Bimetallic Cleavage of Aromatic C−H Bonds by Rare-Earth-Metal Complexes

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Ⓢ *Supporting Information*

ABSTRACT: A new type of C−H bond activation mediated by rare-earth metals under reducing conditions is reported. The synergy between reductants and rare-earth-metal complexes allows the cleavage of unactivated aromatic C−H bonds. The reaction between rare-earth-metal iodides supported by a 1,1′-ferrocenediamide ligand and potassium graphite in benzene leads to the formation of a 1:1 metal molar ratio of the corresponding metal hydride and metal phenyl complex. A proposed mechanism involving an inverse sandwich arene bimetallic intermediate is supported by experimental and computational studies.

Organometallic compounds have been found to be particularly useful in mediating C−H activation, and a significant effort has been spent on understanding how such transformations work.[1−3] Four types of nonradical mechanisms are widely accepted: σ-bond metathesis with polarized metal−carbon bonds,[4] oxidative addition with electron-rich, low-valent late transition metals,[5] 1,2-CH addition across a polarized metal−element multiple bond,[6,7] and electrophilic activation with electron-deficient late transition metals.[8,9] Recent experimental and computational studies suggest that electrophilic activation with late transition metals follows a pseudo-σ-bond metathesis mechanism, in which a σ-coordinated complex forms prior to C−H activation.[9,10] Despite the fact that multiple mechanisms are available for late transition metals, σ-bond metathesis has been the only mechanism known for rare-earth metals. Most noteworthy is the absence of oxidative addition for early transition metals and f elements (lanthanides and actinides), because they usually have a d^0 electron configuration in complexes. In this respect, the lack of oxidative addition for early transition metals limits their use in C−H transformations.

Herein, we report a new type of C−H bond activation mediated by rare-earth metals that cannot be classified as σ-bond metathesis. The reaction occurs from a metal halide in the presence of a reductant and an arene and leads to the formation of a metal hydride and a metal aryl species. A detailed mechanistic study suggests that an inverse sandwich intermediate featuring a benzene dianion asymmetrically bridging two metal centers is formed prior to the C−H activation step.

Recently, we reported the synthesis and reactivity of rare-earth-metal fused-arene complexes supported by a ferrocenediamide ligand, 1,1′-fc(NSi^{t}BuMe$_2$)$_2$ (NN^{fc}): [(NN^{fc})M(THF)$_x$]$_2$(μ-arene) (M = Sc, x = 0, arene = naphthalene, anthracene; M = Y, La, Lu, x = 1, arene = naphthalene; THF = tetrahydrofuran).[11−13] Later

on, we prepared a series of 6C, 10-π-electron aromatic systems, [(NN^{fc})M(μ-arene)]$_2$[K(solvent)]$_2$ (M = Sc, Y, La, Lu, arene = biphenyl, *p*-terphenyl, 1,3,5-triphenylbenzene, solvent = THF, toluene, [18]-crown-6).[14] The two classes of complexes were both obtained from (NN^{fc})MI(THF)$_2$ (**1**: M = Sc, **1a**; M = Y, **1b**; M = Lu, **1c**) in the presence of potassium graphite (KC$_8$) and a stoichiometric amount of arene in THF. We then turned our attention to benzene, the prototypical arene. Addition of 1.8 equiv of KC$_8$ to a benzene solution of **1a** (eq 1) resulted
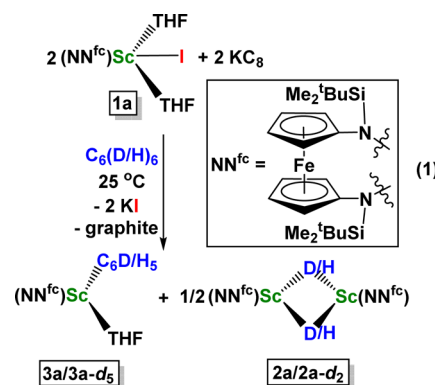
in no immediate color change. However, after 2 h of stirring at 25 °C, the characteristic golden brown color of KC$_8$ disappeared and graphite precipitated out. After insoluble matter and volatiles were removed, an orange solid was obtained. The ^{1}H NMR spectrum of the solid suggested that two products were obtained in a 1:1 scandium molar ratio that were separated on the basis of their different solubilities. The product ratio was determined by ^{1}H NMR spectroscopy and did not change during the reaction (Figures S1−S3, Supporting Information). X-ray crystallography unambiguously established one of the products to be a scandium hydride, [(NN^{fc})Sc(THF)](μ-H)$_2$[Sc(NN^{fc})] (**2a**) (Figure 1a). The other product, the scandium phenyl complex (NN^{fc})Sc(C$_6$H$_5$)(THF) (**3a**), was characterized by its independent synthesis. The related compound (NN^{fc})Sc(*p*-tolyl)(THF) (**4p**) was characterized by X-ray crystallography. When the reaction was carried in benzene-d_6, [(NN^{fc})Sc(THF)](μ-D)$_2$-[Sc(NN^{fc})] (**2a-d_2**) and (NN^{fc})Sc(C$_6$D$_5$)(THF) (**3a-d_5**) were formed and identified by ^{1}H and ^{2}H NMR spectroscopy (Figure S50, Supporting Information). These data unambiguously
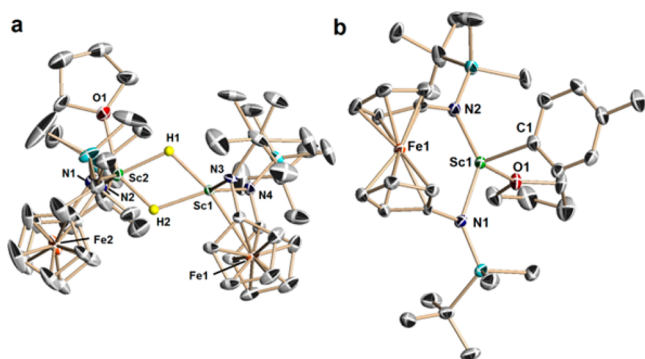
Figure 1. Thermal ellipsoid (50% probability) representations of **2a** (left) and **4p** (right). Hydrogen atoms are omitted for clarity, except for hydrides.

established that the hydride and phenyl moieties originated from benzene.

Other reaction variables tested include the gas atmosphere (N_2, H_2, Ar, and reduced pressure) and reductants (KC_8, sodium mirror, and sodium amalgam). We found that benzene activation proceeded in a similar fashion under various gas atmospheres. Evans et al. reported the first and only structurally characterized scandium dinitrogen complex by reacting a scandium(III) complex with KC_8 under an N_2 atmosphere.[15] Presumably, a similar reaction could have taken place in the reaction of **1a** and KC_8 under N_2 and the in situ generated scandium dinitrogen complex could react with benzene to form the observed products, **2a** and **3a**. However, since benzene activation proceeded under an argon atmosphere as well as under reduced pressure (high vacuum), this is unlikely the case. In addition, it is important to note that no excess formation of **2a** was observed under an H_2 atmosphere, suggesting that the reaction does not follow a σ-bond metathesis mechanism, which would favor the formation of **2a**.[16] Regarding reductants, sodium mirror worked similarly to KC_8, suggesting that the benzene activation reactivity is not reductant specific; however,
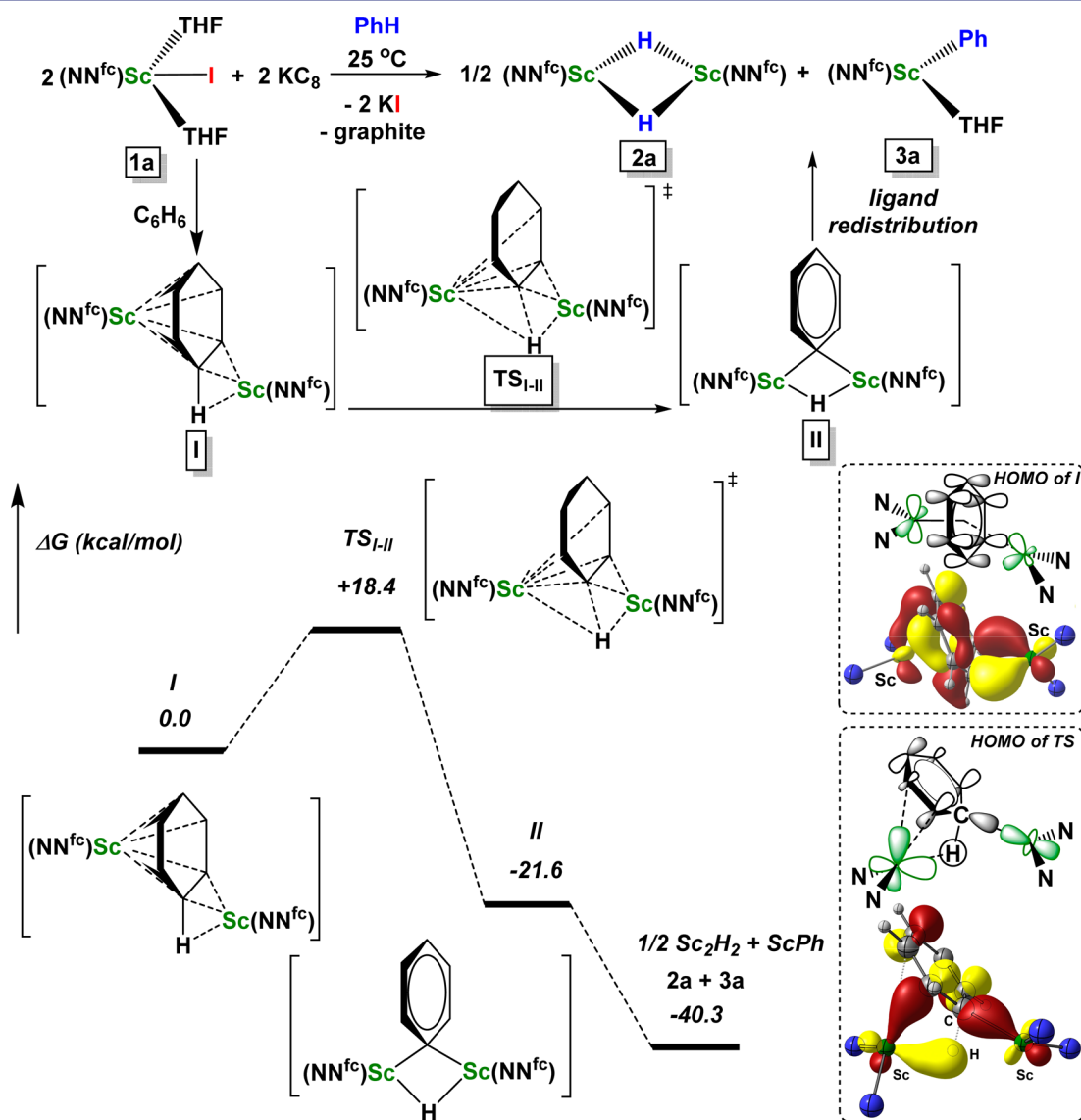

Figure 2. (top) Proposed mechanism for C−H bond activation of benzene by **1a** and KC_8. (bottom left) Reaction coordinates of benzene activation by **1a** and KC_8 calculated by DFT methods. (bottom right) HOMO of intermediate **I** and HOMO of transition state TS_{I-II} (only the nitrogen atoms of the ferrocenediamide ligand are shown).

a weaker reductant, sodium amalgam,[17] did not lead to benzene activation even at a high sodium concentration (2.5 wt %).

To the best of our knowledge, the activation of aromatic C−H bonds by an early-transition-metal complex to form an equimolar mixture of metal hydride and metal phenyl complexes is unprecedented. A close example is the oxidative addition of halogens and the reductive elimination of biphenyl on a d^0 Zr(IV) center supported by a redox-active o-iminoquinone ligand reported by Heyduk et al.[18,19] We propose the following mechanism for the present reaction (Figure 2): the reduction of **1a** with KC$_8$ in the presence of benzene leads to intermediate **I** ([[(NN^{fc})Sc]$_2$(μ-benzene)), featuring a benzene dianion bridging two scandium(III) centers in an unsymmetrical fashion. **I** then undergoes C−H activation to give the bridging hydride-aryl dinuclear complex **II**. Ligand redistribution from **II** accounts for the observed products, **2a** and **3a**. A benzene dianion supported by rare-earth metals had been isolated in [K([18]-crown-6)][Cp″$_2$Ln(μ_2,η^6:η^4-C$_6$H$_6$)] (Cp″ = η^5-C$_5$H$_3$(SiMe$_3$)$_2$-1,3, Ln = La, Ce, Nd), showing a boat conformation and best described as a 1,4-cyclohexa-2,5-dienyl ligand, although no further reactivity to form metal hydride and/or phenyl products was reported.[20] In our case, monitoring the reaction in benzene-d_6 by ^{1}H NMR spectroscopy did not allow the observation of species other than **1a**−**3a**.

DFT calculations support the proposed mechanism (Figure 2). The heterogeneous nature of KC$_8$ reduction prevented us from carrying out calculations of the reaction coordinate prior to the formation of **I**; therefore, we started with **I**. **I** was calculated to have a slightly distorted chair conformation that differs from the previously isolated benzene boat conformation of [K([18]-crown-6)][Cp″$_2$Ln(μ_2,η^6:η^4-C$_6$H$_6$)];[20] the mean C−C distance of 1.45 Å for the aromatic ring is indicative of the reduction of the benzene ligand. Inspection of the HOMO of **I** indeed confirms that the lowest unoccupied π^*(e$_{2u}$) orbital of benzene is populated in **I**. Notably, the coordination of the two scandium(III) centers to the benzene dianion is unsymmetrical and, while one Sc^{3+} binds to six carbon atoms (Sc−C 2.52−2.76 Å), the second metal ion stabilizes preferentially one C−C bond (Sc−C 2.28 and 2.31 Å). **I** is kinetically and thermodynamically unstable, and its conversion to **II** is exothermic ($\Delta_r G° = -21.6$ kcal/mol) with a low activation barrier of 18.4 kcal/mol. Importantly, the transition state **TS$_{I-II}$** connecting **I** and **II** has unique geometric and electronic features and the two Sc^{3+} ions play distinct roles in the C−H activation process. Whereas both metal centers stabilize the formation of a bridging hydride ligand (Sc−H 2.08 and 2.33 Å), one Sc^{3+} ion facilitates the formation of a Sc−C σ bond (2.21 Å), while the second Sc^{3+} ion stabilizes the π electrons on the reduced benzene ligand. The HOMO of **TS$_{I-II}$** reveals a strong mixing between the occupied π^* orbital on the reduced arene and the vacant C−H σ^* orbital. The C−H bond cleavage, therefore, results from a reduction of the C−H bond and, unlike the case in late-transition-metal chemistry, the two electrons responsible are provided by the extra π^* electrons of the benzene dianion. The role of the rare-earth ions is thus to enable the intraligand $\pi^* \rightarrow \sigma^*$ electron transfer by breaking the symmetry of the s/p separation on the aromatic ring and stabilize the energy of the accepting σ^*_{CH} orbital through coordination to the C and H donors.

Although a benzene discandium intermediate could not be observed, we decided to probe whether a similar reaction is observed from an analogous naphthalene complex (Scheme 1a). Variable-temperature ^{1}H NMR spectra of [(NN^{fc})Lu(THF)]$_2$-(μ-C$_{10}$H$_8$) (**5c**) showed that this compound displays fluxional

Scheme 1. Mechanistic Studies

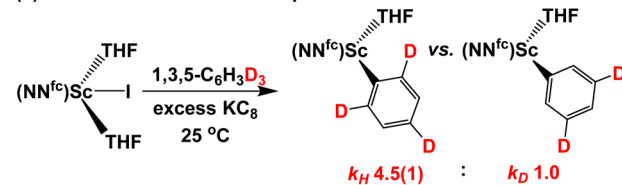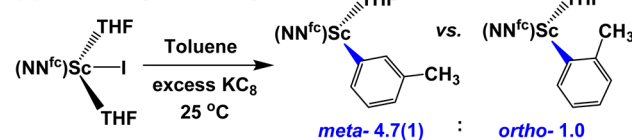**(a) C-H Activation from a dianionic naphthalene complex**
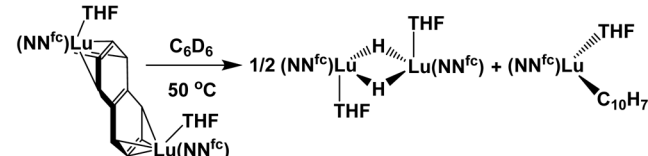
(b) Intermolecular kinetic isotope effect
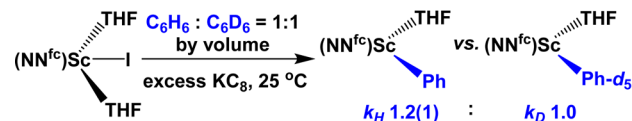
(c) Intramolecular kinetic isotope effect

(d) Toluene regioselectivity

behavior in a benzene solution.[12] We hypothesized that the fluxional behavior of **5c** may bring the two lutetium centers in close proximity to enable the C−H bond activation step. Indeed, heating a benzene-d_6 solution of **5c** at 50 °C led to C−H cleavage of naphthalene to form **2c** and (NN^{fc})Lu(C$_{10}$H$_7$)(THF) (**6c**) in a 1:1 lutetium molar ratio. The analogous reaction of [(NN^{fc})Sc]$_2$(μ-C$_{10}$H$_8$) (**5a**) led to only trace amounts of **2a** and (NN^{fc})Sc(C$_{10}$H$_7$)(THF) (**6a**) upon heating at 85 °C. This was attributed to the lack of fluxional behavior of **5a** in solution and to the instability of the products **2a** and **6a** at elevated temperature. These findings are confirmed by the reaction profiles computed for the C−H activation reactions of **5a** and **5c** (Schemes S2 and S3, Supporting Information). Although we were unable to confirm the regiochemistry of naphthalene activation unambiguously, experimental and computational results as well as literature precedents[21] indicate that the C−H activation likely takes place at the 2-position.

In order to learn more about the reaction mechanism, we determined the *inter*molecular and *intra*molecular kinetic isotope effects (KIEs) (Scheme 1b,c). The *inter*molecular KIE was found to be 1.2(1), the relatively small number indicating that the C−H activation is not rate determining. For comparison, the KIE was 2.8 for the σ-bond metathesis reaction of (Cp*-d_{15})$_2$ScCH$_3$ with C$_6$H$_6$ and C$_6$D$_6$ at 80 °C.[16] The *intra*molecular KIE was found to be 4.5(1). Since no scrambling was observed between **2a** or **3a** and benzene-d_6, the isotope effects can be considered truly kinetic in origin. The *intra*molecular KIE was calculated to be 4.4 on the basis of the mechanism proposed in Figure 2. This value is in excellent agreement with the experimental measure. The large difference between the *inter*- and *intra*molecular KIEs indicate that the C−H bond cleavage does not occur from the direct insertion of a metal species into a C−H bond but rather from an intermediate containing both the metal and benzene.[22] This is consistent with the proposed mechanism: i.e., formation of a bridging benzene dianion prior to C−H bond cleavage.

We also studied whether the reaction shows any regioselectivity if toluene is used. Toluene contains four chemically different C−H bonds: benzylic, ortho, meta, and para positions. For the σ-bond metathesis reaction between scandium alkyl complexes and toluene, Bercaw et al. found no selectivity for the meta and para positions, consistent with no involvement of the π system.[16] In our case, using toluene instead of benzene, a product distribution of 4.7:1 of the m-tolyl vs o-tolyl product was obtained without any p-tolyl or benzyl formation observed. DFT calculations support the experimental results: the C−H activations of the ortho and meta positions had similar activation barriers (14.5 and 14.6 kcal/mol, respectively), being 3 kcal/mol lower than the barrier for the para position (17.6 kcal/mol) and much lower than that for the benzylic position (50.4 kcal/mol) (Scheme S4, Supporting Information). This selectivity precludes a σ-bond metathesis mechanism as well as a radical mechanism since σ-bond metathesis has no preference for meta over para positions and a radical process would favor the weakest benzylic C−H bonds. Also, the observed selectivity is reminiscent of the 2,5-selectivity observed for Birch reductions of arenes with electron-donating alkyl substituents.[23] In the calculated transition state TS_{I-II} (Scheme S4), the HOMO mostly rests on the carbon undergoing C−H bond cleavage; therefore, the observed regioselectivity could be qualitatively explained by the fact that ortho and meta positions bear the negative charges more readily than does the para position. The excellent match between experimental results and theoretical predictions for toluene regioselectivity enhances the credence of the proposed mechanism.

In summary, we observed a new type of mechanism for aromatic C−H activation mediated by rare-earth-metal complexes. The electrons required to break the C−H bond are stored in the π* orbitals of the arene, which acts as a bridging ligand to two rare-earth metals. This intermediate could not be observed for benzene due to its high energy and fast subsequent C−H bond cleavage; however, a corresponding naphthalene bridging complex showed the expected C−H activation upon heating. The reaction reported herein answers the long-sought question of whether oxidative addition can occur with early transition metals. Although the d^0 configuration precludes the metal center to transfer electrons directly to C−H bond, such electrons can be stored on coordinated arene ligands.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Text, tables, figures, and CIF files giving details about the experiments and DFT calculations as well as NMR spectra and X-ray structures. 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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