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Iron and Cobalt Metallotropism in Remote-Substituted NHC Ligands, Metallation to Abnormal NHC Complexes or NHC Ring Opening

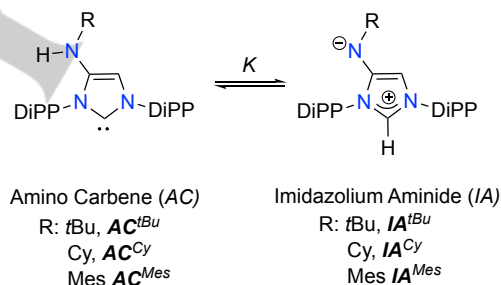
Andreas A. Danopoulos,^{*[a],[b]} Alexandre Massard,^[a] Gilles Frison,^[c] and Pierre Braunstein^{*[a]}

Dedicated to Prof. Richard J. Puddephatt on the occasion of his 75th birthday, with our warmest congratulations and best wishes.

Abstract: Metallotropism of the $M[N(\text{SiMe}_3)_2]_2$ metal fragment in the tautomeric system $IA^R \rightleftharpoons AC^R$ involving imidazolium salts / N-heterocyclic carbenes with remote amine / aminide substituents, respectively, is manifested by its C_{NHC} carbophilicity ($R = t\text{Bu}$, $M = \text{Co}$, Fe) or $\text{NR}_{\text{aminido}}$ nitrogenophilicity ($R = \text{Cy}$, $M = \text{Co}$, Fe ; $R = \text{Mes}$, $M = \text{Fe}$) and has been rationalized on the basis of steric and electronic effects. The thermolysis products of the $[M\{N(\text{SiMe}_3)_2\}_2] / IA^R \rightleftharpoons AC^R$ system are also substituent-dependent, leading to a rearranged aminide-functionalized aNHC Co_2 complex of an unprecedented type or to ring-opened metallaketanimines; they are postulated to originate from different metalloisomers. The results are interpreted on the basis of the X-ray diffraction analysis of 11 new compounds.

Molecular complexity in metal-centered chemistry heavily relies on ligands, and their own versatility is enhanced by their functionalization. If simple N-heterocyclic carbene (NHC) ligands have already led to impressive achievements in numerous areas of chemistry, functionalized NHC often bring about additional properties of considerable impact in structural chemistry, catalysis, material science, medicine, etc.. N-heterocyclic 'remote'-substituted imidazol-2-ylidenes $r(\text{NHCs})$ with heteroatom substituents at the 4- and / or 5-positions of the heterocycle (denoted as $r(\text{substituent})$) have been studied *apropos* of modulating the nucleophilicity and donor properties of the NHC functionality by means of the inductive and mesomeric effects of the $r(\text{substituent})$. Diverse substituent types have been described, resulting in NHC ligands that are charge-neutral, cationic or anionic (e.g. $r(\text{N}_{\text{exo}}\text{R}_2)$, $r(\text{N}_{\text{exo}}\text{HR})$, $r(\text{PPh}_2)$, $r(\text{RS})$, $r(\text{SiMe}_3)$, $r(\text{SiPh}_3)$,^[1] or $r(\text{PPh}_3^+)$ and $r(\text{N}_{\text{exo}}\text{H}_3^+)$ ^[2] or $r[\text{B}(\text{Ar}^{\text{F}_3})]$, $r(\text{O}^-)$ and $r(\text{N}_{\text{exo}}\text{R}^-)$, respectively).^[1f,1g,3] Neutral and anionic $r(\text{substituents})$ can render the $r\text{NHCs}$ ambident, occasionally acting as bridging ligands.^[4] Competition between the C_{NHC} and $r(\text{substituent})$ sites for metal coordination is sterically and electronically tunable.^[3a]

Tautomeric equilibria involving the C_{NHC} basic site and the $r(\text{substituent})$, altering the nature and electronic characteristics of the donors, can lead to increased bonding diversity (*cf.* equilibria involving Nitron, recently extended to its alkyl analogues^[5] and other mesomeric betaines^[6]). With 1,3-bis-(DiPP)imidazolium systems (DiPP = diisopropylphenyl), the tautomerism between the Imidazolium Aminide (**IA**) (with anionic $r(\text{N}_{\text{exo}}\text{R}^-)$) and the Amino Carbene (**AC**) (with neutral $r(\text{NHR})$) depends on the nature of R: aromatic and *t*Bu substituents favor the **IA** and **AC** forms, respectively (Scheme 1).^[7] When $R = t\text{Bu}$, both tautomers could be isolated from the equilibrium mixture $IA^{t\text{Bu}} \rightleftharpoons AC^{t\text{Bu}}$ and crystallographically characterized: the **IA**^{*t*Bu} [7] by cooling at -40°C and the **AC**^{*t*Bu} by slow solvent evaporation at room temp. (Supporting Information and Figure S2.1).



Scheme 1.

Whereas efforts are directed towards the use of well-defined earth-abundant NHC metal complexes in homogeneous catalysis, competent Fe and Co complexes are often generated *in-situ*, unexpected transformations being possibly overlooked.^[8] Herein, we describe fully characterized complexes obtained in the course of a study on metallotropism in **IA** and **AC** associated with $[M\{N(\text{SiMe}_3)_2\}_2]_2$ ($M = \text{Co}$, Fe) as a function of R in $r(\text{N}_{\text{exo}}\text{R})$ and $r(\text{N}_{\text{exo}}\text{HR})$. Two types of unexpected and unprecedented products were obtained from thermolysis of the system $IA^R \rightleftharpoons AC^R$ ($R = t\text{Bu}$, Mes) and $[M\{N(\text{SiMe}_3)_2\}_2]_2$, the different nature of which can be traced to metallotropism. All the reactions and manipulations were carried out under inert atmosphere (glove-box, N_2 -sealed ampoules) and all described complexes are (very) sensitive in solution and solid-state to air/moisture (see SI).

The equilibrium mixture $IA^{t\text{Bu}} \rightleftharpoons AC^{t\text{Bu}}$ (K_{eq} at rt ca. 0.5) reacted with 0.5 equiv. $[M\{N(\text{SiMe}_3)_2\}_2]_2$ ($M = \text{Co}$, Fe) in toluene to give selectively **1a** and **1b** as green and orange crystals, respectively (Scheme 2). Despite their paramagnetism, **1a** and **1b** exhibit diagnostic $^1\text{H-NMR}$ spectra in the region δ 100 to -50 ppm

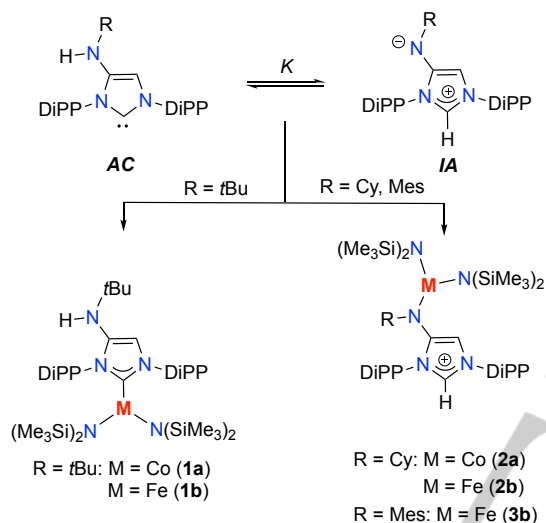
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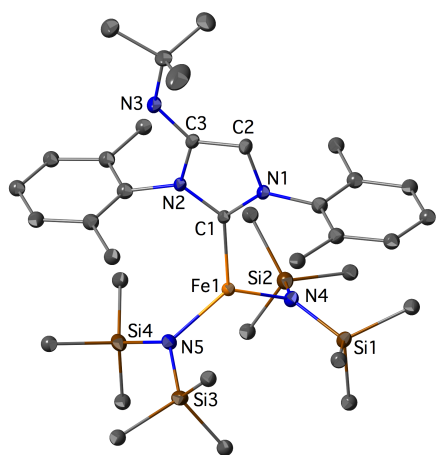
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(see SI); no other paramagnetic product could be detected in solution by NMR spectroscopy. The molecular structure of **1b** (Figure 1) reveals trigonal planar geometry with C_{NHC} -coordinated AC^{tBu} and two bis(trimethylsilyl)amide ligands; the metrical data are very similar to the archetypical $[Fe(IPr)\{N(SiMe_3)_2\}_2]$ with identical sterics (*cf.* $Fe-C_{NHC} = 2.182(2) - 2.184(2) \text{ \AA}$ vs. $2.192(3)$ in **1b**); the NHC plane makes an angle of *ca.* 42° with the metal coordination plane.^[9] The data set from the weakly diffracting crystals of **1a** established identical atom connectivity to **1b** (Figure S2.3). Interestingly, preliminary reactions of $IA^{tBu} \rightleftharpoons AC^{tBu}$ with the sterically exposed anhydrous $CoCl_2$ led to the C_{NHC} -metallated halide-bridged complex $[Co(AC^{tBu})Cl(\mu-Cl)]_2$ (Figure S2.5), further underlining the preferred coordination site of the AC^{tBu} tautomer. Insight into the apparent metal carbophilicity when $R = tBu$ resulted from computational studies (see below).

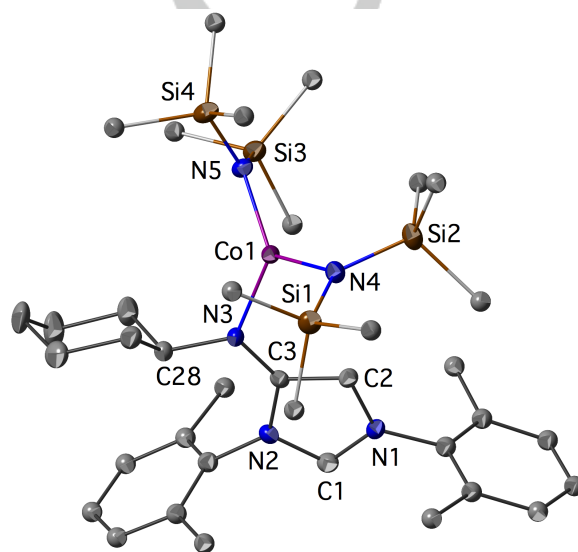


Scheme 2.

Figure 1. Molecular structure of **1b**; DiPP methyls are omitted (metrical data in SI).

In contrast to the above where $R = tBu$, the reaction of $IA^{Cy} \rightleftharpoons AC^{Cy}$ (K_{eq} at *rt ca.* 3.2) with $[M\{N(SiMe_3)_2\}_2]$ ($M = Co, Fe$) led to the isostructural **2a** and **2b** in good yields, as green and

light yellow paramagnetic solids (Figures 2 and S2.7, respectively). The metals in **2a/2b** are in a trigonal planar environment, with a N_{exo} -coordinated IA^{Cy} . In **2a** there are two types of Co-N bonds, $Co-N_{exo}$ ($1.993(2) \text{ \AA}$) being longer than $Co-N_{N(SiMe_3)_2}$ ($1.943(2)$ and $1.956(2) \text{ \AA}$). A analogous metrical trend was found in $[Co\{N(SiMe_3)_2\}_2(\text{pyridine})]$, with $Co-N_{pyridine}$ and $Co-N_{N(SiMe_3)_2}$ at $2.055(5) \text{ \AA}$, $1.904(3) \text{ \AA}$, respectively;^[10] this comparison places the $Co-N_{exo}$ bond distances in the region of $Co-N_{imine}$ bonds. The conjugated mesomeric betaine IA^{Cy} can be classified as an imidazolin-4-imine and expands the class of regioisomeric imidazolin-2-imines recently described.^[11] Similar considerations apply to the structure of **2b**.

Figure 2. Molecular structure of **2a** (metrical data in SI).

DFT calculations have been performed at the (U)M06-2X level for AC^R and IA^R tautomers and their metal complexes for $R = tBu, Cy$ and Mes . The case $R = H$ has been also studied to serve as a reference (see the SI for the computational methods and detailed discussion). Each tautomer IA^R and AC^R can exist in two isomeric forms, with the R substituent at the N_{exo} site being proximal or distal to the neighboring DiPP. Owing to the steric hindrance of the latter, distal isomers are more stable than proximal ones for $R \neq H$, in particular for $R = tBu$. Similarly, the presence of the DiPP substituent renders the coordination of a large metal fragment such as $M\{N(SiMe_3)_2\}_2$ to the N_{exo} atom of $IA^{R_{distal}}$ computationally impossible, in contrast to N_{exo} coordination of $IA^{R_{prox}}$; these results are in agreement with the experimental structures **2a/b** and **3b**. Consequently, coordination of $M\{N(SiMe_3)_2\}_2$ fragments has been further analyzed only for $AC^{R_{distal}}$ and $IA^{R_{prox}}$ isomers ($R = H, Cy, tBu, Mes$) (Figure 3), the latter ligand being less stable than the former ($G(IA^{R_{prox}}) - G(AC^{R_{distal}}) = 26.2, 56.2$ and $10.4 \text{ kJ}\cdot\text{mol}^{-1}$ for $R = Cy, tBu$ and Mes , respectively), except for $R = H$ ($-2.2 \text{ kJ}\cdot\text{mol}^{-1}$) (Table S4.1).

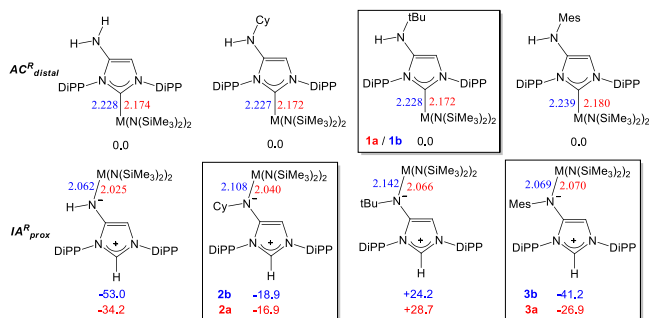


Figure 3. Coordination of ACR^{distal} and IAR^{prox} isomers ($R = H, Cy, tBu, Mes$) to $M\{N(SiMe_3)_2\}_2$ fragments. Bond lengths (in Å) and relative free energies (in $\text{kJ}\cdot\text{mol}^{-1}$) computed at the UM06-2X/def2-TZVPP//UM06-2X/def2-SVP level for $M = Fe$ (blue) and Co (red). The structures corresponding to those obtained experimentally have been framed.

The relative free energies of the metal complexes, depending on the ACR^{distal} vs. IAR^{prox} ligand nature, are in excellent agreement with the experimental results: only the most stable complexes have been observed experimentally. Calculations of the Percent Buried Volume ($\%V_{bur}$) of ligands ($N\{SiMe_3\}_2$)₂, ACR^{distal} and IAR^{prox} reveal severe steric congestion around the metal center and the larger steric demand of ligand ACR^{distal} relative to IAR^{prox} for $R = Cy$ and Mes , whereas the opposite is found for $R = tBu$.

Even for $R = H$, there is steric hindrance between DiPP and $N(SiMe_3)_2$ ligands and IA^H_{prox} complexes are significantly more stable than AC^H_{distal} (-53.0 and -34.2 $\text{kJ}\cdot\text{mol}^{-1}$ for $M = Fe$ and Co , respectively). The coordination of the IA^R_{prox} ligand to $[M\{N(SiMe_3)_2\}_2]_2$ remains preferred to that of AC^R_{distal} for $R = Cy$ and Mes because the steric repulsion between R and DiPP groups in IA^R_{prox} induces only a relatively small destabilization and the steric bulk of IA^R_{prox} remains smaller than that of AC^R_{distal} . In contrast, IA^{tBu}_{prox} is strongly destabilized relative to AC^{tBu}_{distal} due to steric hindrance between the DiPP and tBu groups. Furthermore, IA^{tBu}_{prox} is bulkier than AC^{tBu}_{distal} . These combined steric effects induce the preferred formation of **1a** / **1b** with AC^{tBu}_{distal} .

The mixture $IA^{Mes} \rightleftharpoons AC^{Mes}$ reacted with $[Fe\{N(SiMe_3)_2\}_2]_2$ only under forcing conditions (toluene, 110 °C, 3 d) and in the presence of excess $[Fe\{N(SiMe_3)_2\}_2]_2$ (2:1 on metal basis) giving complex **3b** (isolated in two different isomorphs, Scheme 2, SI and Figures S2.8 and S2.9). In stark contrast, heating of $IA^{Mes} \rightleftharpoons AC^{Mes}$ with $[Co\{N(SiMe_3)_2\}_2]_2$ (1:1 ratio on metal basis) at 90 °C in toluene for ca. 16 h gave brown crystals of the paramagnetic **4a** (Scheme 3 and Figure 4). Plausible reaction steps leading to **4a** are presented in the SI (Scheme S3.3). In contrast, $[Fe\{N(SiMe_3)_2\}_2]$ was unreactive under these conditions and only the starting materials were recovered. The structure of **4a** unveiled a unique binuclear mixed-valence complex featuring metalation of the heterocyclic ring *ortho* to the N_{exo} substituent. In **4a**, both Co centres ($Co1$ and $Co2$ in Figure 5) adopt distorted planar T-shaped geometries (assuming one coordination site along the $Co-Co$ vector). The $Co1-Co2$ distance ($2.5628(3)$ Å) is comparable to that in $[Co_2(CO)_8]$ (2.52 Å).^[12] All $Co-N$ distances ($Co1-N3$, $Co1-N4$, $Co2-N5$) fall into the narrow range

characteristic of amidine ligands, with a typical $Co-C_{NHC}$ bond distance ($1.951(1)$ Å).^[13] Thus, a plausible description of the ligand system in **4a** emerging from the metrical data is an amidine-functionalized mesoionic aNHC, leading to consider $Co1$ and $Co2$ as Co^{II} as Co^I , respectively. Alternative resonance formulations can be found in the SI (Scheme S3.2). Interestingly, **4a** is the only dinuclear complex with two $Co\{N(SiMe_3)_2\}$ moieties and nonbridging $N(SiMe_3)_2$ groups and represents a rare example of heteroatom-functionalized aNHC.

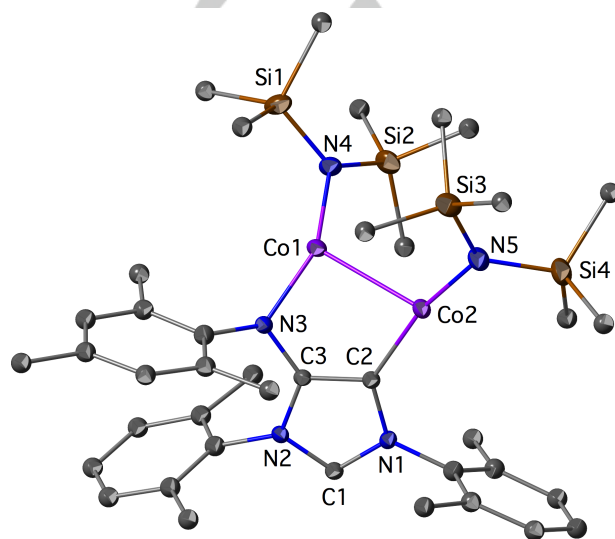
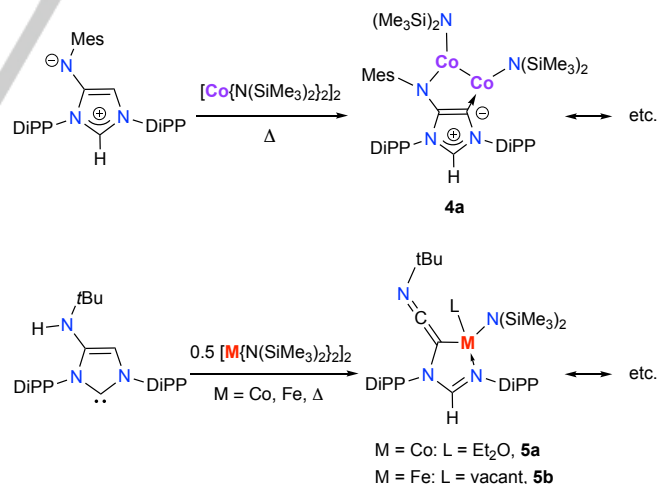


Figure 4. Molecular structure of **4a**; DiPP methyls are omitted (metrical data in SI).



Scheme 3. Thermal rearrangement products of $IA^{Mes} \rightleftharpoons AC^{Mes}$ with $[Co\{N(SiMe_3)_2\}_2]_2$ (**4a**) and of $IA^{tBu} \rightleftharpoons AC^{tBu}$ with $[M\{N(SiMe_3)_2\}_2]_2$ ($M = Co$ (**5a**), Fe (**5b**)); description by alternative resonance forms is given in the SI.

In contrast to **1a/1b**, complexes **5a** and **5b** were obtained from the reaction of the tautomeric mixture $IA^{tBu} \rightleftharpoons AC^{tBu}$ with

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$[M\{N(SiMe_3)_2\}_2]$ ($M = Co, Fe$) in toluene at room temperature for 3 d or heating at 90 °C for 1 h (Scheme 3 and Figures 5 and 6). They were isolated in good yields as purple and red solids that were crystallized from ether or pentane, respectively.

The crystal structures of **5a** and **5b** established the atom connectivity of a ring-opened, rearranged ligand system, and the metrical data proved crucial in extracting the bond orders between the constituent atoms.

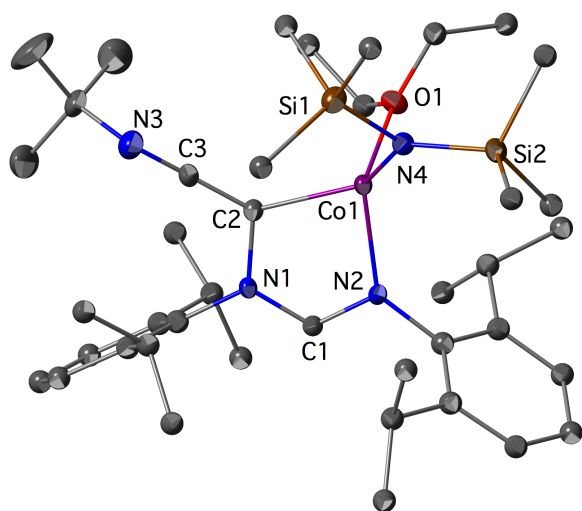


Figure 5. Molecular structure of complex **5a** (metrical data in SI).

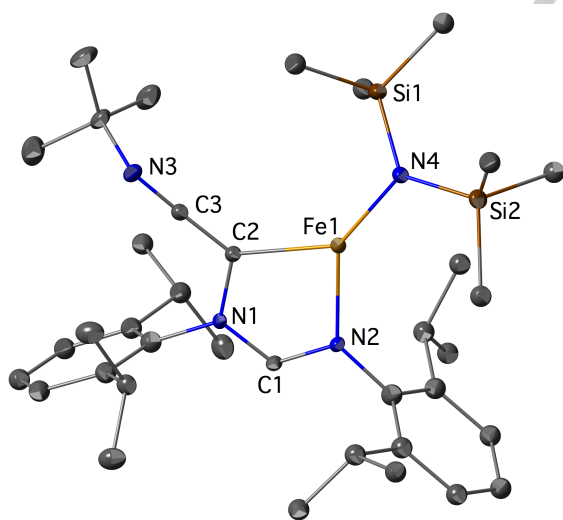


Figure 6. Molecular structure of complex **5b** (metrical data in SI).

Although the metals in **5a** and **5b** adopt pseudo-tetrahedral and trigonal planar coordination geometries, respectively, due to coordination of an ether molecule in **5a**, the skeleton of the ligand and the associated $\kappa N, \kappa C$ -coordination are identical in both cases. The metrical data (see SI) support the depicted resonance forms showing the metallated ketenimine structures (Schemes 3 and

S3.3). When complexes **1a** and **1b** were heated in C_6D_6 at 90 °C for 1 h, they fully converted to **5a** and **5b**, respectively, which strongly indicates their intermediacy in the formation of the latter, although possible lability of the $M\{N(SiMe_3)_2\}_2$ fragment in **1a/1b**, may point to an alternative rearrangement mechanism (SI).

Skeletal rearrangements of coordinated imidazol(in)-2-ylidenes are rare but not unprecedented. Heterocycle ring opening reactions may be preceded by migratory insertion of alkyl co-ligands to the C_{NHC} (Ni),^[14] (Hf),^[15] or not;^[16] imidazol(in)-2-ylidene ring expansion to 6-membered metallacycles can take place *via* metal insertion into the C-N bond (Ni,^[17] Ru).^[18] Ring expansions involving insertion of heteroelements have been described and recently reviewed;^[19] remote lithiation preceding SIMes ring opening has recently been reported.^[20] Furthermore, hydrolytic cleavage of expanded NHC coordinated to Cu has been described.^[21] However, the transformation of **1** to **5** constitutes the first example of *r*NHC skeletal rearrangement and the formation of metalla-ketenimines, which may be initiated by remote coordination of the *r*NHCs species.

In conclusion, we have demonstrated experimentally and theoretically that the tautomers involved in the equilibrium $IA^R \rightleftharpoons AC^R$ adopt diverse coordination modes with the fragment $M\{N(SiMe_3)_2\}_2$ ($M = Co, Fe$), depending on the nature of the R substituent of the N_{exo} atom. The preference towards κC or κN coordination as a function of R correlates with the nature of the most abundant tautomer in the $IA^R \rightleftharpoons AC^R$ equilibrium. Owing to the bulk of the metal fragment, its coordination to the IA^R forms (R = Cy, Mes) is accompanied by reorientation of the $N_{exo}R$ group from dist to prox; in the AC^{tBu} case, reorientation is irrelevant, since the metal fragment is coordinated to the C_{NHC} . However, the reactivity of the $IA^{tBu} \rightleftharpoons AC^{tBu} / M\{N(SiMe_3)_2\}_2$ system at elevated temperature features ring opening of the heterocyclic ring moiety and rearrangement to metallacycles comprising metallated ketenimines. In contrast, with $IA^{Mes} \rightleftharpoons AC^{Mes}$, formation of a dinuclear mixed valence complex with functionalized *a*NHC occurred for $M = Co$ only. Based on the computed stability of the *r*(NHC) metal silylamide adducts, it may be plausible to associate the divergent rearrangement patterns with the metallotropy, *i.e.* coordination of the C_{NHC} or N_{exo} sites. This contention is based on coordination modes established by X-ray diffraction on well-defined complexes, but *in-situ* mechanistic investigations were hampered by paramagnetism. Predisassociation of $M\{N(SiMe_3)_2\}_2$ governed by temperature or electronic and steric effects of the substituent cannot be ruled out. At present, studies of the catalytic chemistry with *r*NHC complexes, in particular of 3d metals, are very sparse, and the results described herein point to a complex coordination chemistry, which may have considerable repercussions in future catalytic applications.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: cobalt • dinuclear complex • N-heterocyclic carbenes • iron • metallotropism

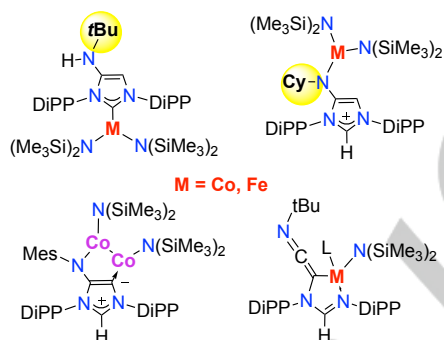
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COMMUNICATION

Metallo-tropism in tautomers

arises from stereoelectronic fine-tuning of (Fe or Co){N(SiMe₃)₂}₂ bonding to C_{NHC} or remote N in NHCs/imidazolium salts with amine/aminide substituents, respectively. Thermally-induced unexpected formation of a Co^I-Co^{II} dinuclear complex and NHC ring opening leading to metallaketenimines were observed.



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Iron and Cobalt Metallo-tropism in Remote-Substituted NHC Ligands, Metallation to Abnormal NHC Complexes or NHC Ring Opening