Facile and Regioselective C–H Bond Activation of Aromatic Substrates by an Fe(II) Complex Involving a Spin-Forbidden Pathway

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 Supporting Information

ABSTRACT: The Fe(II) complex Cp*Fe(CO)(NCMe)Ph (Cp* = η5-pentamethylcyclopentadienyl) is shown to mediate facile and highly regioselective C–H activation of aromatic substrates including benzene, furan, thiophene, thiazole, and 2-methylfuran. Experimental and computational evidence suggest a mechanism for C–H activation that involves NCMe dissociation, multiple spin inter system crossings, C–H bond coordination, and C–H bond cleavage by a σ-bond metathesis reaction.

INTRODUCTION

The majority of homogeneous catalysts for hydrocarbon C–H bond activation and functionalization are based on second- or third-row transition metals.1–3 Although first-row transition metal oxo, alkoxide and amide complexes can functionalize C–H bonds,4–10 they typically function via net H abstraction and are often limited to relatively weak C–H bonds.11,12 While nature has evolved highly selective enzymes for C–H functionalization using net H abstraction by metal oxo complexes (including Fe oxo complexes), extending the high reactivity and selectivity to synthetic systems has been a substantial challenge.13,14 Thus, it is desirable to develop nonradical, nonoxo metal C–H activation catalysts based on inexpensive Earth-abundant transition metals (Scheme 1). However, there are several challenges associated with developing catalysts based on the first row of the transition metal series including typically weaker metal carbon bond strengths, propensity toward single-electron chemistry, complications due to the possibility of spin crossover, and access to multiple oxidation states.15,16 These challenges have limited the number of examples of non-o xo, nonradical stoichiometric C–H activation reactions based on 3d transition metals.17,18 Some examples of catalytic C–H activation and functionalization by first-row transition metals have been disclosed.17–19

Two of our groups have previously reported that TpRu(L)(NCMe)Ph [Tp = hydridotris(pyrazolyl)borate; L = CO, PMe3, P(OCH2)3C6Et, 2,6,7-trioxo-1-phosphabicyclo[2.2.1]heptane, P( N-pyrrolyl)3] complexes readily activate aromatic and olefinic C–H bonds.20–24 We envisioned that a similar (Y)Fe(L)(NCMe)Ph (Y = monoanionic, six-electron donor ligand) complex with an Fe(II) metal center might also provide entry into C–H activation.25 Because of the similarities between Tp and Cp*,26 we chose Cp*Fe(CO)(NCMe)Ph (2) as the initial complex. Herein, we report experiments and calculations that showcase the success of this Fe(II) complex for regioselective aromatic C–H activation under mild conditions.

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RESULTS AND DISCUSSION

The target complex 2 was prepared by reaction of Cp*Fe(CO)25 with CuOTf and Bu3SnPh, which gave Cp*Fe(CO)2Ph (1) in 67% isolated yield. Complex 1 has been previously reported, albeit in lower yields. The photolysis of an NCMe solution of 1 produced Cp*Fe(CO)(NCMe)Ph (2) in 87% isolated yield (Scheme 2). Complexes 1 and 2 were both characterized by single crystal X-ray diffraction (Figure 1).

Scheme 2. Synthesis of Cp*Fe(CO)(NCMe)Ph (2)

Figure 1. ORTEP drawings of Cp*Fe(CO)2Ph (1) and Cp*Fe(CO)(NCMe)Ph (2) (50% probability ellipsoids; H atoms omitted). Complex 1 (left). Selected bond lengths (Å): Fe C7/C7 1.756(1), Fe C8 2.002(2), C7 O1/C7 O1 1.151(2). Selected bond angles (°): C7 Fe C7 96.87(8), C7/C7 Fe C8 91.30(5). Complex 2 (right). Selected bond lengths (Å): Fe C14 1.990(1), Fe C11 1.741(1), Fe N1 1.903(1), C11 O1 1.154(2). Selected bond angles (°): C11 Fe N1 98.00(6), C11 Fe C14 91.79(6), N1 Fe C14 89.79(5).

For an initial test of C–H activation, 2 was heated to 50 °C in C6D6. Cp*Fe(CO)(NCMe)(Ph-d5) (2-d5) forms in 80% yield based on NMR spectroscopy (eq 1). The formation of 1 and 1-d5 (10%) and other uncharacterized products make up the remaining 20% of Fe complexes. Under pseudo-first-order conditions in C6D6 at 49 °C, k12k0 is 4.6(5) × 10⁻⁴ s⁻¹ for the C–D activation of Cp*CD6.

To explore the mechanism of C–D bond activation by 2, we utilized M0625,30 density functional calculations with SMD solvent corrections to calculate possible intermediates and transition states.30 Comparison of the M06 optimized structure of 2 (Figure 2) shows highly similar bond lengths and angles compared to the X-ray structure shown in Figure 1. Starting from complex 2, C–H activation begins with NCMe dissociation to create a vacant coordination site. The enthalpic (ΔH) penalty for complete NCMe dissociation along the singlet energy surface is 27.1 kcal/mol. The resulting Cp*Fe(CO)(Ph) singlet complex (3S) shows an unrestricted wave function with a spin contamination <S²> value of 0.23, which suggests open-shell character and a possible high-spin state of lower energy. Indeed, the triplet Cp*Fe(CO)(Ph) complex (3T) is adiabatically 16.4 kcal/mol more stable than 3S. The structures 3S and 3T show that after complete loss of NCMe, the CO and Ph groups recede slightly, but the only major bond length change is a decrease in the Fe–Ph bond length from 1.98 Å in 2 to 1.91 and 1.94 Å in 3S and 3T, respectively. The structures 3S and 3T are highly similar.

Consideration of spin states and their interconversion is important for first row transition metals.32–34 Direct conversion of 3S to 3T can occur through a singlet triplet intersystem crossing, called a minimum energy crossing point (MECP). The optimized structure of MECP-1 (Figure 3) connects 3S to 3T and has an energy and geometry nearly identical to 3T. Although it is possible that NCMe completely dissociates before singlet triplet intersystem crossing, there is a lower energy pathway for conversion of complex 2 to 3S. This pathway involves singlet triplet interconversion with partial NCMe dissociation (Fe N = 2.18 Å) via MECP-2 with a ΔH value of 9.0 kcal/mol relative to 2. Optimization of the resulting triplet structure after MECP-2 resulted in the triplet NCMe π complex 4T with H = 4.6 kcal/mol. Structure 3T is then accessed upon NCMe dissociation. These structures suggest that NCMe dissociation is facile through a dissociative mechanism. An interchange coordination mechanism that remains on the singlet energy surface is unlikely due to the reluctance of the Fe metal center to increase its ligand coordination number.

Scheme 3 outlines the lowest energy pathway calculated for benzene C–H activation by complex 2. As discussed above, 3S is generated via MECP-2 followed by NCMe loss. Although 3T is a viable intermediate, Fe Ph group exchange from this species on the triplet energy surface showed barriers too high to be reasonable, and it is therefore a dead-end intermediate. As a result, a second intersystem crossing step to return to the singlet energy surface is required during the C–H bond coordination/activation mechanistic stage. There are two possible pathways for this intersystem crossing. The first pathway involves conversion of 3S to 3T via MECP-1 followed...
by benzene coordination on the singlet surface. The second pathway, which is lower in energy, involves intersystem crossing along with benzene coordination via MECP-3 to give singlet 5'). The structure and energy of MECP-3 is nearly identical to 5) (Figure 4). The enthalpy of triplet 5') is 24.0 kcal/mol and confirms that the singlet-triplet crossing point occurs just prior to structure 5').

Structure 5) involves \( \eta^2 \)-C,H-benzene coordination. Because of the orientation of the Fe Ph group, no true \( \eta^3 \)-C,\( \eta^2 \)C,C-benzene coordination complex could be located. For Ru(II) complexes, \( \eta^2 \)-C,H-benzene coordination is preferred to \( \eta^2 \)-C,C-benzene coordination has been taken to imply steric congestion at the metal center.\(^{22} \) From intermediate 5), the lowest energy pathway for C-H bond cleavage occurs via a four-centered \( \sigma \)-bond metathesis type transition state 6-TS (Figure 4) with a calculated \( \Delta H \) of 29.4 kcal/mol. In this transition structure, the Fe Ph bond length is stretched to 2.04 \( \text{Å} \), and the benzene C-H bond partial bond length is 1.49 \( \text{Å} \). The transition state 6-TS directly connects to another \( \eta^2 \)-C,H-benzene coordination complex 5). At this point NCMe can replace coordinated benzene from 5) to regenerate 2. This last step is also susceptible to spin intersystem crossings, but they are not pictorially represented in Scheme 3.

We have ruled out several other C-H activation mechanisms for Fe Ph group exchange. The first involves the generation of a so-called tuck-in type complex directly from 2. In this mechanism, a methyl C-H bond of the Cp group undergoes intramolecular \( \sigma \)-bond metathesis with the Fe Ph group to give a cyclometalated Cp\( ^* \) group and \( \eta^2 \)-C,H-benzene coordination. The calculated \( \Delta H \) for this process is 50.9 kcal/mol. The G for forming the tuck-in complex after dissociation of NCMe is 54.6 kcal/mol. We have observed no
deuterium incorporation into the Cp* methyl resonances (1H NMR spectroscopy) for the reaction of 2 and CdD₆.

We have also considered the Fe(II) to Fe(IV) oxidative addition from 3a and 3b to give the seven-coordinate diphenyl hydride intermediate Cp*=Fe(CO)/(Ph)(Ph)(H). All optimizations starting with seven-coordinate Fe hydride structures reverted back to 5a. Lastly, our calculations suggest several hydrogen abstraction mechanisms from both 3a and 3b are unlikely pathways. For example, the H to give Cp*=Fe(CO)-(Ph)(H) and -C₆H₆ is 48.4 kcal/mol relative to 3a. Eisenstein et al. have found similar results for their study on the TpFe motif.³⁵

The ability of 2 to activate benzene prompted us to explore the possibility of 2 activating heteroaromatic substrates under similar mild conditions. Indeed, complex 2 regioselectively activates furan, thiophene, thiazole and 2-methylfuran at or below room temperature (Scheme 4). To optimize stability, the products from the C-H activation of furan, thiophene and 2-methylfuran were isolated as their PPh₃ adducts. Cp*=Fe(CO)-(PPh₃)(2-furyl) (7) and Cp*=Fe(CO)(PPh₃)(2-thienyl) (8) were isolated in 96 and 97% yield, respectively, from the reaction of 2 with the furan or thiophene followed by the addition of PPh₃.

The 1H and 13C NMR spectra for complexes 7 and 8 exhibit broadened resonances in the aromatic region. A variable-temperature 1H NMR experiment was performed on 8, and decoalescence of the Cp* resonance was observed (Figure 5). When free thiophene (0.5 eqn.) was added to a THF-d₈ solution of 8, no changes to the peak shape or chemical shifts for 8 in the 1H NMR spectrum were observed. These data, taken in account with only one carbonyl stretching frequency in the IR spectrum and one resonance in the 13C NMR spectrum, implies that the fission reaction observed is not due to reversible phosphine cycoaddition but possibly a result of hindered rotation of PPh₃. The structure of 7 has been determined by single-crystal X-ray diffraction (Figure 6), which confirms the regioselectivity of C-H activation at the 2-position.

The reaction of 2 with thiazole produces Cp*=Fe(CO)-(thiazole)(2-thiazolyl) (9) in 36% isolated yield. Calculations suggest the N-bound thiazole complex is more favorable than the S-bound isomer by 13.5 kcal/mol (Scheme 5, see Supporting Information). The formation of 9 proceeds via an intermediate (observed by 1H NMR spectroscopy), which is likely Cp*=Fe(CO)(thiazole)Ph.

The C-H activation of 2-methylfuran by 2 is selective for the 5-position over the methyl group. The reaction of 2 with 2-methylfuran followed by the addition of PPh₃ produced Cp*=Fe(CO)(PPh₃)(2-(5-methylfuryl)) (10) in 82% isolated yield. Similar to complexes 7 and 8, complex 10 also exhibits broadened 1H and 13C NMR resonances in the downfield region of the spectra, which may also be attributed to slow rotation around the Fe PPh₃ bond. This selectivity, in which Fe activates a stronger aromatic C-H bond in preference to a weaker CH₂ bond, suggests that C-H activation proceeds via a pathway that does not involve the formation of free radicals in accordance with the MO6 density functional calculation predictions (see above).

To experimentally probe these C-H activation reactions we studied several kinetic features for the reaction of 2 with furan. Under pseudo-first-order conditions in 2 at 3 °C, a plot of [2] vs time shows a first-order exponential decay (Figure 7). Varying the equivalents of furan relative to 2 revealed that the
The reaction rate has a first-order dependence on the concentration of furan at low concentrations with saturation kinetics at higher concentrations (Figure 8). The rate of reaction is dependent on the concentration of free NCMe (Figure 9). Treating complex 2 with 10 equiv of a 1:1 molar solution of furan and furan-d₈ and analyzing the relative quantities of C₆H₆ and C₆H₆D by GC/MS revealed a kinetic isotope effect of 5.0(4). Additionally, we have examined the kinetic isotope effect with a large excess of furan (50 equiv), and k_H/k_D = 4.8(1), which is statistically equivalent with that determined with 10 equiv of furan. Kinetic data for the C·H activation of furan (10 equiv) were obtained from 12 to 13 °C. An Eyring plot (in which the experimentally determined kₑ are corrected to remove the concentration of free NCMe (Figure 9). Treating complex 2 with 10 equiv of a 1:1 molar solution of furan and furan-d₈ and analyzing the relative quantities of C₆H₆ and C₆H₆D by GC/MS revealed a kinetic isotope effect of 5.0(4). Additionally, we have examined the kinetic isotope effect with a large excess of furan (50 equiv), and k_H/k_D = 4.8(1), which is statistically equivalent with that determined with 10 equiv of furan. Kinetic data for the C·H activation of furan (10 equiv) were obtained from 12 to 13 °C. An Eyring plot (in which the experimentally determined kₑ were corrected to remove [furan]) gave activation parameters of $H = 23.5(4)$ kcal/mol and $S = 12(2)$ cal/mol·K (Figure 10).

![Figure 7](image1.png) Sample first-order decay plot for the reaction of 2 and furan (10 equiv) at 3 °C ($R^2 = 0.99$).

![Figure 8](image2.png) Plot of pseudo-first-order rate constants ($k_{obs}$) versus [furan] for the reaction of 2 with excess furan at 3 °C.

![Figure 9](image3.png) Plot of 1/$k_{obs}$ versus [NCMe] ($R^2 = 0.99$) for the reaction of 2 with excess furan.

We computed the enthalpy profile for reaction of 2 with furan in THF solvent (Scheme 6). We have found a nearly identical mechanism for benzene and furan C·H activation by 2. The initial steps of NCMe dissociation and intersystem crossing are identical with the benzene mechanism shown in Scheme 3. The energies of MECP-2, 4, and 3' in THF solvent are a few tenths of a kcal/mol lower than in benzene solvent. From 3' furan coordinates via MECP-4 (Figure 11, $H = 15.9$ kcal/mol) to give singlet 11', which involves the formation of a true $n^1$C,C-C complex Cp²Fe(CO)(NCMe)2 (2) with a $H$ of 13.0 kcal/mol.

The $n^1$C,C-complex 11' is less endothermic than the benzene complex 5' because it involves $\pi$ forward- and back-bonding in contrast to mainly $\sigma$ type interactions in 5'. For Lewis basic metals, furan is known to bind stronger than benzene in a diphospho-coordination mode.36 The calculated $H$ for C·H bond cleavage of furan via the $\sigma$-bond metathesis transition state 13-TS = 22.2 kcal/mol, which is in good agreement with the experimental value for $H$ of 25.4(4) kcal/mol. Despite the 8 kcal/mol computed stronger C·H bond strength of furan ($H = 118$ kcal/mol) versus benzene ($H = 110$ kcal/mol), the $H$ value for furan C·H activation is 7 kcal/mol lower than the benzene $H$ value. The lower $H$ for C·H activation of furan could be interpreted as a result of the lower energy $n^1$C,C-complex 11'. However, prior to 13-TS the $n^1$C,C-complex rearranges to an $n^1$C,H-complex 12' with coordination to the furan $\sigma$ C·H bond rather than the furan $\pi$ bond. An alternative explanation for the lower $H$ value for furan C·H activation versus benzene C·H activation is the result from a more stable Cp²Fe(CO)(2-furyl)($n^2$C,H-benzene) intermediate 14' ($H = 12.7$ kcal/mol) compared with 5'. The thermodynamic stability of 14' is manifested in 13-TS as stability gained from formation of a more stable Fe·furyl bond compared with the formation of a Fe·Ph bond in 6-TS (see Supporting Information for details).

On the enthalpy surface the furan C·H bond cleavage transition state 13-TS is higher in energy than MECP-2 and MECP-4 points. This suggests that the rate of Fe·Ph group transformation into a Fe·furyl group is controlled by 13-TS, which is in accordance with the relatively large KIE value (5) observed experimentally.

On the basis of calculations and experimental results, a proposed mechanism and corresponding rate law for the C·H
Scheme 6. Calculated Enthalpies (Free Energies at 298 K) for C-H Activation of Furan by Cp*Fe(CO)(NCMe)Ph (2) in THF Solvent (kcal/mol)

Figure 11. Furan C-H activation structures. Bond lengths reported in Å and angles in degrees.

activation of furan by 2 is shown in Scheme 7. Reversible NCMe dissociation via a spin-forbidden pathway yields the coordinatively unsaturated intermediate. After furan coordination and subsequent C-H bond cleavage with concomitant release of benzene, acetonitrile recoordinates completing the transformation. The rate law predicts 1/[NCMe] inhibition (Figure 8) and saturation kinetics in concentration of furan (Figure 9).

Using the proposed rate law, $k_1$ can be independently determined from the data in Figure 8 and Figure 9. Under saturation conditions (Figure 8), the rate law is reduced to rate $\sim k_1[2]$, and using the data in Figure 8, $k_1 = 8.8 \times 10^{-4}$ s$^{-1}$. The value of $k_1$ can also be determined from the y-intercept of Figure 9, which yields $k_1 = 7.1 \times 10^{-4}$ s$^{-1}$. Thus, the two independently determined values of $k_1$ are in good agreement.

Scheme 7. Proposed Mechanism and Corresponding Rate Law for the C-H Activation of Furan by Cp*Fe(CO)(NCMe)Ph (2)

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Under saturation conditions in furan, \( k_{\text{obs}} = k_1 \), which provides the rate of NCMa dissociation from 2 (see above). Thus, an Eyring analysis was performed under saturation conditions (30 equiv of furan, 22 to 3 °C) in order to extract the activation parameters for the NCMa dissociation sequence (Figure 12). For NCMa dissociation, \( H = 20.2(3) \text{ kcal/mol} \) and \( S = 0(2) \text{ cal/mol-K} \). Scheme 6 shows that the lowest energy pathway for NCMa dissociation results in 3'. Comparison of the enthalpy of 3' with the measured \( H \) shows that the predicted value is 10 kcal/mol too low. We examined the possibility that this discrepancy is due to the M06 density functional. However, all other functionals tested predict lower enthalpy values for 3'. We note that \( k_1 \) values have been determined using an indirect method, and despite the discrepancy in experimental and calculated values, the comparison of overall energetics between theory and experiment is a good fit, and the predicted rate limiting C-H activation is in accord with the observed kinetic isotope effects.

We also explored the kinetics of thiophene activation by 2. Using 20 equiv of thiophene at 3 °C the \( k_{\text{obs}} = 3.2(4) \times 10^{-4} \text{ s}^{-1} \), which is approximately 2.5 times slower than the reaction with furan. Because no intermediates were observed through the course of the reaction (\(^1\text{H} \text{ NMR} \) spectroscopy), we speculate that the decrease in rate from the reaction with furan might be explained from the smaller energy stabilization gained from the formation of the Fe thienyl from the breaking C-H bond versus the analogous transformation with furan.

The regioselective activation of furan \(^{33,35,36} \) prompted us to investigate the underlying reasons for this observed selectivity. Calculations show a 3.8 kcal/mol \( H \) value between the 13-TS and the regioisomeric transition state at the 3-position of furan. Again, the regioselectivity can be rationalized on the basis of the relative stability gained by formation of an Fe C2(furyl) bond versus an Fe C3(furyl) bond in the transition state. The Fe C2(furyl) intermediate generated from C-H bond cleavage has a \( H \) value of 12.7 kcal/mol, while the Fe C3(furyl) intermediate generated from C-H bond activation has a \( G \) value of 17.1 kcal/mol. Quantitative analysis of so-called transition state bond energies \(^{37} \) showed that in 13-TS the Fe C2(furyl) bond energy is 8 kcal/mol more stable than the Fe C3(furyl) bond energy in the alternative regioisomeric C-H activation transition state. Eisenstein, Perutz, and Jones have also suggested thermodynamic influence on the rates of metal-mediated C-H activation.\(^{39,41} \)

**SUMMARY**

We have reported an Fe(II) complex, Cp*Fe(CO)(NMe)Ph (2) (\( R^2 = 0.99 \) 22 to 3 °C). Under these conditions, \( k_{\text{obs}} = k_1 \) (see Scheme 7), which gives the rate of NCMa dissociation.

**EXPERIMENTAL SECTION**

**General Considerations.** Unless otherwise noted, all synthetic procedures were performed under anaerobic conditions in a nitrogen-filled glovebox or by using standard Schlenk techniques. Glovebox purity was maintained by periodic nitrogen purges and was monitored by an oxygen analyzer (O2 < 15 ppm for all reactions). Tetrahydrofuran and n-pentane were dried by distillation from sodium/benzophenone and P2O5, respectively. Diethyl ether was distilled over CaH2. Benzene was purified by passage through a column of activated alumina. Benzene-d6, acetone-d6, CD3CN, and 1,4-dioxane-d4 were used as received and stored under a N2 atmosphere over 4 Å molecular sieves. For kinetic experiments, THF-d8 was degassed by two conventional freeze pump thaw cycles and stored over 4 Å molecular sieves. H-31C NMR spectra were recorded on a Varian Mercury 300 or Varian Inova 500 MHz spectrometer, and 31P NMR spectra were recorded on a Varian Inova 500 MHz spectrometer (operating frequency 125 MHz) or Bruker Avance III 500 MHz spectrometer (operating frequency 201 MHz). All 1H and 31C spectra are referenced against residual protons signal (31C NMR) or 31P resonances (31C NMR) of the deuterated solvents and are reported in ppm. 31P NMR spectra were obtained on a Varian Mercury hyperpolarized (operating frequency 121 MHz) spectrometer and referenced against an external standard of H3PO4 (\( \delta = 0 \)). GC/MS was performed using a Shimadzu GCMS-QP2010 Plus system with a 30 m \( \times 0.25 \text{ mm} \) RTx-Qbond column with 8 µm thickness using electron impact ionization. IR spectra were obtained on a Shimadzu IRAffinity-1 Fourier transform infrared spectrophotometer. Samples were prepared in solution flow cells. Photolysis experiments were performed using UV vis radiation generated by a 450 W power supply (Model #7830, Ace Glass, Inc.) equipped with a water-cooled 450 W in. arc IMMIR UV vis lamp (Model #7825-34, Ace Glass, Inc.). Furan-d5 was purchased from Aldrich and distilled prior to use. All other chemicals were used as purchased from commercial sources. Elemental analyses were performed by Atlantic Microlab, Inc. Cp*Fe(CO)2 (1) was prepared according to the literature procedure.

Cp*Fe(CO)2Ph (1). A mixture of Cp*Fe(CO)2I (0.533 g, 1.43 mmol), CuOTf (0.480 g, 1.91 mmol), Bu4SnH (0.610 mL, 1.87 mmol) and 1,4-dioxane (6 mL) was prepared. The mixture was stirred at 60 °C for 4 h during which time the mixture turned from dark brown to orange-beige. After cooling to room temperature, the mixture was filtered through a short plug of silica gel on a fine porosity frit followed by the in vacuo removal of the volatiles from the filtrate.

The resulting residue was dissolved in a minimal amount of THF and chromatographed on silica gel eluting with 1:10 (v/v) diethyl ether/hexanes. A yellow band was collected and dried in vacuo. The resulting solid was triturated with a minimal amount ofpentane to yield a yellow solid (0.311 g, 67%). A crystal suitable for single crystal X-ray diffraction was grown by the slow evaporation of a pentane solution of 1. 1H NMR (300 MHz, CD3CN): \( 7.38 \) (2H, d, \( \delta = 6 \) Hz, phenyl ortho), \( 7.16 \) (2H, t, \( \delta = 6 \) Hz, phenyl meta), 7.07 (1H, t, \( \delta = 6 \) Hz, phenyl meta).

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H₂ phenyl para), 1.32 (1H, s, C₄Me₃). ¹³C NMR (75 MHz, C₄D₄): 218.3 (CO), 128.6, 143.4, 123.2 (Ph), 96.2 (C₄Me₃), 9.3 (C₄Me₃) (Note: 1 resonance of phenyl is missing presumably from coincidental overlap). IR (KCl Me solution): νₓ₀ = 1994, 1937 cm⁻¹. Anal. Caled for C₄H₇F₃Cl: C 66.6, H 6.22; found C 66.6, H 6.39.

**Cp³Fe(CO)(NMe₃)Ph (2).** A solution of 1 (0.356 g, 1.67 mmol) in acetonitrile (10 mL) was irradiated in an ice bath with stirring for a total of 1 h. After the first and second hour, photolysis was ceased and 2 conventional freeze pump/toluene cycles were performed on the reaction flask. After 3 h, the volatiles were removed in vacuo. The resulting residue was extracted with diethyl ether (10 mL) and filtered through Celite. Removal of volatiles produced a red solid, which was washed with pentane (10 mL in portions) to yield a red-orange solid (0.45g, 87% yield). This compound is moderately stable at room temperature in the solid state, but was typically stored at -35°C.

**Cp³Fe(CO)(NMe₃)Ph (2) and C₄D₄.** A solution of 2 (0.044 g, 0.12 mmol) was added 2- methylnitriam (0.11 mL, 1.2 mmol). After stirring the red solution for 1 h, PPh₃ was dissolved in the reaction mixture. The volatiles were removed in vacuo. The solid was washed with pentane (3 mL) and dried in vacuo to obtain a red solid of 5 (0.056 g, 82% yield). ¹¹H NMR (300 MHz, acetone-d₆): 7.56 (1H, br m, PPh₃), 5.52 (2H, overlapping, methyl 3 and 4), 2.12 (3H, s, methyl), 1.43 (1H, s, C₄Me₃). ¹³C NMR (201 MHz, acetone-d₆): 224.8 (d, JCP = 27 Hz, CO), 173.5 (d, JCP = 32 Hz, thienyl ipso), 156.9 (s, PPh₃), 135.0 (br s, PPh₃), 130.3 (s, PPh₃), 128.5 (s, methyl), 122.6 (s, methylnitriam), 108.3 (s, methyl), 94.0 (s, C₄Me₃), 14.2 (s, methyl), 10.1 (s, C₄Me₃). Note: The ipso carbon for PPh₃ could not be located due to coincidental overlap.

**PPh₃** NMR (121 MHz, acetone-d₆): JCP = 77.7. IR (THF solution): νₓ₀ = 1913 cm⁻¹. Anal. Caled for C₅H₇F₃P: C 72.60, H 6.27; found C 72.61, H 6.26.

**Reaction of Cp³Fe(CO)(NMe₃)Ph and C₄D₄.** In a screw-cap NMR tube, 2 (0.005 g, 0.02 mmol) and hexamethyldisilane (HMDS), internal standard, 1 µL were dissolved in C₄D₄ (0.25 mL). The NMR tube was heated to 50°C in a temperature-controlled oil bath. The reaction was periodically monitored by ¹¹H NMR spectroscopy until completion using a delay time of 5 s. During that time, the phenyl resonances decreased in intensity relative to HMDS. Using the integrations of the Cp³ methyl peaks versus the integration of HMDS, an approximate yield of 80% was determined for the formation of 2-d₃.

**Deposition of the Rate of Benzene C D Activation.** A stock solution of 2 (0.024 g, 0.071 mmol) and HMDS (3 µL) was prepared in 1.5 mL of C₄D₄. Three 0.4 mL aliquots of this stock solution were added to three different screw-cap NMR tubes. The samples were frozen until it was time to collect data. Each sample was subsequently monitored by ¹¹H NMR spectroscopy in a temperature-regulated probe (calibrated at 49°C) through 2 half-lives, collecting spectra every 5 min (5 s delay). The reaction was monitored through only half-lives due to decompensation at longer reaction times. A plot of [2]-t vs time was created and fitted to an exponential decay curve. The rate constants were extracted from these plots to yield kobs = 4.65(5.4) × 10⁻⁴ s⁻¹ (see Supporting Information).

**Dependence on Furan Concentration for the C H Activation of Furan by Cp³Fe(CO)(NMe₃)Ph (2).** A representative experiment follows. Two stock solutions were prepared in 2 separate 1 mL volumetric flasks. In the first stock solution, complex 2 (0.027 g, 0.080 mmol) was dissolved in 1 mL of THF-d₄. In the second stock solution, furan (128 µL) and HMDS (8 µL) were added and diluted to 1 mL with THF-d₄. From the first stock solution, 275 µL (0.002 mmol of 2) aliquots were transferred to 3 separate screw-cap NMR tubes equipped with Teflon-lined septa. The second stock solution was transferred to a dram vial with a Teflon-lined septum cap. Outside the glovebox, one NMR tube was cooled in an ice/water bath. Using a microsyringe, a 125 µL (10 equiv of furan) aliquot of the second stock solution was injected through the cap of the NMR tube. The tube was vigorously shaken and placed in a temperature calibrated NMR probe (3°C). ¹¹H NMR spectra (5 s delay, every 2.5 min) were acquired through at least 3 half-lives. By monitoring the disappearance of the ortho-phenyl protons of 2 versus HMDS, a plot of [2] vs time was created (see Supporting Information). Following the decay curve allowed the rate constant to be extracted. This was repeated for the two remaining NMR tubes. The whole procedure was performed for 7, 10, 15, 20, 25, 30, 35 equiv of furan.

**Dependence on NMe₃ Concentration for the C H Activation of Furan by Cp³Fe(CO)(NMe₃)Ph (2).** A representative experiment follows. Two stock solutions were prepared in 2 separate 1 mL volumetric flasks. In the first stock solution, complex 2 (0.027 g, 0.080 mmol) was dissolved in 1 mL of THF-d₄. In the second stock
solution, furan (2.56 μL), NCMc (18.3 μL, 5% v/v in THF-δ4), and HMDS (8 μL) were diluted to 1 mL with THF-δ4. From the first stock solution, 275 μL (0.022 mmol of 2) aliquots were transferred to 3 separate screw-cap NMR tubes equipped with Teflon-lined septa. The second stock solution was transferred to a 1-dram vial with a Teflon-lined septum cap. Outside the glovebox, one NMR tube was cooled in an ice-water bath. Using a microsyringe, a 125 μL (20 equiv of furan, 0.1 equiv of NCMc) aliquot of the second stock solution was injected through the cap of the NMR tube. The tube was vigorously shaken and placed in a temperature calibrated NMR probe (3 °C). 3H NMR spectra (5 s delay, every 5 min) were acquired through at least 3 half-lives. By monitoring the disappearance of the ortho-phenyl protons of 2 versus HMDS, a plot of [2] vs time was created (see Supporting Information pp. S6-S7). Fitting the data to an exponential decay curve allowed the rate constant to be extracted. This was repeated for the two remaining NMR tubes. The whole procedure was performed for 0.05, 0.1, and 0.2 equiv of NCMc. A plot of 1/δobs vs [NCMe] showed an excellent linear correlation.

**Eyring Plot for the CαH Activation of Furan by Cp*Fe(CO)(NCMe)Ph (2).** The procedure described above for measuring the dependence of rate of furan activation on furan concentration was repeated at 12, 6, and 3 °C using 10 equiv of furan (3 runs each, see Supporting Information). Plotting ln(δobs/T) vs 1/T gave an excellent linear fit and allowed the determination of the activation parameters. The plotted δobs value is the value determined after dividing the experimentally determined δobs value by [furan].

**Determination of the Rate of Thiophene CαH Activation.** Two stock solutions were prepared in 2 separate 1 mL volumetric flasks. In the first stock solution, complex 2 (0.027 g, 0.080 mmol) was dissolved in 1 mL of THF-δ4. In the second stock solution, thiophene (281 μL) and HMDS (8 μL) were added and diluted to 1 mL with THF-δ4. From the first stock solution, 275 μL (0.022 mmol of 2) aliquots were transferred to 3 separate screw-cap NMR tubes equipped with Teflon-lined septa. The second stock solution was transferred to a 1 dram vial with a Teflon-lined septum cap. Outside the glovebox, one NMR tube was cooled in an ice-water bath. Using a microsyringe, a 125 μL (20 equiv of thiophene) aliquot of the second stock solution was injected through the cap of the NMR tube. The tube was vigorously shaken and placed in a temperature calibrated NMR probe (3 °C). 3H NMR spectra (5 s delay, every 2.5 min) were acquired through at least 3 half-lives. By monitoring the disappearance of the ortho-phenyl protons of 2 versus HMDS, a plot of [2] vs time was created (see Supporting Information p. S9). Fitting the data to an exponential decay curve allowed the rate constant to be extracted. This was repeated for the two remaining NMR tubes.

**Variable Temperature NMR for Cp*Fe(CO)(PPPh2)(2-thienyl) (8).** A 1.00 mM solution of 4 dissolved in THF-δ4 was incrementally cooled in a 600 MHz NMR probe. Upon cooling, the resonance assigned to the Cp* methyl protons decoalesced into 2 singlets. Spectra were acquired at the following temperatures (not calibrated): 25 °C, 0 °C, 20 °C, 40 °C, 50 °C, 60 °C, 80 °C. Monitoring Cp*Fe(CO)(PPPh2)(2-thienyl) (8) in the Presence of Excess Thiophene. Complex 4 (0.011 mg, 0.020 mmol) was dissolved in THF-δ4 (0.4 mL) and transferred to an NMR tube sealed with a Teflon-lined screw cap. Following the acquisition of an initial 3H NMR spectrum, thiophene (0.8 μL, 0.010 mmol) was added. A 3H NMR spectrum of the resulting solution was acquired and revealed the presence of free thiophene and identical chemical shifts and peak shapes of the resonances assigned to 4 as observed in the initial spectrum.

**Experimental Evidence against the Formation of a Tuck-In Complex during the Reaction of Cp*Fe(CO)(NCMe)Ph (2) and Cp6Me6.** While monitoring the reaction of 2 and Cp6Me6 the total integration for the Cp* peaks relative to HMDS remained constant (within deviation), suggesting there is no H/D exchange into the methyl resonances of the Cp* ligand during the course of the reaction. The total deviation for the integrations of the Cp* region is 4%.

**Eyring Plot for the CαH Activation of Furan by Cp*Fe(CO)(NCMe)Ph (2) Under Saturation Conditions.** Two stock solutions were prepared in 2 separate 1 mL volumetric flasks. In the first stock solution, complex 2 (0.027 g, 0.080 mmol) was dissolved in 1 mL of THF-δ4. In the second stock solution, furan (334 μL) and HMDS (8 μL) were added and diluted to 1 mL with THF-δ4. From the first stock solution, 275 μL (0.022 mmol of 2) aliquots were transferred to 2 separate screw-cap NMR tubes equipped with Teflon-lined septa. The second stock solution was transferred to a 1 dram vial with a Teflon-lined septum cap. Outside the glovebox, one NMR tube was cooled in an ice-water bath. Using a microsyringe, a 125 μL (30 equiv of furan) aliquot of the second stock solution was injected through the cap of the NMR tube. The tube was vigorously shaken and placed in a temperature calibrated NMR probe (12 or 12 °C). 3H NMR spectra (5 s delay, every 15 or 25 min) were acquired through at least 2.5 half-lives. By monitoring the disappearance of the ortho-phenyl protons of 2 versus HMDS, a plot of [2] vs time was created (see Supporting Information p. S10). Fitting the data to an exponential decay curve allowed the rate constant to be extracted. Plotting ln(δobs/T) vs 1/T gave a very good linear fit and allowed the determination of the activation parameters.

**Computational Details.** All stationary points were optimized in the gas phase using either restricted or unrestricted M06 density functional theory with the 6-31G(d,p) basis set for all atoms except Fe. The LANLDZ2 basis set and pseudopotential was utilized for Fe during optimization. Single point energies were further refined using the M06 functional with the 6-311++G(3df,3pd) basis set for light atoms and LANLDZ2Z(f) with an f exponent of 2.462 for Fe.90 Solvent energy corrections were calculated using the SMD solvent model of benzene and furan. Solvation calculations were performed on the gas-phase optimized structures.90 Optimization, single point, and solvation calculations were all carried out in Gaussian 09.91 Location of singlet triplet intersystem crossing points, also called minimum energy crossing points (MECPs), was done using the algorithm of Harvey,44 in conjunction with Gaussian 09. Although MECPs are not stationary points, frequency calculations were carried out on these structures to obtain approximate enthalpy and free energy corrections.

**ASSOCIATED CONTENT**

**Supporting Information**

Computational details, supporting figures, full reference 43, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**

The authors declare no competing financial interest.

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