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Regiocontrol of Cyclometalation in a $P_4Ru(II)$ System. Unusual Base-Induced Metalation within a Chelate Ring versus Activation of a Methyl Group

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Summary: The internally cyclometalated complex (MeSi-$(CH_2PMe_2)_2CHPMe_2)(PMe_3)RuH$ has been prepared by the treatment of $MeSi(CH_2PMe_2)_3PMe_3Ru(H)(Cl)$ with base, and an analogue has been structurally characterized by X-ray diffraction. The externally cyclometalated isomer $MeSi(CH_2PMe_2)_3PMe_2CH_2RuH$ has been cleanly generated by the thermolysis of $MeSi(CH_2PMe_2)_3PMe_3$-Ru(H)(Me), and the two isomers have been contrasted in terms of their spectroscopic features, calculated energies, and relative reactivities toward cresol and H_2. The two isomers are surprisingly resistant to interconversion. A chloride derivative, $(MeSi(CH_2PMe_2)_2CHPMe_2)(PMe_3)$-RuCl, has also been prepared, and its reactivity has shown the internally cyclometalated framework to be surprisingly stable.

Cyclometalation reactions are ubiquitous in the chemistry of reactive transition metal centers[1,2] and can function either as obstacles to the development of catalytic processes[3,4] or as key components within them.[5−8] Intramolecular activation of precoordinated groups can also be employed synthetically in the preparation of various targets including catalysts,[9−12] optical materials,[13] and biological agents.[14] Cyclometalation reactions may be triggered by a variety of events, including ligand dissociation or elimination, group abstraction, and deprotonation,[1,2] but in the vast majority of reported systems these reactions are complementary processes: they convert structurally similar starting materials to a common product. Herein we report evidence that this need not be the case and describe a system in which thermolysis and deprotonation of similar precursors yield two different cyclometalation isomers. Despite the fact that one of them has a novel, unusually strained structure, we find that it is essentially impossible to interconvert them.

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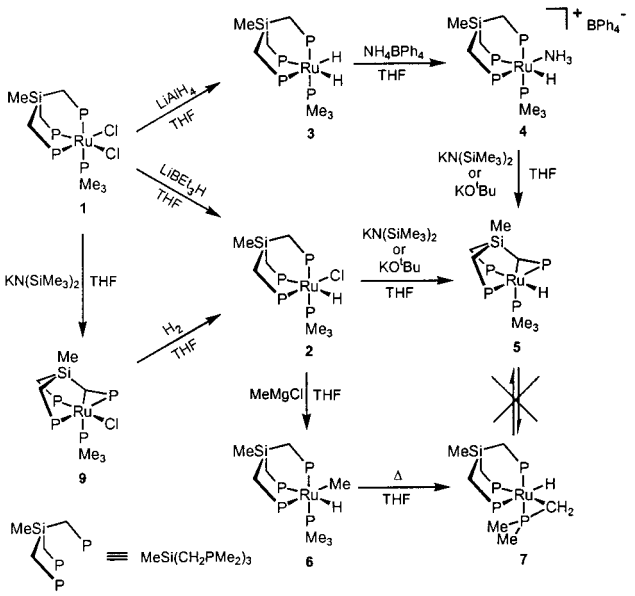
Scheme 1



In the course of efforts to synthesize ruthenium alkoxide and amide complexes bearing a variety of phosphine ligands,[15] we have prepared compounds of the general type $(MeSi(CH_2PMe_2)_3)(PMe_3)Ru(H)(X)$ ($X^- = Cl^-$, $NH_3BPh_4^-$) and found that they undergo cyclometalation upon addition of strong base (Scheme 1). Treatment of the dichloride complex **1** with $LiBEt_3H$ yields the corresponding hydridochloride complex **2** in 36% isolated yield. Alternatively, the dihydride complex **3** can be prepared in 91% yield by treating **1** with $LiAlH_4$, and addition of 1 equiv of NH_4BPh_4 to **3** provides ammonia complex **4** in 83% yield.[16] Treatment of either **4** or chloride **2** with strong base (KO^tBu or $KN(SiMe_3)_2$) does not result in attack on the PMe_3 or NH_3 protons. Instead, the internally cyclometalated complex **5** is formed in >70% isolated yield. No other cyclometalation products are observed in these reactions. The ^1H NMR spectrum of **5** is characterized by a broad singlet at δ −0.96 ppm integrating to one proton (relative to the three-proton Si−Me resonance at δ 0.48 ppm and the Ru−H signal at δ −8.63 ppm) and corresponding to the remaining hydrogen on the ruthenium-bound carbon. The ^{13}C NMR spectrum also features a characteristic upfield resonance at δ −15.0 ppm associated with the corresponding methine carbon.

The solid-state structure of product **5** was confirmed by an X-ray diffraction study of the ^{t}Bu analogue (Figure 1). The molecule possesses a strongly distorted octahedral geometry (P1−Ru1−P2 = 129.25(6)°, P1−Ru1−P4 = 120.25(7)°, P4−Ru1−C1 = 163.4(2)°), but its Ru−P bonds are not substantially elongated relative to those of other complexes bearing the intact ligand set.[17] While the Ru−C bond is long (2.282(6) Å; 2.18(1) Å was observed for a Ru−C bond in a related complex[17]), the Ru−P bond involved in cyclometalation is rather short (2.243(2) Å) and the bonds from the activated carbon to silicon and phosphorus (1.822(6) and 1.766(6) Å, respectively) are 0.05 Å shorter than CH_2−Si and CH_2−P bonds elsewhere in the molecule. This suggests that delocalization may significantly relieve strain and stabilize the molecule.

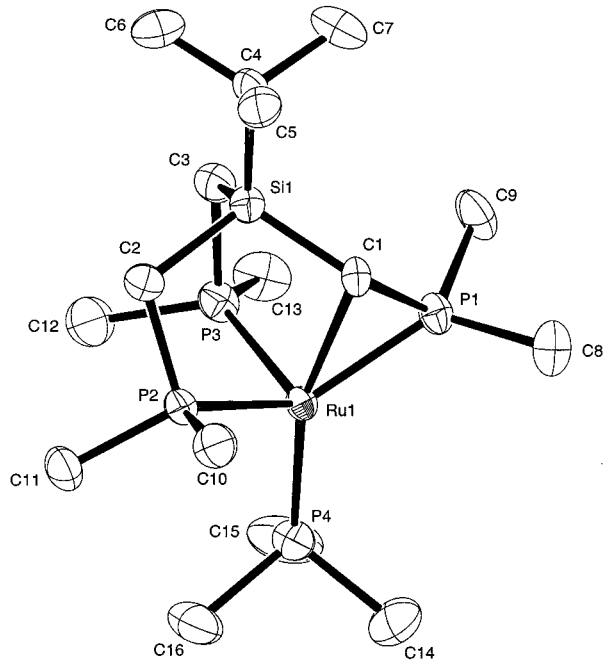


Figure 1. ORTEP diagram of **5-^{t}Bu** (thermal ellipsoids are shown at 50% probability). Hydrogen atoms have been omitted for clarity. Selected bond distances (Å) and angles (deg): Ru1−P1, 2.243(2); Ru1−P2, 2.279(2); Ru1−P3, 2.326(2); Ru1−P4, 2.258(2); Ru1−C1, 2.282(2); P1−C1, 1.766(6), P1−C8, 1.822(7); P2−C2, 1.838(6); Si1−C1, 1.822(6), Si1−C3, 1.880(7); P1−Ru1−P2, 129.25(6); P1−Ru−P3, 93.16(6); P1−Ru−P4, 120.25(7); P2−Ru−P3, 93.66(6); P2−Ru1−P4, 107.93(6); P3−Ru1−P4, 99.69(7); P1−Ru1−C1, 45.9(1); P1−C1−Si1, 130.8(3).

While the synthetic route to complex **5** is well precedented, its actual structure is less so. Deprotonation is an established method of inducing the cyclometalation of aryl groups,[18] and similar reactions involving methyl-substituted phosphines have also been observed.[19−22] There are, however, very few examples of cyclometalation *within* the chelate ring of an alkyl multidentate phosphine ligand. Even activation of any secondary C−H bond is relatively rare: Field has observed cyclometalation involving a methylene unit of an ethyl substituent in the $(DEPE)_2Fe$ system,[23,24] although in a similar *n*-propyl-substituted system no methylene positions are activated.[25] In a related system with an expanded six-membered chelate ring investigated by Karsch, the occurrence of internal cyclometalation was proposed, but the regiochemistry of cyclometalation could not be definitively established.[26] Deprotonation of

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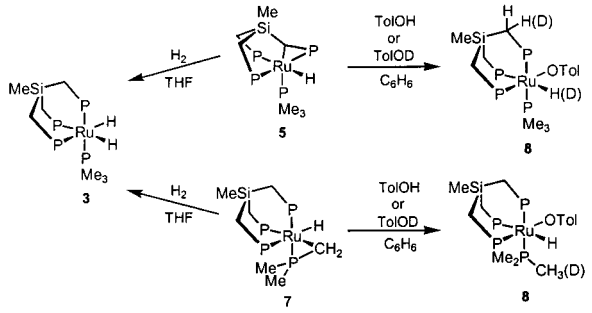
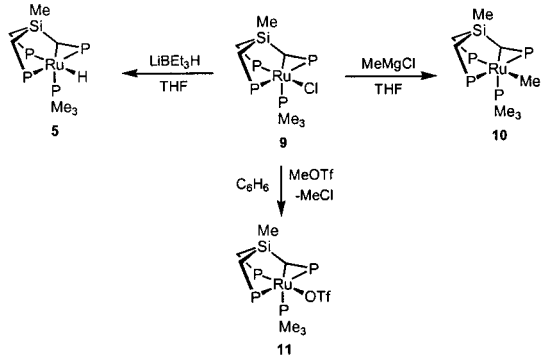
Scheme 2



Scheme 3



methylene-bridged bis-phosphines is well known, and Karsch has observed cyclometalation within a six-membered chelate ring at a methylene group activated by two adjacent phosphorus atoms.[27] As silicon is known to enhance the acidity of adjacent C−H bonds, and base-induced cyclometalation of Si−Me groups is known,[28] it seems likely that the presence of silicon plays a key role in activating precursors **2** and **4** toward deprotonation-induced cyclometalation at the methylene position.

To better understand the unusual regiochemistry of cyclometalation that yields complex **5**, we sought to effect cyclometalation in the $(MeSi(CH_2PMe_2)_3)(PMe_3)$-Ru system in the absence of base. Chloride **2** reacts with MeMgCl to afford the methyl hydride **6**, and thermolysis of this compound at 100 °C for 10 h induces elimination of methane to generate exclusively the externally cyclometalated isomer **7**. This complex has been reported previously,[29,30] but a brief discussion of its characterization is warranted for the purpose of comparison to isomer **5**. The ^{1}H NMR spectrum of complex **7** features two broad signals at δ 0.30 and −0.47 ppm, corresponding to the diastereotopic protons of the ruthenium-bound methylene, and eight phosphorus-bound methyl signals (δ 1.7−1.1 ppm, eight doublets integrating to 3H each) indicating that the PMe_3 ligand (rather than another PMe group) has been activated. Both the ^{31}P and ^{13}C NMR spectra include upfield peaks consistent with cyclometalation at a methyl group, and all of these spectroscopic features are similar to those observed for the known analogue $(PMe_3)_3(PMe_2CH_2)RuH$.[31]

The isomeric nature of products **5** and **7** presents an opportunity to contrast the two modes of cyclometalation represented. The deprotonation product **5** appears much more strained, and DFT calculations (BP86/LACVP**) suggest that it is less stable than **7** by approximately 7 kcal/mol. The two isomers can also be compared in terms of their reactivity. Both complexes react with cresol to yield cresolate complex **8** (Scheme 2). When TolOD is used in this reaction, D incorporation is observed in the PMe_3 group (δ 1.23 ppm) of the product formed from **7** and in both the methylene and hydride positions (δ 0.35 and −6.71 ppm, respectively) of the product **8** derived from complex **5**. A competition experiment showed that cresol reacts much more rapidly with externally cyclometalated complex **7** than with **5**. Both species also undergo addition of H_2 to yield the dihydride **3** (Scheme 2), although in this case the reaction is dramatically slower for externally cyclometalated complex **7** than for isomer **5**.

Perhaps the most striking aspect of the chemistry of the two cyclometalated complexes **5** and **7** is that we have been unable to induce their interconversion by any means. Treatment of either isomer with a catalytic amount of acid, base, buffer, silane, arene, or hydrogen yields no reaction or irreversible conversion to new products, as does the thermolysis or photolysis of either complex. Interconversion via a Ru(0) intermediate would be unlikely in this system due to the inaccessibility of a square-planar coordination geometry[32] (without dechelation), but it is not evident why isomerization through a Ru(IV) complex or Ru(II) cation does not occur.

To further explore the stability of the cyclometalated framework in **5**, we prepared the chloride analogue **9** via the reaction of dichloride **1** with $KN(SiMe_3)_2$ (Scheme 1). The crystalline yellow product was isolated in 84% yield from pentane. This complex reacts with dihydrogen (Scheme 1), affording hydridochloride complex **2** in 95% yield by ^{1}H NMR spectroscopy. The chloride **9** can be treated with $LiBEt_3H$ to yield the hydride analogue **5** or with MeMgCl to afford the methyl analogue **10** (Scheme 3). Perhaps most surprisingly, treatment of **9** with MeOTf does not result in addition across the presumably highly polarized Ru−C bond, but rather anion metathesis to yield ruthenium triflate **11** and MeCl. This further demonstrates the remarkable kinetic stability of the internally cyclometalated complex.

In summary, we have observed that deprotonation of ruthenium complexes bearing tripod $MeSi(CH_2PMe_2)_3$ and a suitable leaving group yields an unusual cyclometalation product bound to ruthenium through a bridging methine rather than a methylene group. In contrast, thermolysis of the corresponding methyl hydride yields exclusively the more conventionally cyclometalated isomer. Although the internal deprotonation product appears strained (and is indeed calculated to be less thermodynamically stable), it is not always more reactive than its isomer and even features a Ru−C bond that is stable to substitution chemistry elsewhere in the

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(30) In the above reference complex **7** was prepared by Na/Hg reduction of the dichloride, but we have found that this procedure also yields a significant amount of complex **5**.

(31) Grotzig, J.; Werner, H.; Werner, R. *J. Organomet. Chem.* **1981**, *209*, c60.

(32) According to DFT calculations, the Ru(0) intermediate resulting from reductive elimination of either cyclometalation product **5** or **7** would be 34 kcal/mol less stable than isomer **5**.

molecule. Most significantly, the two cyclometalated complexes resist interconversion when subjected to heat, light, and a variety of reagents. These results demonstrate that in contrast to the general observation that all routes to cyclometalation in a given system lead to the same product, the specific route by which intramolecular M−C bond formation occurs can play a critical role in determining the structure, and thus subsequent reactivity, of a cyclometalated product.

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Supporting Information Available: Complete details for the synthesis of all compounds, spectroscopic data, and X-ray crystallographic data for **5-^{t}Bu**. This material is available free of charge via the Internet at http://pubs.acs.org.

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