

Published on Web 04/07/2007

## Intermolecular Activation of C–X (X = H, O, F) Bonds by a Ti=C<sup>t</sup>Bu Linkage

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High oxidation state transition metal imide complexes are a wellknown class of systems which can undergo 1,2-CH bond addition of arenes and alkanes across the M=N multiple bond.<sup>1,2</sup> Likewise, early transition metal alkylidenes<sup>3,4</sup> and alkylidynes<sup>5</sup> are also becoming popular reagents for intermolecular 1,2-CH bond addition of both aromatic hydrocarbons and Si(CH<sub>3</sub>)<sub>4</sub>. Despite these functionalities being versatile for the hydrocarbon substrate in question, 1,2-addition reactions across M=X linkages (X = NR or CHR) have been limited almost exclusively to the prototypical carbonhydrogen bonds and, in some cases, to the weaker NH/OH bonds.6 To date, the only example of a hetero-1,2-CX bond addition (X =F) reaction was reported by Bergman and co-workers using NC<sub>5</sub>F<sub>5</sub>.<sup>2</sup> For the latter reaction, they attribute the C-F bond breaking step to be driven by a combination of the inherent reactivity of the pyridine ortho C-F bond as well as formation of a strong Zr-F bond.<sup>2</sup>

In this work, we report that the transient titanium alkylidyne, (PNP)Ti=C'Bu (PNP<sup>-</sup> = N[2-P(CHMe<sub>2</sub>)<sub>2</sub>-4-methylphenyl]<sub>2</sub>),<sup>5</sup> can engage in not only regioselective intermolecular 1,2-addition reactions of aromatic C–H bonds of anisoles but also an unprecedented intermolecular C–O bond cleavage of CH<sub>3</sub>OC<sub>6</sub>F<sub>5</sub>, as well as the C–F bond splitting of fluorocarbons such as C<sub>6</sub>F<sub>6</sub> and CF<sub>3</sub>C<sub>6</sub>F<sub>5</sub>. Consequently, the intermolecular C–O and C–F activation reactions result in formation of novel, disubstituted alkylidene functionalities on titanium and represent the first examples of intermolecular aryl C–O and C–F bond activation advocated by a metal–carbon multiply bonded linkage (in addition to C–H activation).

We recently reported that the transient alkylidyne (PNP)Ti=C-<sup>t</sup>Bu (A) can readily activate the C–H bonds of  $C_6H_6$  or Si(CH<sub>3</sub>)<sub>4</sub>.<sup>5</sup> Not surprisingly, when the synthon to A, (PNP)Ti=CH'Bu(CH<sub>2</sub>-<sup>t</sup>Bu) (1), is dissolved in neat anisole, ortho-aryl C-H bond activation rapidly takes place to quantitatively afford the alkylidene aryl (PNP)Ti=CH'Bu(C<sub>6</sub>H<sub>4</sub>-2-OCH<sub>3</sub>) (2) (Scheme 1).<sup>7</sup> Complex 2 likely forms via the hypothetical intermediate (PNP)Ti $\equiv$ C'Bu(CH<sub>3</sub>OC<sub>6</sub>H<sub>5</sub>), which renders the ortho-hydrogens more susceptible to C-H bond cleavage. Legzdins and co-workers have investigated similar C-H bond activation reactions of anisoles with transient W neopentylidenes and attribute this selectivity to be more thermodynamic rather than kinetic in nature.<sup>4</sup> Regioselective ortho C-H activation, with respect to the aryl fluoride group, occurs when 1 is treated with 2-fluoroanisole to afford (PNP)Ti=CH<sup>/</sup>Bu(C<sub>6</sub>H<sub>3</sub>-2-F-3-OCH<sub>3</sub>) (**3**). Only traces of the regioisomer having C-H bond activation adjacent to the OMe group is observed (<3% by <sup>31</sup>P NMR spectroscopy).<sup>7</sup>

When the two *ortho*-hydrogens in anisole are replaced with fluorines (2,6-difluoroanisole), bond breaking ensues at the more vulnerable meta position to form (PNP)Ti=CH'Bu(C<sub>6</sub>F<sub>2</sub>H<sub>2</sub>OCH<sub>3</sub>) (**4**) (Scheme 1).<sup>7</sup> Therefore, C–H bond activation occurs only ortho to dative groups, which in this case happens to be the fluoride substituent. Interestingly, when 4-fluoroanisole is treated with **1**, the regioisomers (PNP)Ti=CH'Bu(C<sub>6</sub>H<sub>3</sub>-2-F-5-OCH<sub>3</sub>) (**5**) and (PNP)Ti=CH'Bu(C<sub>6</sub>H<sub>3</sub>-5-F-2-OCH<sub>3</sub>) (**6**) (Scheme 1) are observed

Scheme 1. Intermolecular C–H Activation Reactions of Arenes



Scheme 2. Intermolecular C-O and C-F Activation Reactions



spectroscopically in a 3:1 mixture,<sup>7</sup> respectively. This result implies that intermediate **A** is somewhat discriminative for ortho C–H activation next to the fluoride group.<sup>8</sup> Intuitively, the ether group is expected to be a better donor; however, preference for the *ortho*fluoride C–H bond might be the result of steric constraints imposed by the more protected ether linkage. However, incipient negative charge, inflicted by the fluoride, at the ortho-carbon might be playing a crucial role in these types of reactions. Reactions leading to formation of complexes **2**–**6** must be performed in neat reagent given the promiscuity of **1** (or intermediate **A**) to react with any solvent media.<sup>5</sup> Complexes **2**–**6** have been characterized by <sup>1</sup>H, <sup>13</sup>C, <sup>31</sup>P, and in some certain cases <sup>19</sup>F (**3**–**6**) NMR spectroscopy. Regioselectivity, in certain cases, was further scrutinized by singlecrystal X-ray diffraction (XRD) studies (compounds **2** and **4**).<sup>7</sup>

Aryl C–H bonds are not the only linkages amenable to 1,2addition reactions. Hence, C–O bond cleavage occurs when **1** is treated with CH<sub>3</sub>OC<sub>6</sub>F<sub>5</sub>, concurrent with formation of the disubstituted alkylidene complex (PNP)Ti=C['Bu(C<sub>6</sub>F<sub>5</sub>)](OCH<sub>3</sub>) (**7**) in 59% yield (Scheme 2).<sup>7</sup> Complex **7** displays NMR spectroscopic signatures consistent with a Ti–OCH<sub>3</sub> group (<sup>1</sup>H: 3.72 ppm), an alkylidene functionality (<sup>13</sup>C: 310.2 ppm),<sup>9</sup> and one isomer (rotamer). As anticipated, the solid-state structure of **7** is consistent with the *syn* isomer and shows a disubstituted alkylidene carbon (Ti=C, 1.953(2) Å) and a titanium methoxide ligand (Ti–O, 1.789-(7) Å) resulting from C–O bond cleavage by the Ti=C linkage.<sup>7</sup> It is well-known that the C–F linkage in C<sub>6</sub>F<sub>6</sub> has a much higher enthalpic dissociation energy (154 kcal/mol) than the C–H bond



**Figure 1.** Molecular structures of **8**-*syn* and **9**-*syn* depicting thermal ellipsoids at the 50% probability level (right). Hydrogen atoms, solvent molecules, and isopropyl methyls on phosphorus have been omitted for clarity. Selected metrical parameters are reported in the Supporting Information.

in benzene (110 kcal/mol).<sup>10</sup> Despite this, complex 1 transforms (48 h, 50 °C, 78% isolated yield), in neat C<sub>6</sub>F<sub>6</sub>, to a pentafluorophenyl-substituted alkylidene (PNP)Ti= $C[^{t}Bu(C_{6}F_{5})](F)$  (8) (Scheme 2).7 Interestingly, the <sup>13</sup>C NMR (323.5 and 317.0 ppm) and <sup>31</sup>P NMR spectroscopic data for 8 reveal two alkylidene isomers in solution (65/35 ratio).7 XRD analysis of suitable red crystals for 8 only permitted structural elucidation of isomer 8-syn (F and perfluoroaryl groups on the same side). The structure of 8-syn also clearly portrays a novel system bearing both perfluorophenyl and <sup>t</sup>Bu groups on the alkylidene α-C. As anticipated for a disubstituted alkylidene ligand, the Ti=C linkage is long (1.946(2) Å, Figure 1). Fortunately, we found that crystals of the syn rotamer of 8, 8-syn (red crystals), can be physically separated (85/15 ratio of syn/anti isomers) from the reaction mixture (red crystals and orange powder), and thermolysis of such (3 days, 25 °C) results in conversion back to an equilibrium mixture (65/35, vide supra) of the two rotamers 8-syn/8-anti.7 The same equilibrium mixture can also be achieved more rapidly by heating the 85% pure 8-syn at 105 °C for 1 h. Hence, it appears that the anti isomer originates from the syn via an intramolecular rotation mechanism.11

When octafluorotoluene ( $C_6F_5CF_3$ ) is treated with 1, intermolecular aryl C-F activation in the para position ensues to afford  $(PNP)Ti=C[^{t}Bu(C_{6}F_{4}CF_{3})](F)$  (9) as the major and isolable product (Scheme 2).7 Examination of the crude mixture by <sup>19</sup>F NMR spectroscopy reveals at least five C-F activation products to be generated.<sup>7</sup> As observed with  $\mathbf{8}$ , predominately two rotamers are present in solution (13C NMR: 320.6 and 315.7 ppm).7 XRD of one of the isomers of 9 clearly portrays a disubstituted alkylidene system bearing both perfluorophenyl and 'Bu groups (Ti=C: 1.949-(8) Å), as well as a terminal fluoride ligand (Ti-F: 1.829(1) Å). The C<sub>6</sub>F<sub>4</sub>CF<sub>3</sub> group is oriented along the same side of the titanium fluoride ligand, thus rendering this complex the syn isomer (9-syn, Figure 1). The structure of **9**-syn reveals a Ti=C bond length which is significantly longer than monosubstituted alkylidene derivatives bearing the same ancillary ligand.<sup>5</sup> Unlike 8, however, we were able to obtain structural data for the anti rotamer of 9, namely, 9-anti. Accordingly, XRD of 9-anti exposes the other alkylidene rotamer having the perfluoroaryl group oriented opposite from the metal fluoride ligand.<sup>7</sup> The Ti=C linkage is comparable to the syn rotamer (1.951(7) Å), which is also reflected by similar  $Ar_F-C-$ <sup>t</sup>Bu angles (116.0(4)° for **9-syn**; 114.4(4)° for **9-anti**). In fact, for structures 7, 8-syn, 9-syn, and 9-anti, the plane defined by the disubstituted alkylidene ligand bisects the PNP framework.7

On the basis of previous studies,<sup>5</sup> we propose that complexes 7-9 are likely formed via 1,2-CO and -CF bond addition across the transient Ti=C'Bu bond. However, as observed in the ring-

opening metathesis of pyridines with  $\mathbf{A}$ ,<sup>12</sup> [2 + 2] cycloaddition could refute our original proposed mechanism and facilitate the formation of a strong Ti–X bond through a  $\beta$ -X elimination pathway (X = OMe, F).

In conclusion, our results present a mild process by which strong C-X bonds can be activated by a highly polarized Ti=C linkage. The ability of intermediates such as (PNP)Ti=C'Bu to intermolecularly cleave aryl C-O and C-F bonds offers an excellent opportunity to not only construct potentially important Wittig-type reagents but also study a novel mechanism surrounding the cleavage of strong C-heteroatom linkages. Given the heterogeneous nature of these reactions, we are currently exploring the mechanism behind the formation of compounds such as 7-9 using high-level DFT studies.

Acknowledgment. We thank Indiana University—Bloomington, the Dreyfus Foundation, the Sloan Foundation, and the NSF (CHE-0348941, PECASE award to D.J.M.) for financial support of this research.

**Supporting Information Available:** Experimental preparation and reactivity (all compounds), crystallographic data (2, 4, 7–9), and additional discussion. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA0684646