The π_x/π_x^* , however, do change between the two ancillary ligands. The stronger σ -donating β -diketiminate destabilizes π_x^* which remains unpopulated in the ground state. Similarly, the corresponding bonding π_x would be lowered in energy with respect to **4**. Thus the radical recombination step could be affected by the orbital energy changes and diminish the probability for the recombination step.

Akin to (ArL)Co(NR) imido complexes which thermally access open shell configurations permitting C-H bond activation to occur,²⁷ the high-spin Fe^{III} imido complexes reported herein can facilitate nitrene transfer including C-H bond functionalization. Furthermore, the high-spin imido complexes can be synthesized utilizing both alkyl and aryl-imido fragments, suggesting the sextet configuration is energetically preferred even when the MLMB unit ligand field strength is increased. Comparing the results demonstrated herein with the known reactivity of ferric imido complexes spanning electronic configurations of $S = \frac{1}{2} \rightarrow \frac{5}{2}$, the sextet configuration is the only electronic structure that permits both H-atom abstraction and the subsequent recombination reaction to occur. Thus, one could envision catalytic intra- or intermolecular nitrene delivery reactions to be developed, so long as the high-spin electronic structure is maintained for the MLMB fragment. Given that both the ferric imido and iminyl radical species have been shown to be competent for intermolecular nitrene delivery into C-H bonds, we are now interested in understanding how the oxidative potency is varied between the species. Research is currently underway to probe this factor for group transfer catalysis.



Figure 5. Frontier molecular orbital description of $Fe^{III}(NAd)$ reaction profile for H-atom abstraction from PhCH₃ and the subsequent radical rebound event.

(1) Ortiz de Montellano, P. R., Cytochrome P450 : Structure, Mechanism, and Biochemistry. 4th ed.; Kluwer Academic/Plenum Publishers: New York, 2005.

Supporting Information. Crystallographic data, X-ray crystal

structure images, magnetic data, Mössbauer, and ¹H NMR

spectra. This material is available free of charge via the ACS

This work was supported by grants from the NSF (CHE-

0955885) and NIH (GM-115815), and from Harvard Uni-

versity. M.W. would like to thank the NSF for a Predoctoral

- (2) Mehn, M. P.; Peters, J. C. J. Inorg. Biochem. 2006, 100, 634.
- (3) Bess, E. N.; Deluca, R. J.; Tindall, D. J.; Oderinde, M. S.; Roizen, J.
- L.; Du Bois, J.; Sigman, M. S. J. Am. Chem. Soc. 2014, 136, 5783.
- (4) Liu, W.; Groves, J. T. J. Am. Chem. Soc. 2010, 132, 12847.
- (5) Nugent, W. A.; Mayer, J. M., Metal-Ligand Multiple Bonds: The Chemistry of Transition Metal Complexes Containing Oxo, Nitrido, Imido, or Alkylidyne Ligands. Wiley-Interscience: New York, 1988.
- (6) Cenini, S.; Gallo, E.; Caselli, A.; Ragaini, F.; Fantauzzi, S.; Piangiolino, C. Coord. Chem. Rev. 2006, 250, 1234.
- (7) Chen, M. S.; White, M. C. Science 2007, 318, 783.

ASSOCIATED CONTENT

AUTHOR INFORMATION

betley@chemistry.harvard.edu

Corresponding Author

Funding Sources

Graduate Fellowship.

REFERENCES

Publications website at http://pubs.acs.org.

- (8) Chen, M. S.; White, M. C. Science 2010, 327, 566.
- (9) Davies, H. M. L.; Lian, Y. Acc. Chem. Res. 2012, 45, 923.
- (10) Davies, H. M. L.; Long, M. S. Angew. Chem. Int. Ed. 2005, 44, 3518.
- (11) Geng, C.; Ye, S.; Neese, F. Dalton Trans. 2014, 43, 6079.
- (12) Halfen, J. A. Curr. Org. Chem. 2005, 9, 657.
- (13) Krebs, C.; Fujimori, D. G.; Walsh, C. T.; Bollinger, J. M. Acc. Chem. Res. 2007, 40, 484.
- (14) Li, A.-H.; Dai, L.-X. Chem. Rev. 1997, 97, 2341.
- (15) Liao, K.; Negretti, S.; Musaev, D. G.; Bacsa, J.; Davies, M. H. Nature 2016, 533, 230.
- (16) McGarrigle, E. M.; Gilheany, D. G. Chem. Rev. 2005, 105, 1563.
- (17) Müller, P.; Fruit, C. Chem. Rev. 2003, 103, 2905.
- (18) Munoz, I., S. B.; ; Lee, W.-T.; Dickie, D. A.; Scepaniak, J. J.; Subedi,
- D.; Pink, M.; Johnson, M. D.; Smith, J. M. Angew. Chem. Int. Ed. 2015, 54, 10600.
- (19) Xia, Q.-H.; Ge, H.-Q.; Ye, C.-P.; Liu, Z.-M.; Su, K.-X. Chem. Rev. 2005, 105, 1603.
- (20) Ye, S. F.; Neese, F. Curr. Opin. Chem. Biol. 2009, 13, 89.
- (21) Rittle, J.; Green, M. T. Science 2010, 330, 933.
- (22) King, E. R.; Hennessy, E. T.; Betley, T. A. J. Am. Chem. Soc. 2011, 133, 4917
- (23) King, E. R.; Betley, T. A. Inorg. Chem. 2009, 48, 2361.
- (24) Iovan, D. A.; Betley, T. A. J. Am. Chem. Soc. 2016, 138, 1983.
- (25) Hennessy, E. T.; Liu, R. Y.; Iovan, D. A.; Duncan, R. A.; Betley, T. A. Chem. Sci. 2014, 5, 1526.
- (26) Hennessy, E. T.; Betley, T. A. Science 2013, 340, 591.

- (27) King, E. K.; Sazama, G.; Betley, T. A. J. Am. Chem. Soc. 2012, 134, 17858.
- (28) Brown, S. D.; Betley, T. A.; Peters, J. C. J. Am. Chem. Soc. 2003, 125, 322
- (29) Betley, T. A.; Peters, J. C. J. Am. Chem. Soc. 2003, 125, 10782.
- (30) Lu, C. C.; Saouma, C. T.; Day, M. W.; Peters, J. C. J. Am. Chem. Soc. 2007, 129, 4.
- (31) Scepaniak, J. J.; Young, J. A.; Bontchev, R. P.; Smith, J. M. Angew. Chem. Int. Ed. 2009, 48, 3158.
- (32) Cowley, R. E.; Holland, P. L. Inorg. Chem. 2012, 51, 8352.
- (33) Bart, S. C.; Lobkovsky, E.; Bill, E.; Chirik, P. J. J. Am. Chem. Soc. 2006, 128, 5302.
- (34) Cowley, R. E.; DeYonker, N. J.; Eckert, N. A.; Cundari, T. R.; DeBeer, S.; Bill, E.; Ottenwaelder, X.; Flaschenriem, C.; Holland, P. L. Inorg. Chem. 2010, 49, 6172.
- (35) Stoll, S.; Schweiger, A. J. Magn. Reson. 2006, 178, 42.
- (36) Brown, S. D.; Peters, J. C. J. Am. Chem. Soc. 2005, 127, 1913.
- (37) Cowley, R. E.; Eckert, N. A.; Vaddadi, S.; Figg, T. M.; Cundari, T. R.; Holland, P. L. J. Am. Chem. Soc. 2011, 133, 9796.
- (38) Klinker, E. J.; Jackson, T. A.; Jensen, M. P.; Stubna, A.; Juhász, G.; Bominaar, E. L.; Münck, E.; Que, L. Angew. Chem. Int. Ed. 2006, 45, 7394
- (39) Moret, M. E.; Peters, J. C. Angew. Chem. Int. Ed. 2011, 50, 2063.
- (40) Ni, C.; Fettinger, J. C.; Long, G. J.; Brynda, M.; Power, P. P. Chem. Commun. 2008, 6045.
- (41) Nieto, I.; Ding, R.; Bontchev, R. P.; Wang, H.; Smith, J. M. J. Am. Chem. Soc. 2008, 130, 2716.
- (42) Thomas, C. M.; Mankad, N. P.; Peters, J. C. J. Am. Chem. Soc. 2006, 128, 4956.
- (43) Verma, A. K.; Nazif, T. N.; Achim, C.; Lee, S. C. J. Am. Chem. Soc. 2000, 122, 11013.
- (44) Wang, L.; Hu, L.; Zhang, H.; Chen, H.; Deng, L. J. Am. Chem. Soc. 2015, 137, 14196.
- (45) Stoian, S. A.; Yu, Y.; Smith, J. M.; Holland, P. L.; Bominaar, E. L.; Munck, E. Inorg. Chem. 2005, 44, 4915.
- (46) Greenwood, N. N.; Gibb, T. C., Mössbauer Spectroscopy. Springer: Netherlands, 1971.
- (47) Gütlich, P.; Bill, E.; Trautwein, A. X., Mössbauer Spectroscopy and Transition Metal Chemistry: Fundamentals and Applications. Springer: New York, 2010.
- (48) Hagen, W. R. Mol. Phys. 2007, 105, 2031.
- (49) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M. J.; Heyd, J.; Brothers, E. N.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A. P.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, N. J.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, Ö.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. Gaussian 09, Gaussian, Inc.: Wallingford, CT, USA, 2009. (50) Cowley, R. E.; Eckert, N. A.; Elhaik, J.; Holland, P. L. Chem.
- Commun. 2009, 1760.
- (51) Eckert, N. A.; Vaddadi, S.; Stoian, S. A.; Lachicotte, R. J.; Cundari, T. R.; Holland, P. L. Angew. Chem. Int. Ed. 2006, 45, 6868.
- (52) Cowley, R. E.; Holland, P. L. Inorg. Chim. Acta 2011, 369, 40.
- (53) Luo, Y.-R., Handbook of Bond Dissociation Energies in Organic Compounds. CRC Press LLC: Boca Raton, FL, 2003.

TOC GRAPHIC

