ORGANOMETALLICS

Article

Comparative Investigations of Cp*-Based Group 9 Metal-Catalyzed Direct C-H Amination of Benzamides

Travis M. Figg,^{†,⊥} Sehoon Park,^{‡,§,⊥} Juhyeon Park,^{§,‡} Sukbok Chang,^{*,‡,§} and Djamaladdin G. Musaev^{*,†}

[†]Cherry L. Emerson Center for Scientific Computation, Emory University, 1515 Dickey Drive, Atlanta, Georgia 30322, United States [‡]Center for Catalytic Hydrocarbon Functionalizations, Institute for Basic Science (IBS), Daejeon 305-701, Republic of Korea [§]Department of Chemistry, Korea Advanced Institute of Science & Technology (KAIST), Daejeon 305-701, Republic of Korea

Supporting Information

ABSTRACT: Key mechanistic features of the $[Cp*MCl_2]_2$ (M = Ir, Rh, Co; all are in group 9) catalyzed C-H amination of benzamides with organic azides were investigated with a strong emphasis on the *metal effects on the reaction mechanism*, revealing that the Rh- and Ir-catalyzed reactions follow a similar reaction profile, albeit with different individual kinetic and thermodynamic parameters. The observation that the Irbased system was much superior in terms of the rates and efficiency in comparison to Rh was attributed to *the intrinsically*



strong relativistic effects in iridium. While a cobalt system $[Cp^*Co^{III}]$ showed little catalytic activity for most azides examined, plausible $[(BA)(Cp^*)CoNR]^+$ intermediates of these reactions were characterized as a "Co(III)-nitrenoid radical" species with a weak ("one electron-two center type") Co-NPh bond. Its Rh and Ir analogues are characterized as diamagnetic metal nitrenoids with a strong M=NR double bond. The provided experimental and computational investigations indicate that the rate-limiting step of the reaction resides in the final stage (protodemetalation) that takes place via a concerted metalationdeprotonation (CMD) mechanism. While experimental measurements of thermodynamic parameters were in good agreement with DFT calculations, theoretical predictions on the electronic nature of key intermediates and energy barriers were successfully used to rationalize the experimentally observed reactivity pattern.

INTRODUCTION

Less oxophilicity and rich functional-group compatibility of late-transition-metal complexes, relative to those of early transition metals, enable their employment as catalysts to install numerous polar functional groups into desired substrate matrices in organic molecules.¹ These properties of latetransition-metal catalysts offer an efficient synthetic tool for accessing diverse heteroatom containing compounds. Among the numerous notable transformations, C-N bond formation is one of the best examples,² because this reaction serves as a versatile and efficient synthetic strategy that provides access to key building blocks widely utilized in medicinal, materials, and synthetic organic chemitsry.³ To date, the Cu-⁴ and Pdcatalyzed⁵ cross-coupling of aryl halides with amines via the assistance of external ligands has been proven to be one of the most practical methods for the synthesis of various aryl amines. However, this procedure generates stoichiometric amounts of chemical wastes such as base salts.

A more atom-economical alternative to the aforementioned cross-coupling reaction is the direct amination of C–H bonds by amines or their precursors. This reaction allows the formation of aniline products without requiring prefunctionalized aryl halides as starting materials. Due to such distinguished advantages of the direct C–H amination approach, a range of metal-mediated procedures, including Fe,⁶ Ru,⁷ Rh,⁸ Pd,⁹ and Cu catalysis,¹⁰ have been developed. Recently, our group has

also developed the Cp*-based $Rh(III)^{11a-f}$ and $Ir(III)^{11g-j}$ catalysts for the direct C–H amination of arenes, alkenes, and alkanes using various organic azides as the nitrogen source (Scheme 1).





Although previously we have investigated mechanistic aspects of the Rh(III)- and Ir(III)-catalyzed direct C–H amination,^{11f,g,i} a parallel comparison of mechanistic details between metal complexes has not been carried out, either experimentally or computationally. Furthermore, we envisioned the extension of the Rh and Ir systems to their cobalt analogues in group 9 of the periodic table. Gratifyingly, the availability (or synthetically easy accessibility) of the metal complexes $[Cp*MCl_2]_2$ (M = Ir, Rh, Co) offers an ideal situation to perform a comparative

 Received:
 June 2, 2014

 Published:
 July 30, 2014

study in the direct C–H amination of arenes using organic azides. Since metals of the same group have different physicochemical properties (such as ionization potentials, electronegativity, electron affinity, and electronic configurations), it is highly rewarding to investigate factors controlling their catalytic activities. To solve these problems, the use of comprehensive and integrated experimental and theoretical approaches would be essential. Herein we report findings from our joint experimental and computational studies of the mechanisms and controlling factors of the Co-, Rh-, and Ircatalyzed C–H amination of arenes with azides (Scheme 2).

Scheme 2. Cp*-Based Group 9 Metal Catalysts for the Direct C–H Amination of Benzamides with Azides



RESULTS AND DISCUSSION

C–H Amination of Benzamides with Various Organic Azides. We initially carried out amination reactions of *N*-tertbutylbenzamide (1a, BA-H) with four different types of organic azides using Cp*M^{III} complexes (M = Co, Rh, Ir) as catalysts (Table 1). On the basis of our previous optimized conditions,¹¹ [Cp*MCl₂]₂ was used as a precatalyst in the presence of AgSbF₆ (4 equiv relative to the dimeric metal species) in 1,1,2,2-tetrachloroethane at room temperature. Knowing the reactivity pattern of the Rh-^{11b,c} and Ir-catalyzed^{11h} C–H amination of benzamides, we decided to use aryl and benzyl

Table 1. Amination Reaction with Several Sets of Reagents^a

\sim	NK	[Cp	*MCl ₂] ₂ (4 mol%) (M = Co, AgSbF ₆ (16 mol %)	Rh, Ir)	, ^o k
\square	Ĥ	(-IN3	1,1,2,2-TCE-d ₂ , 1.5 h		, н мн
1a		2	Temp		Ŕ 3
$\begin{bmatrix} R = & & & \\ & & & & \\ & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & $					
entry	azide	М	temp (°C)	product	yield $(\%)^b$
1	2a	Rh	65	3a	5
2	2a	Ir	65	3a	93
3	2b	Rh	110	3b	54 ^c
4	2b	Ir	110	3b	7^c
5	2c	Rh	65	3c	8
6	2c	Ir	65	3c	47
7	2d	Rh	23	3d	<1
8	2d	Ir	23	3d	95
9	2a	Co	65	3a	<1
10	2b	Co	110	3b	10 ^c
11	2c	Co	65	3c	<1
12	2d	Co	23	3d	<1

^{*a*}Conditions: **1a** (0.25 mmol), **2** (0.35 mmol), $[Cp*MCl_2]_2$ (0.01 mmol), and AgSbF₆ (0.04 mmol) in 1,1,2,2-tetrachloroethane- d_2 (0.5 mL). ^{*b*}Average yield of two runs determined by ¹H NMR of the crude reaction mixture using 1,4-dioxane as the internal standard. ^{*c*}For 24 h.

azides possessing *electron-withdrawing* substituents to ensure reasonable product yields. Since the relative catalytic performance was weighted and discussed on the basis of product yields determined by ¹H NMR analysis of crude reaction mixture, each reaction was conducted twice, and an average value is presented in this study for the sake of accuracy. Trace amounts of amines (RNH₂) were often observed in the course of amination, which were derived from the employed azides (RN₃).

It was revealed that the reaction yield is keenly dependent on the combination of metals and azides employed. While an Ir catalyst system smoothly performed amination of 1a to give 93% yield at 65 °C when tosyl azide (2a) was employed (entry 2), the amidation efficiency was much lower for an Rh catalyst under otherwise identical conditions (entry 1). However, the reactivity trend became completely opposite when benzyl azide (2b) was used: while the Rh system afforded a modest product yield at 110 °C (entry 3), the outcome was much inferior for the Ir catalyst (entry 4). Similar to the case for tosyl azide, the amination with an aryl azide (2c) was observed to be more effective for the Ir catalyst than for the Rh catalyst at 65 °C (entries 5 and 6). Interestingly, the reactivity difference between these two catalytic systems was dramatic when acyl azide (2d) was employed as a reactant: whereas no desired product was observed with the Rh system (entry 7), an amido product was obtained quantitatively by the Ir catalysis within 1.5 h at room temperature (entry 8). Unlike the Rh and Ir catalyst systems, the $[CoCp*Cl_2]_2$ complex was not effective, in general, for these amination reactions. In fact, we observed only small amounts of amination products of benzamide when benzyl azide (2b) was employed (entry 10), while amination with tosyl, aryl, or acyl azide (entries 9, 11, and 12) were almost negligible.

We were highly intrigued by these contrasting reaction behaviors upon the altered combination of metal catalyst and azides, prompting us to launch comparative theoretical studies to elucidate key mechanistic details. We envisioned that it would be highly instructive and rewarding to compare mechanistic details of the $[Cp*M^{III}]$ -catalyzed direct C–H amination, wherein the catalysts bear the same family of transition metals (i.e., group 9 metals) with an identical ligand system.

Computational Methods. The presented calculations were carried out using the Gaussian 09 suite of programs.¹² The geometries of all reported reactants, intermediates, transition states, and products were optimized without symmetry constraint at the M06 level of density functional theory (DFT)¹³ in conjunction with the Lanl2dz basis set and corresponding Hay-Wadt effective core potential (ECP) for all transition metals (M = Co, Rh, Ir) and Sb.¹⁴ Standard 6-31G(d,p) basis sets were used for all remaining atoms (below we call this approach M06/{Lanl2dz+[6-31G(d,p)]} or M06/ BS1). In these calculations, the Cp* ligand, used in the experiments, was modeled by Cp.¹⁵ A comparison of the calculated parameters for the reaction of $[(BA)(Cp)Rh]^+$ and $[(BA)(Cp^*)Rh]^+$ with Ph-N₃ shows that the Cp*-to-Cp substitution only slightly changes the calculated energies and important geometries of the reactants, intermediates, transition states, and products and does not affect the final conclusions (see below and also the Supporting Information). NBO analysis was performed on each stationary point. The orbital occupations, natural charges, and M-N orbitals were computed

Organometallics

by NBO program as implemented in the current version of Gaussian 09.

The nature of each stationary point was characterized by the presence of 0 or 1 imaginary frequency for minima and transition states, respectively. Energetics were calculated under standard conditions (1 atm and 298.15 K) and are reported as relative free energies and enthalpies in kcal/mol with the notation of ΔG (ΔH). Solvent effects were accounted for by the PCM formalism¹⁶ in 1,2-dichloroethane (1,2-DCE, $\varepsilon = 10.4$), although the experiments were carried out in 1,1,2,2-tetrachloroethane (1,1,2,2-TCE, $\varepsilon = 8.4$) as a solvent due to the inappropriately lower boiling point of 1,2-dichloroethane. The calculated parameters and geometries of key intermediates and transition states in the course of DFT studies *barely* changed upon substitution of 1,2-DCE with 1,1,2,2-TCE. Cartesian coordinates for all reported structures are given in the Supporting Information.

On the basis of our previous report,^{11f} a proposed catalytic cycle would comprise four key steps: (i) the formation of catalytically active species from the corresponding neutral dimeric precursors, (ii) azide coordination and subsequent N_2 dissociation leading to the formation of a metal–nitrenoid intermediate, (iii) intramolecular insertion of the nitrenoid moiety into a metallacyclic metal– C_{aryl} bond, and finally (iv) protodemetalation giving rise to the formation of an aminated product (Figure 1).



Figure 1. Proposed catalytic cycle of the amination of *N*-tertbutylbenzamide with azides, where M = Co, Rh, Ir and Z = Ts (2a), Me, Ph, $(m-CF_3)_2C_6H_3$ (2c), $(p-NO_2)C_6H_4$ (2e).

In this article, we describe factors affecting the energetics and geometries of the proposed intermediates, transition states, and products of steps 2–4 postulated in Figure 1 in the amination reaction with aryl azides using group 9 metal catalysts Cp^*M^{III} , where M = Co, Rh, Ir. In a similar manner, we have also performed computational studies on the analogous reaction with alkyl and tosyl azides to understand the *azide effects on the reactivity*. For the sake of clarity, we present these data in the Supporting Information. However, we excluded acyl azides as the nitrogen source in our computational study because it readily undergoes Curtius rearrangement under certain reaction

conditions, which may complicate the discussion of reactivity patterns.^{11k} Below, at first, we discuss in detail the mechanistic aspects of the reaction $[CpRh^{III}](SbF_6)_2 + Ar-N_3$ followed by metal effects on the catalytic activity by establishing and comparing energetics of the same reaction under $[CpCo^{III}]^ (SbF_6)_2$ and $[CpIr^{III}](SbF_6)_2$ catalyst systems.

Key Mechanistic Features of the [CpRh^{III}](SbF₆)₂-Catalyzed Amination of N-tert-Butylbenzamide. Formation of catalytically active species, $[(BA)(Cp)Rh](SbF_6)$, from $CpRh^{III}(SbF_6)_2$ and *N-tert*-butylbenzamide (BA-H, 1a) was calculated to be exergonic by 4.7 kcal/mol, where "BA" refers to an ortho-deprotonated benzamide moiety bound to the metal center (step 1). In general, this reaction may proceed via either (a) deprotonation of 1a by SbF_6^- and subsequent coordination of the deprotonated arene (BA⁻) to Rh through the oxygen atom of its carbonyl group or (b) benzamide (1a) coordination to Rh through a carbonyl oxygen atom and then deprotonation at the ortho position of the arene. The amination reaction of 1a with **2a** under standard conditions using $[Cp*MCl_2]_2$ (M = Rh, Ir) and $AgNTf_2$ (instead of AgSbF₆) as a catalyst gave 10% and 96% yields of product 3a, respectively. These are very close to the yields in entries 1 and 2 of Table 1. It implies that the ortho deprotonation by a counteranion (i.e., SbF_6^- or NTf_2^-) is not a rate-determining step but a facile process.^{11f-h} Therefore, we do not report details of structures involved in this step (step 1) of the amination reaction.

Our extensive computations have shown that the presence of the counteranion ${\rm SbF_6}^-$ displays negligible effects on the calculated parameters in the reaction [(BA)CpRh^{III}](SbF_6) + Ph-N_3 (see the Supporting Information). Therefore, for simplicity, through the paper we assume that the cationic metal complex [(BA)(Cp)M]⁺ (**1_M**, where M = Co, Rh, Ir) would be a catalytically active species.

Step 2: [(BA)(Cp)Rh]⁺ + Ph-N₃ → [(BA)(Cp)Rh=NPh]⁺ + N₂. The calculated reactants, intermediates, and transition states involved in the formation of the Rh-nitrenoid intermediate 2_Rh_Ph (i.e., step 2), with their characteristic geometrical parameters, are presented in Figure 2. As expected, the initial step of this reaction is coordination of PhN₃ to [(BA)(Cp)Rh]⁺ (1_Rh) leading to the formation of the adduct 1_Rh_Ph (where "Ph" stands for the R group of azides R-N₃) with a bond distance of 2.24 Å between the Rh center and N₃Ph (not shown in Figure 2). This process is endergonic by 4.1 kcal/mol. From the resultant adduct the reaction proceeds via N₂ dissociation and Rh-nitrenoid bond formation (see Figure 3), which occurs with an energy barrier of 30.9 kcal/mol (in comparison to the separate reactants: 1_Rh + Ph-N₃) at the transition state TS1_Rh_Ph and is exergonic by 11.9 kcal/mol.

The exergonicity of this step (step 2) can be attributed to the generation of the N₂ molecule (the calculated ΔG value of the reaction Ph-N₃ \rightarrow PhN (³A) + N₂ is -7.8 kcal/mol) accompanied by the formation of a Rh=NPh bond. NBO analysis of the resultant **2_Rh_Ph** complex reveals the existence of a well-established double bond between the Rh center and NPh fragment: a σ bond formed by electron donation from the nitrogen atom to the Rh center and a π bond generated by back-donation from the occupied d_{π} orbital of the Rh center to the π^* orbital of the NPh fragment (Figure 4). Close examination of the structures **1_Rh_Ph** and **2_Rh_Ph** provides additional support for this conclusion: the calculated Rh–N bond length (1.91 Å) in **2_Rh_Ph** is significantly shorter than that in **1 Rh Ph** (2.24 Å). In the latter, the Rh–N interaction

Organometallics



Figure 2. Optimized structures and geometries of **1_M**, **TS1_M_Ph**, and **2_M_Ph** involved in the Ph-N₃ coordination to $[(BA)(Cp)M]^+$, N₂ dissociation, and M-nitrenoid formation (i.e., step 2). Values given in the first line are for the singlet/triplet states of M = Co, and those given in the second and third lines are for M = Rh, Ir, respectively. Bond lengths are given in Å.

is weak and has no covalent character (see the Supporting Information for details).

Thus, the presented computational analysis shows that step 2, $[(BA)(Cp)Rh]^+$ + Ph-N₃ $\rightarrow [(BA)(Cp)Rh=NPh]^+$ + N₂, involves a soft oxidation of the rhodium center from Rh(III) to



Figure 4. Visualization of the bonding (left) and antibonding (right) counterparts of the σ donation and π back-donation orbitals of the M=NPh bond in the intermediate **2_M_Ph**.

Rh(V). In the resultant intermediate 2_Rh_Ph, the formed Rh=NPh has a double-bond character with donation (σ bond) and back-donation (π^* bond) components. Furthermore, upon



Figure 3. Calculated potential energy surface for the direct oxidative C–H amination of *N*-*tert*-butylbenzamide with the $[(BA)(Cp)M^{III}]^+$ catalyst, **1_M**, where M = Rh, Ir, utilizing aryl azide as the nitrogen source. Energetics are compared to those of complex **1_M** + PhN₃ and given as ΔG (ΔH) in kcal/mol.

the formation of **2_Rh_Ph**, slight reorganization of electron density between (BA)Rh and NPh fragments occurs, mostly via a π channel: the calculated natural charges are +0.22 and -0.34 (in **1_Rh_Ph**) and +0.24 and +0.01 (in **2_Rh_Ph**) for Rh and C (arene of BA), and -0.11 (in **1_Rh_Ph**) and -0.26 (in **2_Rh_Ph**) for the N center. The calculated Rh–N Wiberg bond order is 1.0.

Step 3: Nitrenoid C–Rh Insertion of [(BA)(Cp)Rh=NPh]⁺ Leading to C–N Bond Formation. As expected, the Rh–nitrenoid intermediate 2_Rh_Ph is thermodynamically fragile and, thus, would easily undergo a nitrenoid insertion process. In fact, computations show that the nitrenoid insertion into a Rh–C_{aryl} bond to form an Rh(III) amido complex (3 Rh Ph, Figure 5) is exergonic by 41.1 kcal/mol and



Figure 5. Optimized structures of the transition state TS2_M_Ph and intermediate 3_M_Ph involved in the nitrenoid insertion. Values given in the first line are for the singlet/triplet states of M = Co, and those given in the second and third lines are for M = Rh, Ir, respectively. Bond lengths are given in Å.

proceeds with a small energy barrier of 7.5 kcal/mol (calculated relative to the prereaction complex 2_Rh_Ph) at the transition state TS2 Rh Ph.

An inspection of the geometries of 2 Rh Ph, TS2 Rh Ph, and 3 Rh Ph (Figures 2 and 5) shows an increase in the Rh-N bond length from 1.91 Å (in 2 Rh Ph) to 1.96 Å (in TS2 Rh Ph) and then to 2.09 Å (in 3 Rh Ph). This is in line with the loss of the Rh-N double-bond character and, as a result, alteration of the N hybridization from sp² to sp³. Additionally, for the transition state TS2 Rh Ph, NBO analysis shows a loss of the Rh–N π bond and an increase of metal character in the Rh–N σ bond. Thus, the kinetic and thermodynamic feasibility of the nitrene insertion into the Rh-arene bond (2 Rh Ph \rightarrow 3 Rh Ph) is a consequence of reduction of the Rh(V)-nitrene intermediate to the Rh(III)amido complex. Notably, protonation of the nitrene ligand in 2_Rh_Ph and subsequent amido insertion into the Rh-Carvl bond, which is a process accompanied by no net change in the +3 oxidation state of a rhodium metal center, was found to be endergonic by ca. 34 kcal/mol, thus excluding the possibility of this $Rh(III) \rightarrow Rh(III)$ transformation. In the resultant intermediate 3 Rh Ph, the Wiberg bond order of the Rh-N¹ bond was calculated to be 0.55, which is consistent with a long Rh–N¹ bond distance. Furthermore, in 3 Rh Ph, the N¹ center becomes more electron rich (compared to 2 Rh Ph) with a -0.49e natural charge.

Step 4: Protodemetalation with Product Release. From the intermediate **3_Rh_Ph**, the final protodemetalation process in a catalytic cycle may proceed via the coordination of either a second *N-tert*-butylbenzamide substrate or a second azide reactant to the Rh center. Extensive calculations show that both cases are endergonic, by 14.5 and 22.9 kcal/mol, respectively. Since the azide coordination is more demanding energetically by 8.4 kcal/mol than the benzamide coordination, below we discuss in detail only the process initiated by the benzamide coordination. The calculated key reactants, intermediates, and transition states involved in this step of the reaction are presented in Figure 6 with their characteristic geometrical parameters.



Figure 6. Optimized structures of the transition state TS3_M_Ph and product 5_M_Ph involved in the coordination of a second *N-tert*-butylbenzamide to the intermediate 3_M_Ph . Values given in the first line are for the singlet/triplet states of M = Co, and those given in the second and third lines are for M = Rh, Ir, respectively. Bond lengths are given in Å.

Coordination of a second benzamide (BA-H) leads to the formation of the adduct 4 Rh Ph (not shown in Figure 6), where BA-H only weakly interacts with the Rh center via its oxygen atom. This weak interaction initiates a concerted metalation-deprotonation (CMD) process that involves hydrogen transfer from an arene of the second benzamide molecule to the amido nitrogen of the metallacycle 3 M Ph. Overall, step 4 is endergonic by 2.3 kcal/mol, calculated relative to the intermediate 3 Rh Ph and N-tert-butylbenzamide (BA-H), and requires a 40.6 kcal/mol energy barrier at the CMD transition state TS3 Rh Ph (Figures 3 and 6). Comparison of this energy barrier with 30.9 and 7.5 kcal/mol, reported for step 2 (at TS1 Rh Ph) and step 3 (at TS2 Rh Ph), respectively, indicates that the C-H bond cleavage via CMD (at TS3 Rh Ph) mechanism is the rate-determining step in the entire $[(BA)(Cp)Rh]^+$ -catalyzed C-H amination of N-tertbutylbenzamide with phenyl azide. Alternatively, step 4 may proceed via a *stepwise pathway* involving (i) the deprotonation of the second benzamide (BA-H) by a counteranion, and (ii) the protonation of the N¹ center in amido complex 3 Rh Ph by other proton sources from the reaction medium (including previously formed HSbF₆). However, as shown for step 1, the counteranionic effect on the reactivity has not been observed, and we may exclude the possibility of the stepwise pathway as an alternative. This conclusion is also supported by computational findings, which show a negligible impact on the presence of counteranion SbF_6^- and on the calculated parameters of the reaction $[(BA)CpRh^{\rm III}](SbF_6)$ + $Ph\text{-}N_3$ (see the Supporting Information).

As displayed in Figure 6, an inspection of geometries of structures involved in step 4 reveals a direct hydrogen transfer with little to no interaction with Rh, as the Rh–H distances were calculated to be 2.49, 2.00, and 2.65 Å for complexes **4_Rh_Ph**, **TS3_Rh_Ph**, and **5_Rh_Ph**, respectively. It is noted that the Cp-to-Cp* substitution only slightly affects the calculated energetics of this process. Indeed, it does not change the N₂-extrusion barrier (step 2; the calculated barriers are 30.9

and 30.6 kcal/mol for L= Cp, Cp*, respectively), it reduces the nitrenoid insertion barrier (step 3) from 7.5 to 5.6 kcal/mol, and the barrier in the rate-determining C-H activation step (step 4) is only slightly reduced from 40.6 to 38.8 kcal/mol (see also the Supporting Information). Thus, modeling of the Cp* ligand, used in experiments, by the Cp ligand *does not affect our major conclusions* and can be *safely* used for other reactions presented in this paper.

One should emphasize that a change in the electronic nature of the azide fragment could have significant effects on the calculated energetics of the [(BA)(Cp)Rh]⁺-catalyzed C-H amination of N-tert-butylbenzamide (BA-H, 1a). For example, calculations show that substitution of m-H's by CF₃ group(s) $(Ph-N_3 \rightarrow 2c)$ reduces both the N₂-extrusion (from 30.9 to 23.7 kcal/mol) and CMD (from 40.6 to 35.4 kcal/mol) barriers. Incorporation of a NO₂ group at the para position $(Ph-N_3 \rightarrow 2e)$ also reduces both the N₂-extrusion (from 30.9 to 27.0 kcal/mol) and the CMD (from 40.6 to 33.3 kcal/mol) barriers. The calculated trend, N₃-Ph (40.6 kcal/mol) > N₃- $C_6H_3(m-CF_3)_2$ (35.4 kcal/mol) > $N_3-C_6H_4(p-NO_2)$ (33.3 kcal/ mol), in the rate-determining CMD barrier is closely correlated with the electron-rich nature of the N1-center in 3 Rh R: calculated natural charges on N^1 of 3 Rh R are N_3 -Ph $(-0.49e) < N_3 - C_6 H_3 (m - CF_3)_2 (-0.52e) < N_3 - C_6 H_4 (p - NO_2)$ (-0.53e).

Thus, the computational data presented above show that the amination of *N*-tert-butylbenzamide with aryl azides catalyzed by $CpRh^{III}(SbF_6)_2$ is an energy-demanding process and cannot take place under ambient conditions. This computational conclusion is consistent with the experimental data presented in Table 2. As seen in this table, the amination of **1a** (**BA-H**) or its

Table 2. Rh-Catalyzed Amination Reaction with Aryl Azide^a



^{*a*}Conditions: 0.25 mmol of 1, 0.35 mmol of 2e, 0.01 mmol of $[Cp*RhCl_2]_2$, and 0.04 mmol of AgSbF₆ in 0.5 mL of 1,1,2,2-TCE- d_2 . ^{*b*}Average yield of two runs determined by ¹H NMR analysis of crude reaction mixture using 1,4-dioxane as the internal standard.

derivative (1b) bearing a fluoro group at the para position requires a relatively higher temperature (85 °C), giving rise to the corresponding products 3e,f in 33% and 54% yields, respectively (Table 2, entries 3 and 4). Furthermore, the yield of 3f was increased to 68% with prolonged reaction time (entry 5). Computations also reveal insignificant change in the N₂extrusion and CMD activation barriers in the arene C–H bond activation with the use of tosyl azide 2a instead of aryl azide 2c. For tosyl azide 2a, barriers of these two steps were calculated to be 35.3 and 35.2 kcal/mol, respectively, which are comparable with the rate-determining barrier of 35.4 kcal/mol for the aryl azide **2c**. This computational finding is also in good agreement with our experimental data presented in Table 1, showing only slight changes in yields (see entries 1 and 5) upon changing the substrate from **2a** to **2c**.

Metal Effects: $[Cp*lr^{II}](SbF_6)_2$ Catalyst. In experiments (Table 1 and eqs 1 and 2),¹¹ a dramatic difference in reaction



efficiency in terms of product yields was observed between the $[Cp*M^{III}](SbF_6)_2$ -catalyzed amination. In fact, the iridium catalyst $[Cp*Ir^{III}](SbF_6)_2$ displayed faster reaction rates as well as higher product yields than the corresponding rhodium catalyst for the reaction of *N-tert*-butylbenzamide with most azides examined. One exception was the case of benzyl azide, which reacts more efficiently under the $[Cp*Rh^{III}](SbF_6)_2$ catalyst.

In order to elucidate key factors contributing to this dramatic difference in catalytic reactivity, we performed computational studies of an amination reaction with $[Cp*Ir^{III}](SbF_6)_2$ catalyst. We anticipated that a comparison of this result with that of the corresponding $[Cp*Rh^{III}](SbF_6)_2$ system, as discussed above, is going to be instrumental in understanding the observed notable dependence of amination activity on the metal center. Relative energies of reactants, intermediates, transition states, and products calculated for the $[(BA)(Cp)Ir]^+$ (1 Ir)-catalyzed amination of *N*-tert-butylbenzamide with phenyl azide (Ph- N_3) are given in Figures 2-6. As indicated in Figure 3, the step 2 process to form a nitrenoid species, $[(BA)(Cp)Ir]^+ + Ph-N_3 \rightarrow$ $[(BA)(Cp)Ir=NPh]^+ + N_2$, proceeds with a 29.5 kcal/mol energy barrier at the N2-extrusion transition state TS1_Ir_Ph and is 18.9 kcal/mol exergonic. Comparison of these values for M = Ir with the 30.9 kcal/mol barrier and 11.9 kcal/mol exergonicity calculated for M = Rh suggests that the "Rh to Ir replacement" makes the reaction thermodynamically more favorable by 7.0 kcal/mol. This preferential exergonicity in the Ir system over the Rh system is the consequence of the most prominent characteristic feature of the electronic structure of Ir: namely, the existence of strong (in comparison with Rh) relativistic effects in Ir.¹⁷ In general, the relativistic contraction of the 6s orbital in Ir results in greater involvement of its p and d atomic orbitals in the metal-ligand bonding, which is manifested in a stronger Ir-ligand bond (in comparison to the Rh-ligand bond).^{17e} Furthermore, the existence of strong relativistic effects in Ir makes its +5 oxidation state more accessible for the formation of the nitrenoid species [(BA)(Cp)Ir= NPh]⁺ (2 Ir_Ph).

Thus, the relativistic effects in Ir are instrumental in forming a stronger Ir=NPh bond in comparison to Rh=NPh. Indeed, as seen in Figure 4, in both components of the M=NPh bond, i.e. σ -donation and back-donation from nitrenoid to M and from M to nitrenoid, respectively, the weights (percentage) of accepting orbitals (in the case of donation, it is an spd hybrid orbital of M, and in case of back-donation, it is a π^* orbital of the NPh moiety) are larger for M = Ir than for M = Rh. In other words, one can see more efficient electron transfer (and, accordingly, stronger orbital overlap) in both donation and back-donation components for the Ir=NPh bond in comparison to Rh=NPh. Furthermore, this feature of the M=NPh bond is more pronounced in π bonding rather than σ bonding (Figure 4). This difference in the nature of Ir=NPh and Rh=NPh bonds is well reflected in the computed M-NPh bond lengths (1.87 Å for Ir and 1.91 Å for Rh; see Figure 2) and Wiberg bond orders (BO = 1.3 for Ir and 1.0 for Rh). As a result, in **2_Ir_Ph**, the N¹ center is more electron rich with -0.32e natural charge than in **2_Rh_Ph** (with -0.26e natural charge). Thus, the existence of large relativistic effects in Ir, manifested in the generation of a stronger Ir=NPh bond and facile accessibility of the Ir(V) oxidation state, is postulated to be a major reason for greater (than for Rh) exothermicity of the nitrenoid formation reaction: $[(BA)(Cp)Ir]^+ + Ph-N_3 \rightarrow [(BA)(Cp)Ir=$ NPh]⁺ + N₂.

Similar to the case of [(BA)(Cp)Rh]⁺, step 3 involves a nitrenoid insertion into the $Ir-C_{arvl}$ bond in 2 Ir Ph to afford the Ir(III) amido complex (3 Ir Ph). As expected, this process is exergonic by 23.5 kcal/mol with an energy barrier of 7.1 kcal/ mol (calculated relative to the prereaction complex 2 Ir Ph) at the transition state TS2 Ir Ph. Thus, the formation of 3 Ir Ph is 17.6 kcal/mol less exergonic in comparison to the formation of 3 Rh Ph. NBO analysis shows that the N¹ center is more electron-rich in 3 Ir Ph than that in 3 Rh Ph: the calculated NBO charges of N^1 are -0.54e and -0.49e, respectively. Higher electron density in the N1 center of 3 Ir Ph makes the CMD step kinetically less demanding and thermodynamically more favorable for $[(BA)(Cp)Ir]^+$ than [(BA)(Cp)Rh]⁺. Indeed, as seen in Figure 3, a CMD transformation that transfers a hydrogen atom from the second BA-H substrate to the inserted amido nitrogen to form the intermediate 5 Ir Ph is 7.6 kcal/mol exergonic relative to 3 Ir Ph. For M = Rh, this process is 2.3 kcal/mol endergonic. Furthermore, the CMD pathway occurs with a barrier of 33.9 kcal/mol at the transition state TS3 Ir Ph, which is 6.6 kcal/ mol smaller than that for the $[(BA)(Cp)Rh]^+$ catalyst.

On the basis of the above discussions, it becomes obvious that strong relativistic effects in Ir significantly affect steps 2–4. Namely, they increase electron density of the N¹ center, reduce the rate-determining CMD barrier, and make the product formation (step 4) more exothermic. In other words, the existence of relativistic effects in Ir enables the $[(BA)(Cp)Ir]^+$ system to be more efficient than $[(BA)(Cp)Rh]^+$ for this amination reaction. This theoretical consideration is in excellent agreement with our experimental observations (Table 1). Computational data provide a clear explanation of the observed difference in reactivity of $[(BA)(Cp)Ir]^+$ and $[(BA)(Cp)Rh]^+$ catalysts.

Similar to the case of $[(BA)(Cp)Rh]^+$, a change in electronic nature of aryl azides significantly affects the calculated properties of the reaction. Upon the variation of aryl azides from Ph-N₃ to (m-CF₃)₂C₆H₃-N₃ (**2c**) or (p-NO₂)C₆H₄-N₃ (**2e**), the calculated energy barriers are reduced in both N₂extrusion and rate-determining CMD steps. In fact, the activation barriers of the nitrenoid formation with the concomitant release of N₂ are ΔG (ΔH) = 29.5 (14.6) kcal/ mol (for N₃-Ph), 23.9 (8.4) kcal/mol (for **2e**), and 20.1 (6.1) kcal/mol (for **2c**). Likewise, the energy barriers in the CMD step are ΔG (ΔH) = 33.9 (18.4) kcal/mol (for N₃-Ph), 33.1 (16.6) kcal/mol (for **2e**), and 29.5 (13.9) kcal/mol (for **2c**). However, they only slightly affect the exergonicity of steps 2–4. The change in the rate-determining CMD barriers, once again, closely correlates with the electron-rich nature of the N^1 center of metal nitrenoid intermediates.

In order to validate the activation parameters obtained from the computation, mechanistic experiments were conducted (eqs 3 and 4). For the purpose of the kinetic study, several attempts



to isolate or generate in situ 1 M through a stoichiometric reaction of 1a, $[Cp*MCl_2]_2$ (M = Rh, Ir), and AgSbF₆ even in the presence of various bases have been preliminarily carried out, but all were unsuccessful (<10% NMR yield of 1 M). Since an initially designed reaction with $(m-CF_3)_2C_6H_3-N_3$ (2c) was observed to be quite slow at room temperature, tosyl azide (2a) was employed as the nitrogen source instead of 2c for this study. Conversion of BA-H (1a) to the corresponding product (3a) was monitored by ¹H NMR analysis. Excess 2a (10 equiv relative to 1a) led the reaction to rigorously follow pseudo-firstorder kinetics with $k_{obs} = 0.00598 \text{ min}^{-1}$ at 25 °C for the formation of the aminated product 3a. The KIE measurement based on the comparison of the initial rates between 1a and 1a d_5 revealed a notable kinetic isotopic effect of 4.82 at 25 °C, suggesting that the C-H bond cleavage is likely a turnoverlimiting step (eq 3). An Eyring plot of the rate constants obtained at a series of temperatures (25-40 °C) provided the activation parameters for this catalytic system: $\Delta H^{\ddagger} = 20.3$ kcal/mol and $\Delta S^{\ddagger} = 1.5$ cal/(mol K) (eq 4). Significantly, the measured ΔH^{\ddagger} is in good agreement with that ($\Delta H^{\ddagger} = 17.9$ kcal/mol) obtained from the DFT calculations (see the Supporting Information for details on the activation parameters determined by DFT calculations in the (Cp)Ir-catalyzed amination of 1a with 2a).

Metal Effects: $[Cp*Co^{III}](SbF_6)_2$ **Catalyst.** Encouraged by the excellent agreement between the experimental and computational results for M = Rh, Ir systems discussed above, we turned our attention to explore the feasibility of $[CpCo^{III}](SbF_6)_2$ to be a greener and cheaper alternative of the $[CpRh^{III}](SbF_6)_2$ and $[CpIr^{III}](SbF_6)_2$ catalysts. The use of 3d metals in catalytic reactions is of great interest due to their natural abundance, low cost, and potentially unique catalytic activity in comparison to their 4d and 5d counterparts. The fact that *Ir*, *Rh*, and *Co* are all in group 9 in the periodic table provides us an ideal situation to compare the catalytic behaviors of the corresponding complexes $[Cp*M^{III}Cl_2]_2$ bearing identical *ligand systems* working on the same amination reactions.

Since Co(III) complexes may have a high-spin ground electronic state,¹⁸ we initially attempted to explore both singlet and triplet electronic states of each stationary point of the reaction steps 2–4 mediated by $[(BA)CpCo^{III}]^+$. The calculated relative energies of the reactants, intermediates, transition states, and products in the amination of *N-tert*-butylbenzamide (1a) with Ph-N₃ by $[(BA)CpCo^{III}]^+$ (1_Co) catalyst are given in Figures 2, 5, and 6 (full geometries of all calculated structures are given in the Supporting Information).

The ground electronic state of $[(BA)(Cp)Co^{III}]^+$ was found to be the triplet state with almost two (*exactly* 1.81) unpaired electrons located in the Co center. Its closed-shell singlet state was calculated to be 6.5 kcal/mol higher in energy.

Reaction of $[(BA)CpCo^{III}]^+$ (**1_Co**) and phenyl azide (N₃-Ph) proceeds with a free energy barrier of 31.7 kcal/mol at the singlet transition state **TS1_Co_Ph**, leading to the formation of a *triplet* **2_Co_Ph** complex. This intermediate lies 14.5 kcal/mol lower in energy than the reactants (triplet **1_Co** + Ph-N₃). See the Supporting Information for a more detailed potential energy profile of this reaction.

A close examination of electronic structures of the triplet intermediate 2 Co Ph reveals that unpaired electrons are mostly (ca. 1.34e) located on the N^1 center of the Co=NPh bond, whereas the cobalt center bears only a 0.27e unpaired electron. Therefore, this species can be characterized as a "Co(III)-nitrenoid radical" species. Similar types of "nitrene radical species" were previously reported as key intermediates in olefin aziridination¹⁹ and allylic C–H amination.²⁰ In addition, the same electronic features as for the present Co-NPh species (2 Co Ph) were observed by Zhang and coworkers in (Porphyrin)Co^{III}-NC(O)(OMe), where the "nitrenoid ligand" was described as a nitrogen-centered radical species ${\rm [RN^{\bullet]}^{-}}$ (as a "nitrene radical anion ligand").²¹ In fact, NBO analysis shows a weak bonding (with only 0.3 Wiberg bond order) between the Co and NPh in our case, which could be characterized as a weak bond of a "one-electron-two-center type" between the "high-spin" Co(III) center and "nitrene radical anion ligand", suggesting that 2 Co Ph is a highly unfavorable species.

Thus, the 2_Co_Ph intermediate with a "Co(III)-nitrenoid radical" character and weak one-electron-two-center type Co-NPh bond is very different from the nitrenoids 2 Rh Ph and 2 Ir Ph characterized as diamagnetic species with doublebond character between the metal(V) center and the NPh fragment. Such a strong radical character of 2 Co Ph can also lead to different reactivity: for example, either a radical addition reaction with a π nucleophile as a coupling partner or a transformation to a highly favorable 3_Co_Ph intermediate. On the basis of the reported energy barriers for the radical addition reaction of the analogue of 2 Co Ph,^{19b,c,e-i,20a,b,21e-i} we assume that a radical coupling reaction may require an energy barrier larger than 4.4 kcal/mol (at the transition state TS2 Co Ph), which is needed for the 2 Co Ph \rightarrow 3 Co Ph transformation. In fact, this conversion was found to be highly exergonic (47.5 kcal/mol) relative to the Rh (40.1 kcal/mol) and Ir (23.5 kcal/mol) systems. Thus, the formation of a triplet 3 Co Ph intermediate requires a lower barrier and is more exergonic than its Rh and Ir counterparts. Therefore, a subsequent radical addition reaction of the Co-nitrenoid intermediate 2 Co Ph is unlikely.

In the resultant intermediate 3_Co_Ph , the Co center, once again, bears more unpaired electrons (1.22e) than the entire HNPh(BA) fragment, which holds almost 0.68e unpaired spin with 0.44e on the N center. This species can be characterized as a Co(III)-[N(H)Ph(BA)] complex with a Co-N twoelectron-two-center single-bond character (the calculated bond distance is 1.93 Å) and with electron density polarized toward the N center. Again, this species could be involved either in the radical coupling process or in a reaction with another **BA-H** molecule via the CMD mechanism (step 4). The calculated CMD barrier at the transition state **TS3_Co_Ph** is 51.9 kcal/mol, which is much larger than the energy barriers 40.6 kcal/mol for the Rh system and 33.9 kcal/mol for the Ir system. Furthermore, the formation of the final product **5**_**Co_Ph** (step 4) is highly endergonic by 12.1 kcal/mol in comparison to both Rh and Ir catalyst systems, where step 4 is endergonic by 2.3 kcal/mol for M = Rh but 7.6 kcal/mol exergonic for M = Ir. Thus, the large CMD barrier and endergonicity of the present reaction, **3_M_Ph** + **BAH** \rightarrow **5_M_Ph**, eventually render the CMD step kinetically and thermodynamically inaccessible in the [(BA)(Cp)Co^{III}]⁺ catalyst system. This conclusion is in good agreement with our experimental observation given in Table 1.

CONCLUSIONS

Here, we reported integrated experimental and theoretical studies on the key mechanistic features of the $[Cp*M^{III}(SbF_6)_2]$ -catalyzed (where M = Co, Rh, Ir) direct C–H amination of *N*-tert-butylbenzamide with organic azides. Special emphases were made on the *metal and azide effects on the reactivity pattern and energy parameters*.

(1) It was shown that this catalytic reaction is a multistep process that includes *four key steps*: (i) the formation of the catalytically active species $[(BA)Cp^*M^{III}]^+$ (step 1), (ii) azide coordination and N₂ extrusion to form a key nitrenoid species (step 2), (iii) insertion of the formed nitrenoid moiety into the metallacyclic metal–aryl bond (step 3), and (iv) protodemetalation of an inserted amido metallacycle via a concerted metallation–deprotonation (CMD) mechanism to provide a product with the regeneration of a catalytically active species (step 4).

(2) Step 2, i.e. $[(BA)(Cp)M]^+ + R-N_3 \rightarrow [(BA)(Cp)M = NR]^+ + N_2$, was found to be exergonic and to proceed with a significant energy barrier. Its exothermicity decreases in the order M = Ir > Co > Rh, while the N₂-extrusion barrier heights are almost the same for all three metals. The existence of strong *relativistic effects* in Ir, manifested in the formation of a stronger Ir=NR nitrenoid bond and accessibility of the +5 oxidation state, is predicted to be a major reason for greater exothermicity and slightly lower N₂ extrusion barrier for M = Ir in comparison to its Rh analogue.

(3) The product of step 2, i.e. the intermediate $[(BA)(Cp)-M=NR]^+$, was reported to be a M(V)-nitrenoid species with a closed-shell singlet electronic state and M=NR double bond, for M = Rh, Ir. However, for M = Co, it was characterized as a "Co(III)-nitrenoid radical" with a weak single Co-N bond.

(4) Nitrenoid intermediates $[(BA)(Cp)M=NR]^+$ rapidly undergo an amido insertion process to afford a $[(Cp)MN(R)-(BA)]^+$ intermediate with an energy barrier of a few kilocalories per mole regardless of the nature of the metal center. This process was calculated to be highly exergonic.

(5) The rate-determining step of the overall $[Cp*M^{III}(SbF_6)_2]$ -catalyzed C–H amination of *N-tert*-butylbenzamides with organic azides was found to be protodemetalation of the amido intermediate that occurs via a concerted metalation–deprotonation (CMD) mechanism. It is predicted that the *electron-rich nature* of the N¹ center of the amido-inserted metallacyclic intermediates **3_M_R** renders the rate-determining CMD step kinetically less demanding and thermodynamically more favorable for the M = Ir system than the corresponding Rh catalysis.

The findings presented above prove the comparative experimental and computational study to be highly effective in the rationalization of the observed periodic pattern of reactivity and for a better understanding of the origin of metal Ir) direct C–H amination of *N-tert*-butylbenzamide with organic azides. This work is expected ultimately to be an important basis for designing the next catalytic systems with better kinetic and thermodynamic properties, especially by scrutinizing the role of central metals in the same group in the periodic table.

ASSOCIATED CONTENT

Supporting Information

Text, figures, tables, and xyz files giving detailed experimental procedures and characterization data for new compounds, Cartesian coordinates of computed structures, energetics of the $[(BA)(Cp)Rh]^+$ and $[(BA)(Cp)Ir]^+$ -catalyzed direct C–H amination of *N-tert*-butylbenzamide with alkyl and tosyl azides, and potential energy surfaces of the $[(BA)(Cp)Co]^+$ -catalyzed direct C–H amination of *N-tert*-butylbenzamide with aryl azides. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Authors

*E-mail for S.C.: sbchang@kaist.ac.kr. *E-mail for D.G.M.: dmusaev@emory.edu.

Author Contributions

[⊥]These authors contributed equally to this work.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (NSF) under the Center for Chemical Innovation in Stereoselective C–H Functionalization (CHE-1205646), under NSF-MRI-R2 grant (CHE-0958205), and the use of the resources of the Cherry L. Emerson Center for computations. Financial support was provided also from the Institute for Basic Science (IBS) in Korea.

REFERENCES

(1) (a) Crabtree, R. H. The Organometallic Chemistry of the Transition Metals, 4th ed.; Wiley: New York, 2009. (b) Hartwig, J. F. Organotransition Metal Chemistry: From Bonding to Catalysis; University Science Books: New York, 2010. (c) Schrock, R. R. Tetrahedron 1999, 55, 8141–8153. (d) Grubbs, R. H.; Miller, S. J.; Fu, G. C. Acc. Chem. Res. 1995, 28, 446–452. (e) Ittel, S. D.; Johnson, L. K.; Brookhart, M. Chem. Rev. 2000, 100, 1169–1203.

(2) For recent reviews for C-H amination, see: (a) Mueller, P.; Fruit, C. Chem. Rev. 2003, 103, 2905–2920. (b) Beccalli, E. M.; Broggini, G.; Martinelli, M.; Sottocornola, S. Chem. Rev. 2007, 107, 5318–5365. (c) Dick, A. R.; Sanford, M. S. Tetrahedron 2006, 62, 2439–2463. (d) Davies, H. M. L.; Manning, J. R. Nature 2008, 451, 417–424. (e) Collet, F.; Dodd, R. H.; Dauban, P. Chem. Commun. 2009, 5061–5074. (f) Cho, S. H.; Kim, J. Y.; Kwak, J.; Chang, S. Chem. Soc. Rev. 2011, 40, 5068–5083. (g) Stokes, B. J.; Driver, T. G. Eur. J. Org. Chem. 2011, 4071–4088.

(3) (a) Ricci, A. Amino Group Chemistry, From Synthesis to the Life Sciences; Wiley-VCH: Weinheim, Germany, 2007. (b) Hili, R.; Yudin, A. K. Nat. Chem. Biol. 2006, 2, 284–287. (c) Struff, J.; Hövelmann, C. H.; Nieger, M.; Muñiz, K. J. Am. Chem. Soc. 2005, 127, 14586–14587. (d) Tsang, W. C. P.; Zheng, N.; Buchwald, S. L. J. Am. Chem. Soc. 2005, 127, 14560–14561. (e) Huang, X.; Anderson, K. W.; Zim, D.; Jiang, L.; Klapars, A.; Buchwald, S. L. J. Am. Chem. Soc. 2003, 125, 6653–6655.

(4) (a) Evano, G.; Blanchard, N.; Toumi, M. Chem. Rev. 2008, 108, 3054–3131. (b) Monnier, F.; Taillefer, M. Angew. Chem., Int. Ed. 2009, 48, 6954–6971.

(5) (a) Paul, F.; Patt, J.; Hartwig, J. F. J. Am. Chem. Soc. 1994, 116, 5969–5973. (b) Guram, A. S.; Buchwald, S. L. J. Am. Chem. Soc. 1994, 116, 7901–7902. (c) Hartwig, J. F. Acc. Chem. Res. 2008, 41, 1534–1544. (d) Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L. Acc. Chem. Res. 1998, 31, 805–818.

(6) Matsubara, T.; Asako, S.; Ilies, L.; Nakamura, E. J. Am. Chem. Soc. **2013**, 136, 646–649.

(7) (a) Kim, J.; Kim, J.; Chang, S. Chem. Eur. J. 2013, 19, 7328-7333.
(b) Shang, M.; Zeng, S.-H.; Sun, S.-Z.; Dai, H.-X.; Yu, J.-Q. Org. Lett. 2013, 15, 5286-5289. (c) Yadav, M. R.; Rit, R. K.; Sahoo, A. K. Org. Lett. 2013, 15, 1638-1641. (d) Harvey, M.; Musaev, D. G.; Du Bois, J. J. Am. Chem. Soc. 2011, 133, 17207-17216.

(8) (a) Grohmann, C.; Wang, H.; Glorius, F. Org. Lett. 2012, 14, 656–659. (b) Grohmann, C.; Wang, H.; Glorius, F. Org. Lett. 2013, 15, 3014–3017. (c) Zhao, H.; Shang, Y.; Su, W. Org. Lett. 2013, 15, 5106–5109. (d) Yu, S.; Wan, B.; Li, X. Org. Lett. 2013, 15, 3706–3709. (e) Ng, K.-H.; Zhou, Z.; Yu, W.-Y. Chem. Commun. 2013, 49, 7031–7033. (f) Yu, D.-G.; Suri, M.; Glorius, F. J. Am. Chem. Soc. 2013, 135, 8802–8805. (g) Zhou, B.; Yang, Y.; Shi, J.; Feng, H.; Li, Y. Chem. Eur. J. 2013, 19, 10511–10515.

(9) (a) Thu, H.-Y.; Yu, W.-Y.; Che, C.-M. J. Am. Chem. Soc. 2006, 128, 9048–9049. (b) Xiong, T.; Li, Y.; Lv, Y.; Zhang, Q. Chem. Commun. 2010, 46, 6831–6833. (c) Ng, K.-H.; Chan, A. S. C.; Yu, W. Y. J. Am. Chem. Soc. 2010, 132, 12862–1264. (d) Xiao, B.; Gong, T.-J.; Xu, J.; Liu, Z.-J.; Liu, L. J. Am. Chem. Soc. 2011, 133, 1466–1474. (e) Sun, K.; Li, Y.; Xiong, T.; Zhang, J.; Zhang, Q. J. Am. Chem. Soc. 2011, 133, 1694–1697. (f) Yoo, E. J.; Ma, S.; Mei, T.-S.; Chan, K. S. L.; Yu, J.-Q. J. Am. Chem. Soc. 2011, 133, 7652–7655.

(10) (a) Chen, X.; Hao, X.-S.; Goodhue, C. E.; Yu, J.-Q. J. Am. Chem. Soc. 2006, 128, 6790–6791. (b) Tran, L. D.; Roane, J.; Daugulis, O. Angew. Chem., Int. Ed. 2013, 52, 6043–6046. (c) Shang, M.; Sun, S.-Z.; Dai, H.-X.; Yu, J.-Q. J. Am. Chem. Soc. 2014, 136, 3354–3357.

(11) (a) Kim, J. Y.; Park, S. H.; Ryu, J.; Cho, S. H.; Kim, S. H.; Chang, S. J. Am. Chem. Soc. **2012**, 134, 9110–9113. (b) Ryu, J.; Shin, K.; Park, S. H.; Kim, J. Y.; Chang, S. Angew. Chem., Int. Ed. **2012**, 51, 9904–9908. (c) Shin, K.; Baek, Y.; Chang, S. Angew. Chem., Int. Ed. **2013**, 52, 8031–8036. (d) Park, S. H.; Park, Y.; Chang, S. Org. Synth. **2014**, 91, 52–59. (e) Kim, H. J.; Ajitha, M. J.; Lee, Y.; Ryu, J.; Kim, J.; Lee, Y.; Jung, Y.; Chang, S. J. Am. Chem. Soc. **2014**, 136, 1132–1140. (f) Park, S. H.; Kwak, J.; Shin, K.; Ryu, J.; Park, Y.; Chang, S. J. Am. Chem. Soc. **2014**, 136, 2492–2502. (g) Ryu, J.; Kwak, J.; Shin, K.; Lee, D.; Chang, S. J. Am. Chem. Soc. **2013**, 135, 12861–12868. (h) Lee, D.; Kim, Y.; Chang, S. J. Org. Chem. **2013**, 78, 11102–11109. (i) Kim, J.; Chang, S. Angew. Chem., Int. Ed. **2014**, 53, 2203–2207. (j) Kang, T.; Kim, Y.; Lee, D.; Wang, Z.; Chang, S. J. Am. Chem. Soc. **2014**, 136, 4141–4144. (k) Shin, K.; Ryu, J.; Chang, S. Org. Lett. **2014**, 16, 2022– 2025.

(12) 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, J. A., Jr.; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, J. M.; 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, Revision D01; Gaussian, Inc., Wallingford, CT, 2009.

(13) Zhao, Y.; Truhlar, D. G. Theor. Chem. Acc. 2008, 120, 215-241.

Organometallics

(14) (a) Hay, P. J.; Wadt, W. R. J. Chem. Phys. 1985, 82, 299-300.
(b) Hay, P. J.; Wadt, W. R. J. Chem. Phys. 1985, 82, 284-288.
(c) Wadt, W. R.; Hay, P. J. J. Chem. Phys. 1997, 107, 3032-3041.

(15) (a) Davies, D. L.; Donald, S. M. A.; Al-Duaij, O.; Macgregor, S. A.; Pölleth, M. J. Am. Chem. Soc. 2006, 128, 4210–4211. (b) Boutadla, Y.; Davies, D. L.; Macgregor, S. A.; Poblador-Bahamonde, A. I. Dalton Trans. 2009, 5887–5893.

(16) Tomasi, J.; Mennucci, B.; Cammi, R. Chem. Rev. 2005, 105, 2999–3094.

(17) (a) Pyykkö, P.; Desclaux, J.-P. Acc. Chem. Res. 1979, 12, 276–281. (b) Pitzer, K. Acc. Chem. Res. 1979, 12, 271–276. (c) Gorin, D. J.; Toste, F. D. Nature 2007, 446, 395–403. (d) Pyykkö, P. Chem. Rev. 1988, 88, 563–594. (e) Siegbahn, P. E. M. J. Am. Chem. Soc. 1996, 118, 1487–1496. (f) Leyva-Pérez, A.; Corma, A. Angew. Chem., Int. Ed. 2012, 51, 614–635.

(18) (a) Goodwin, H. A. Coord. Chem. Rev. 1976, 18, 293-325.
(b) Kläui, W. J. Chem. Soc., Chem. Commun. 1979, 700. (c) Kläui, W. Inorg. Chim. Acta 1980, 40, X22-X23. (d) Fryzuk, M. D.; Leznoff, D. B.; Thompson, R. C.; Rettig, S. J. J. Am. Chem. Soc. 1998, 120, 10126-10135. (e) Zhang, Z.; Shao, D.-L.; Geng, Z.-R.; Wang, Z.-L. Z. Anorg. Allg. Chem. 2012, 638, 821-825. (f) Ikemoto, H.; Yoshino, T.; Sakata, K.; Matsunaga, S.; Kanai, M. J. Am. Chem. Soc. 2014, 136, 5424-5431. (19) (a) Duran, F.; Leman, L.; Ghini, A.; Burton, G.; Dauban, B. P.; Dodd, R. H. Org. Lett. 2002, 4, 2481-2483. (b) When, P. M.; Lee, J. H.; Du Bois, J. Org. Lett. 2003, 5, 4823-4826. (c) Fiori, K. W.; Fleming, J. J.; Du Bois. Angew. Chem., Int. Ed. 2004, 43, 4349-4352. (d) Fruit, C.; Muller, P. Tetrahedron: Asymmetry 2004, 15, 1019-1026.

(e) When, P. M.; Du Bois, J. Org. Lett. 2005, 7, 4685–4688. (f) Kim, M.; Mulcahy, J. V.; Espino, C. G.; Du Bois, J. Org. Lett. 2006, 8, 1073–1076. (g) Fleming, J. J.; McReynolds, M. D.; Du Bois, J. J. Am. Chem. Soc. 2007, 129, 9964–9975. (h) Olson, D. E.; Du Bois, J. J. Am. Chem. Soc. 2008, 130, 11248–11249. (i) Fiori, K. W.; Espino, C. G.; Brodsky, B. H.; Du Bois, J. Tetrahedron 2009, 65, 3042–3051. (j) Boralsky, L. A.; Marston, D.; Grigg, R. D.; Hershberger, J. C.; Schomaker, J. M. Org. Lett. 2011, 13, 1924–1927. (k) Gao, G.-Y.; Jones, J. E.; Vyas, R.; Harden, J. D.; Zhang, X. P. J. Org. Chem. 2006, 71, 6655–6658.
(l) Ruppel, J. V.; Jones, J. E.; Huff, C. A.; Kamble, R. M.; Chen, Y.; Zhang, X. P. Org. Lett. 2008, 10, 1995–1998. (m) Jones, J. E.; Ruppel, J. V.; Gao, G.-Y.; Moore, T. M.; Zhang, X. P. J. Org. Chem. 2008, 73, 7260–7265. (n) Subbarayan, V.; Ruppel, J. V.; Zhu, S.; Perman, J. A.; Zhang, X. P. Chem. Commun. 2009, 4266–4268.

(20) (a) Kurokawa, T.; Kim, M.; Du Bois, J. Angew. Chem., Int. Ed.
2009, 48, 2777–2779. (b) Zalatan, D. N.; Du Bois, J. J. Am. Chem. Soc.
2008, 130, 9220–9221. (c) Milczek, E.; Boudet, N.; Blakey, S. Angew.
Chem., Int. Ed. 2008, 47, 6825–6828. (d) Lebel, H.; Huard, K.; Lectard, S. J. Am. Chem. Soc. 2005, 127, 14198–14199. (e) Mahy, J. P.; Bedi, G.; Battioni, P.; Mansuy, D. Tetrahedron Lett. 1988, 29, 1927–1930. (f) Yu, X. Q.; Huang, J. S.; Zhou, X. G.; Che, C. M. Org. Lett.
2000, 2, 2233–2236. (g) Kohmura, Y.; Katsuki, T. Tetrahedron Lett.
2001, 42, 3339–3342. (h) Liang, J. L.; Huang, J. S.; Yu, X. Q.; Zhu, N. Y.; Che, C. M. Chem. Eur. J. 2002, 8, 1563–1572. (i) Liang, C. G.; Robert-Pedlard, F.; Fruit, C.; Muller, P.; Dodd, R. H.; Dauban, P. Angew. Chem., Int. Ed. 2006, 45, 4641–4644. (j) Liang, C. G.; Collet, F.; Robert-Peillard, F.; Muller, P.; Dodd, R. H.; Dauban, P. J. Am. Chem. Soc. 2008, 130, 343–350. (k) Collet, F.; Lescot, C.; Liang, C. G.; G.; Dauban, P. Dalton Trnas. 2010, 39, 10401–10413.

(21) (a) Chen, Y.; Ruppel, J. V.; Zhang, X. P. J. Am. Chem. Soc. 2007, 129, 12074–12075. (b) Zhu, S.; Perman, J. A.; Zhang, X. P. Angew. Chem., Int. Ed. 2008, 47, 8460–8463. (c) Zhu, S.-F.; Ruppel, J. V.; Lu, H.-J.; Wojtas, L.; Zhang, X. P. J. Am. Chem. Soc. 2008, 130, 5042–5043. (d) Zhu, S.-F.; Xu, X.; Perman, J. A.; Zhang, X. P. J. Am. Chem. Soc. 2010, 132, 12796–12799. (e) Dzik, W. I.; Xu, X.; Zhang, X. P.; Reek, J. N. H.; de Bruin, B. J. Am. Chem. Soc. 2010, 132, 10891–10902. (f) Belof, J. L.; Cioce, C. R.; Xu, X.; Zhang, X. P.; Space, B.; Woodcock, H. L. Organometallics 2011, 30, 2739–2746. (g) Lu, H.; Dzik, W. I.; Xu, X.; Wojtas, L.; de Bruin, B.; Zhang, X. P. J. Am. Chem. Soc. 2011, 133, 8518–8521. (h) Lyaskovskyy, V.; Suarez, A. I. O.; Lu, H.; Jiang, H.; Zhang, X. P.; de Bruin, B. J. Am. Chem. Soc. 2011, 133,

12264–12273. (i) Olivos Suarez, A. I.; Jiang, H.; Zhang, X. P.; de Bruin, B. Dalton Trnas. 2011, 40, 5697–5705.