ORGANOMETALLICS

Communication

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Organolutetium-Mediated Dearomatization and Functionalization of Pyrimidine Rings

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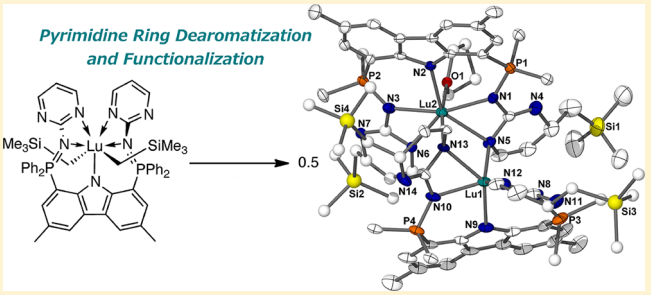
Supporting Information

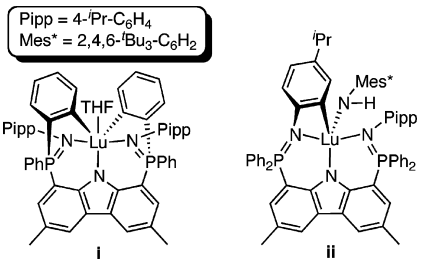
ABSTRACT: The synthesis of a pentadentate *NNNNN* bis(phosphinimine)carbazole pincer ligand bearing two pyrimidine N-aryl rings is reported. A dialkyl lutetium complex of the ligand, prepared by alkane elimination with Lu-$(CH_2SiMe_3)_3(THF)_2$, was found to undergo an unusual transformation involving a double alkyl shift whereby the $-CH_2SiMe_3$ groups on the metal migrated to both pyrimidine rings. This migration afforded a final product that featured alkyl-functionalized, dearomatized ligand pyrimidine rings.



In recent years, there has been a surge in the development of non-carbocyclic ligands for use in supporting highly reactive rare earth complexes.[1−4] This "post-metallocene era" has witnessed a diverse array of new ligand scaffolds that can support these metal ions by providing a wide variety of different steric and electronic environments. As a result, unique coordination modes have often been encountered in lanthanide complexes supported by non-Cp ligands, a trend that remains largely unparalleled by traditional carbocyclic ligands.

To this end, we recently reported two carbazole-based bis(phosphinimine) pincer ligands for use in stabilizing rare earth metals.[5] These ancillary ligands were designed to impart a unique coordination environment on metal complexes and, thus, act as a platform for obtaining new bonding modes and reaction behavior. Unfortunately, initial screening of the scaffolds, as the corresponding lutetium dialkyl complexes, revealed a high degree of steric crowding at the metal center, resulting in cyclometalative decomposition.[6] Specifically, the P-phenyl rings of the phosphinimine functionalities underwent cyclometalation reactions with concomitant loss of alkane to afford doubly cyclometalated lutetium complexes that were coordinated by the ligand in a κ^5 bonding mode via three nitrogen atoms and two *ortho*-metalated P-phenyl rings (complex i, Chart 1). We have also demonstrated that the bis(phosphinimine)carbazole ligand is capable of cyclometalative reactivity at the N-aryl site of the phosphinimine functionality (complex ii, Chart 1).[7] Accordingly, we were inclined to modify the ligand framework so as to prevent such decomposition pathways. Since previous iterations of this ancillary possessing phenyl and 4-isopropylphenyl rings at the N-aryl site of the phosphinimine functionality were prone to C−H bond activation at the *ortho* positions, these moieties were replaced with pyrimidine groups that lack *ortho* C−H bonds. Notably, such pyrimidine rings incorporate additional hard nitrogen donors into the scaffold, thus increasing its potential denticity and capacity to stabilize sterically and

Chart 1. Cyclometalation of a Bis(phosphinimine)carbazole Ligand



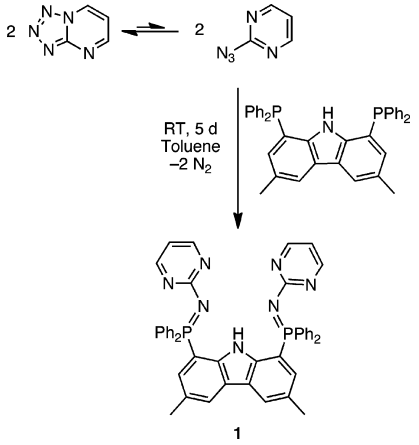
electronically unsaturated rare earth complexes. Herein, we report the effect of pyrimidine ring incorporation into the phosphinimine functionality of our carbazole pincer ligand and its resultant ability to stabilize rare earth metal complexes, using lutetium as a model system. Significantly, our investigation has revealed unique reactivity involving a double alkyl migration reaction that resulted in dearomatization and functionalization of the ligand pyrimidine rings.

Installation of N-aryl groups into the ligand framework can be readily achieved by the reaction of an aryl azide (2 equiv) with 1,8-bis(diphenylphosphino)-3,6-dimethylcarbazole.[5] In this case, we aimed to use 2-azidopyrimidine as the pyrimidine source (Scheme 1). In solution, 2-azidopyrimidine is susceptible to valence tautomerism and exists in equilibrium with its tetrazole form (tetrazolo[1,5-*a*]pyrimidine). This equilibrium is influenced by choice of solvent and temperature, but typically favors the tetrazole tautomer.[8,9] Nonetheless, the desired Staudinger reaction between 1,8-bis(diphenylphosphino)-3,6-dimethylcarbazole and 2-azidopyrimidine proceeds cleanly to afford the anticipated bis-

Received: May 10, 2013

   dx.doi.org/10.1021/om400413e | *Organometallics* XXXX, XXX, XXX−XXX

Scheme 1. Synthesis of Pyrimidine-Substituted Bis(phosphinimine)carbazole Scaffold (1)



(phosphinimine) ligand (**1**) in excellent (97.3%) yield, although the rate of reaction is significantly slower than that observed for other aryl azides, such as phenyl azide or *para*-isopropylphenyl azide.[5]

Proteo ligand **1** is C_{2v} symmetric on the NMR time scale and exhibits a sharp singlet at δ 18.5 (benzene-d_6) in its $^{31}P\{^1H\}$ NMR spectrum. The ^1H NMR spectrum of **1** (benzene-d_6) displays a single carbazole methyl resonance at δ 2.16, a broad NH peak at δ 12.2, and the expected aromatic signals. Diagnostically, the pyrimidine rings on **1** give rise to a triplet (2H) at δ 5.97 and a doublet (4H) at δ 8.02 corresponding to the *para* and *meta* protons, respectively.

In addition to characterization by multinuclear NMR spectroscopy, the ligand structure was unambiguously established by a single-crystal X-ray diffraction study. Proteo ligand **1** crystallized from a concentrated chloroform-*d* solution in the space group $P2_1/c$ with two solvent molecules. A rendering of molecule **1** is depicted in Figure 1 as a thermal ellipsoid plot. In the structure, one phosphinimine donor (N1) participates in a hydrogen bond interaction with the carbazole N–H (d(N···N) = 2.838(5) Å; however, the group lies substantially out of the dimethylcarbazole plane (N1–P1–C1–C12 torsion angle of 33.6(4)°). The other phosphinimine moiety (P2–N3) is rotated significantly away from the carbazole N–H (N3–P2–C8–C9 torsion angle of 159.1(3)°). The phosphinimine P=N bond lengths in **1** (1.597(3) and 1.592(3) Å) are comparable to those found in related structures.[5,7,10]

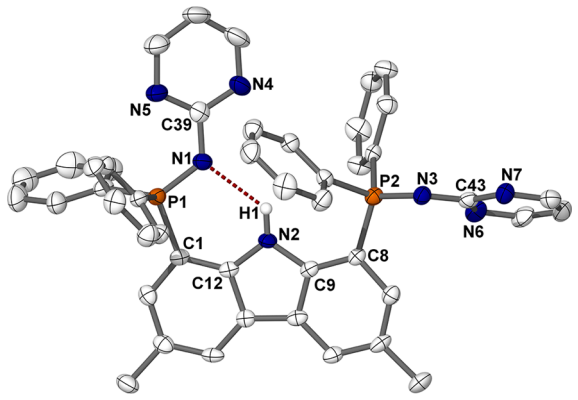
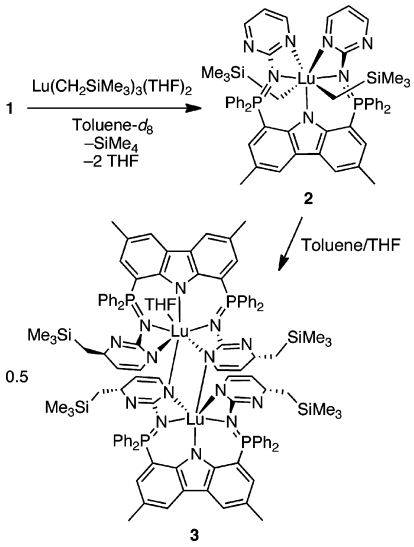


Figure 1. Thermal ellipsoid plot (50% probability) of HL (**1**) with hydrogen atoms (except H1) and two chloroform-*d* solvent molecules omitted for clarity. Selected bond distances (Å), angles (deg), and torsion angles (deg): P1–N1 = 1.597(3), P2–N3 = 1.592(3), N2···N1 = 2.838(5), N1–P1–C1 = 103.4(2), N3–P2–C8 = 114.7(2), N1–P1–C1–C12 = 33.6(4), N3–P2–C8–C9 = 159.1(3).

In order to assess the ability of bis(phosphinimine) ligand **1** to support well-defined organolanthanide complexes, a dialkyl lutetium species was targeted. Proteo ligand **1** reacted readily with $Lu(CH_2SiMe_3)_3(THF)_2$ to give the respective dialkyl lutetium complex via alkane elimination. When this reaction was monitored *in situ* on an NMR tube scale in toluene-d_8, rapid formation of the desired dialkyl metal complex, $(\mathbf{L})Lu(CH_2SiMe_3)_2$ (**2**), one equivalent of $SiMe_4$, and two equivalents of liberated THF were observed.

In contrast to previously reported bis(phosphinimine)-carbazole ligands,[5] ligand **1** presents a chelation environment defined by one nitrogen atom from each pyrimidine ring, in addition to the two phosphinimine donors and the carbazole nitrogen. As such, the alkane elimination reaction of $Lu(CH_2SiMe_3)_3(THF)_2$ with **1** resulted in dialkyl lutetium complex $(\mathbf{L})Lu(CH_2SiMe_3)_2$ (**2**), whereby the ligand was bound κ^5 to the metal center through five nitrogen atoms (Scheme 2). In complex **2**, the presence of two extra nitrogen donors provides enhanced electron donation to the metal center and, as a result, enhanced thermal stability. Compared to previously described lutetium dialkyl species of related bis(phosphinimine)carbazole ligands, which exhibited half-lives on the order of only 20 min at ambient temperature,[5] complex **2** can be left in solution (benzene-d_6/THF) at ambient temperature for over 5 h with only minimal signs of decomposition. Eventually, **2** does decompose to a single new product (*vide infra*), the process of which is rapidly accelerated at elevated temperature. Unfortunately, attempts to isolate **2** as an analytically pure solid were unsuccessful and always resulted in mixtures of **2** and its decomposition product. However, **2** can be quantitatively generated *in situ* at low temperature and used in this form to further investigate reactivity.

Scheme 2. Synthesis of κ^5 Dialkyl Lutetium Complex 2 and Reactivity via Double $-CH_2SiMe_3$ Migration



In the $^{31}P\{^1H\}$ NMR spectrum (toluene-d_8, 263.2 K), a downfield shift of the phosphinimine resonance was observed for $(\mathbf{L})Lu(CH_2SiMe_3)_2$ (**2**) at δ 27.2. As expected, the ^1H

dx.doi.org/10.1021/om400413e | *Organometallics* XXXX, XXX, XXX–XXX

NMR spectrum revealed diagnostic methylene (δ −1.22) and trimethylsilyl signals (δ −0.33) as sharp singlets, integrating to 4H and 18H, respectively. In the aromatic region of the spectrum, three separate signals corresponding to pyrimidine protons were observed at δ 8.28 (br m, 2H), 7.74 (m, 2H), and 6.08 (dd, 2H). Thus, it was concluded that both pyrimidine rings were bound to the lutetium center, affording a metal complex where the ancillary ligand was coordinated in the anticipated κ^5N mode.

Gratifyingly, complex **2** does not suffer from intramolecular cyclometalation pathways previously reported for related bis(phosphinimine)carbazole lutetium complexes.[6] Interestingly, though, **2** undergoes an unusual double alkyl shift, whereby both of the alkyl groups on the metal migrate to the pyrimidine rings, resulting in a final product with trimethylsilylmethyl groups *para* to the nitrogen atom coordinated to lutetium. A result of the double alkyl migration reaction is dearomatization of the pyrimidine rings and, consequently, formation of a formal negative charge on the coordinated pyrimidinyl nitrogen atoms. The product of this alkyl transfer is an asymmetric bimetallic complex, **3**, wherein the ligand is κ^5-coordinated to lutetium through five nitrogen atoms (three anionic nitrogens and two neutral phosphinimine donors). To the best of our knowledge, this is the first example of dearomatization and alkyl group functionalization of pyrimidine rings by a rare earth metal.

Due to the complexity of the reaction product, and the broad, uninformative spectral features in its NMR spectra between −60 and 90 °C, the structure of complex **3** was unambiguously ascertained by a single-crystal X-ray diffraction experiment. The solid-state structure of **3** is depicted in Figure 2 as a thermal ellipsoid plot. In the solid state, the complex was found to dimerize via bridging nitrogen atoms (N5 and N13) of the dearomatized pyrimidinyl rings. As each bridging pyrimidinyl nitrogen atom bears a negative charge, it can be viewed as formally bonding to one lutetium as an anionic ligand and the other metal center as a neutral Lewis base. Correspondingly, N5 exhibits short (2.315(6) Å) and long (2.493(6) Å) bonds to Lu1 and Lu2, respectively. Likewise, N13 is bonded to Lu1 and Lu2 by similar long and short interactions (2.436(5) and (2.354(5) Å), respectively). These contact distances suggest that the bimetallic complex is not held together by Lewis acid−base interactions, but rather by the anionic ligand-to-metal bonds.

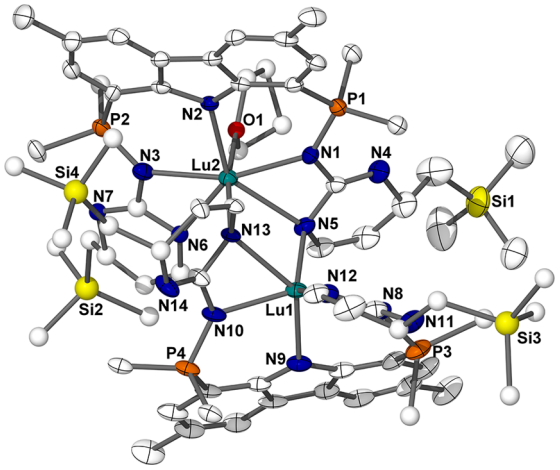


Figure 2. Thermal ellipsoid plot (30% probability) of **3** with hydrogen atoms and P-phenyl rings (except for *ipso* carbons) omitted for clarity. Positionally disordered atoms are depicted as spheres of arbitrary radius. Selected bond distances (Å) and angles (deg): Lu2−N2 = 2.412(5), Lu2−N3 = 2.297(6), Lu2−N1 = 2.321(5), Lu2−N5 = 2.493(6), Lu2−N13 = 2.354(5), Lu2−N6 = 2.389(16), Lu1−N13 = 2.436(5), Lu1−N10 = 2.264(6), Lu1−N5 = 2.315(6), Lu1−N9 = 2.327(5), Lu1−N8 = 2.305(6), Lu1−N12 = 2.240(6), O1−Lu2 = 2.341(11), N13−Lu2−O1 = 170.2(4), N3−Lu2−N2 = 81.4(2), N2−Lu2−N1 = 81.0(2), N1−Lu2−N5 = 56.4(2), N5−Lu2−N6 = 87.2(5), N6−Lu2−N3 = 53.8(5), N12−Lu1−N5 = 129.0(2), N12−Lu1−N10 = 105.1(2), N12−Lu1−N9 = 118.1(2), N9−Lu1−N10 = 81.1(2), N10−Lu1−N5 = 110.7(2), N9−Lu1−N5 = 102.6(2), N8−Lu1−N13 = 138.6(2).

In the complex, one lutetium center (Lu2) is seven-coordinate, while the other metal center (Lu1) is hexacoordinate. The geometry at Lu2 is best described as distorted pentagonal bipyramidal with five nitrogen atoms from one ligand subunit (N1, N2, N3, N5, and N6) occupying the equatorial plane (average N−Lu−N angle = 72.0°). The apical sites of the pentagonal bipyramid are defined by coordination of one molecule of THF (O1) and a bridging pyrimidine nitrogen atom (N13). At 170.2(4)°, the N13−Lu2−O1 angle approaches linearity. In contrast to Lu2, the molecular geometry at Lu1 is not easily assigned. Upon initial inspection, a distorted trigonal prismatic geometry with the trigonal faces defined by N9, N8, and N5 and N10, N12, and N13 was considered. The N−N−N bond angles measured on the N9, N8, and N5 trigonal face range from 50.0(2)° to 65.6(2)° and are in relatively good agreement with the expected value of 60°. However, the N−N−N bond angles measured on the N10, N12, and N13 trigonal face are largely distorted (ranging from 38.4(2)° to 80.2(2)°), the result of which generates a trigonal prismatic geometry with significant twist. Perhaps a better description of the geometry at Lu1 is a bicapped tetrahedron,[11] whereby the tetrahedron is defined by N5, N9, N10, and N12, with N8 and N13 serving as the capping atoms. The average tetrahedral angle at Lu1 was 107.8°, which is slightly less than the ideal value of 109.5°. Notably, a large angle of 138.6(2)° was measured between the capping atoms of the tetrahedron (N8−Lu1−N13), suggesting distortion from this geometry as well.

Alkyl migration involving rare earth metals has been previously documented in complexes containing different N-heterocyclic ligands. For example, a 1,3-alkyl migration was reported by Kiplinger et al. in lutetium alkyl complexes supported by 2,2′:6′,2″-terpyridine (terpy) and 4,4′,4″-tri-*tert*-butyl-2,2′:6′,2″-terpyridine ligands.[12] With the terpy-based scaffolds, migration was limited to a single alkyl group, thus converting the neutral terpy ligand into a monoanionic ancillary; this ligand has since proven useful in supporting a wide range of organometallic lutetium complexes.[13] Likewise, alkyl migration was also documented in group 3 benzyl complexes of a ferrocene diamide ligand coordinated to heterocycles such as isoquinoline, pyridine, and 2,2′-bipyridine.[14,15] Notably, in the systems involving pyridine and 2,2′-bipyridine, initial 1,3-alkyl transfer yielded the corresponding 1,2-dihydroheterocycle as the kinetic product. This was then followed by subsequent isomerization to the 1,4-dihydroheterocycle as the thermodynamic product. Comparable behavior involving pyridine and pyridine-based ligands has also been reported in rare earth hydride,[4,16−22] alkaline earth hydride,[23,24] and transition metal complexes.[25−27]

With our ligand system, the final product of the double migration reaction, **3**, possessed 4-trimethylsilylmethyl-1,4-

dx.doi.org/10.1021/om400413e | *Organometallics* XXXX, XXX, XXX−XXX

dihydropyrimidin-1-yl rings bound to each phosphinimine group of the ligand. In these dearomatized pyrimidinyl rings, the alkyl group is situated *para* to the nitrogen atom bridging the lutetium centers. It is highly probable that dearomatization and functionalization of the pyrimidine rings occur via a mechanism related to those discussed above for other N-heterocycles. Accordingly, we have reasoned that the operative pathway likely proceeds from dialkyl **2** via an initial 1,3-alkyl migration followed by subsequent isomerization, a second 1,3-migration, isomerization, and finally dimerization to afford the final product **3**, which is supported by a remarkable trianionic pentadentate ancillary that possesses two 4-trimethylsilylmethyl-1,4-dihydropyrimidin-1-yl rings.

We were interested in investigating the generality of this migration process and the possibility of extending the observed reactivity to other group 3 metals. Specifically, we utilized the reagents $Sc(CH_2SiMe_3)_3(THF)_2$ and $Y(CH_2SiMe_3)_3(THF)_2$ to prepare dialkyl analogues of complex **2** of the general form $(\mathbf{L})Ln(CH_2SiMe_3)_2$, Ln = Sc and Y. Unfortunately, these derivatives did not cleanly undergo alkyl migration/dearomatization of the ligand pyrimidine rings. This is notable considering that the lutetium derivative **2** exclusively afforded species **3** in high yield. With Sc and Y, however, a complicated blend of products was observed; these intractable mixtures likely formed via competing decomposition routes, and we have thus far been unable to separate the various compounds.

A fine balance is clearly required when tuning the properties of an ancillary ligand for use in rare earth metal chemistry. While incorporation of pyrimidine rings into the ligand scaffold afforded a lutetium complex that was resistant to cyclometalative alkane elimination reactivity, it introduced an alternative route for complex decomposition, namely, pyrimidine ring dearomatization and functionalization. We will mitigate this issue by judiciously selecting non-N-heterocyclic ligand R groups in future iterations of our carbazole scaffold. As a different approach to a "cyclometalation-resistant" bis(phosphinimine)carbazole ligand, we are currently replacing the phenyl rings at the phosphinimine phosphorus atoms with less bulky and geometrically constrained moieties, such as methyl and phospholane groups.

In summary, the new pyrimidine-substituted ligand **1** was utilized to successfully prepare a dialkyl lutetium complex that was resistant to *ortho* cyclometalative decomposition pathways that plagued previous generations of this framework. However, this species proved to be prone to an unusual double alkyl shift that resulted in functionalization and dearomatization of the ligand pyrimidine rings. Despite the unexpected nature of the reactivity of the developed compounds, these well-defined lutetium complexes serve as valuable models for studying the reactivity patterns of potentially useful aromatic ring functionalization processes. Accordingly, future studies will aim to fully explore the potentially rich small-molecule reaction chemistry of complexes **2** and **3**.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental details in PDF format and X-ray crystallographic details in CIF format are available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was financially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Canada Foundation for Innovation (CFI). The authors wish to thank Ms. Breanne Kamenz for preparing the reagent 2-azidopyrimidine.

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