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Intermolecular Activation of C−X (X = H, O, F) Bonds by a Ti≡C^{t}Bu Linkage

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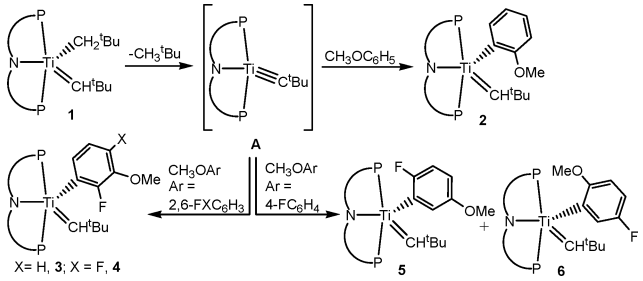
High oxidation state transition metal imide complexes are a well-known class of systems which can undergo 1,2-CH bond addition of arenes and alkanes across the M═N multiple bond.[1,2] Likewise, early transition metal alkylidenes[3,4] and alkylidynes[5] are also becoming popular reagents for intermolecular 1,2-CH bond addition of both aromatic hydrocarbons and $Si(CH_3)_4$. 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 carbon−hydrogen 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_5F_5.[2] 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.[2]

In this work, we report that the transient titanium alkylidyne, (PNP)Ti≡C^{t}Bu (PNP$^-$ = N[2-P(CHMe$_2$)$_2$-4-methylphenyl]$_2$),[5] 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 $CH_3OC_6F_5$, as well as the C−F bond splitting of fluorocarbons such as C_6F_6 and $CF_3C_6F_5$. 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).

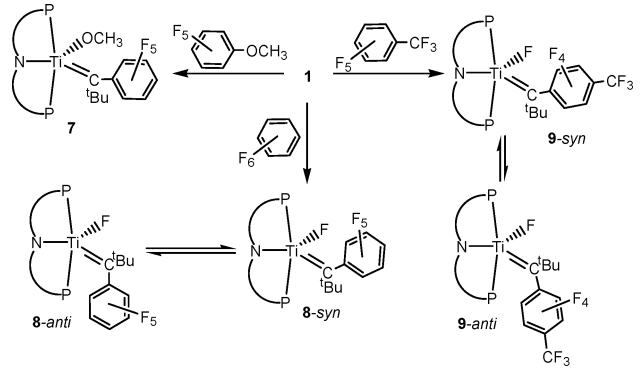
We recently reported that the transient alkylidyne (PNP)Ti≡C-^{t}Bu (**A**) can readily activate the C−H bonds of C_6H_6 or $Si(CH_3)_4$.[5] Not surprisingly, when the synthon to **A**, (PNP)Ti═CH^{t}Bu(CH$_2$-^{t}Bu) (**1**), is dissolved in neat anisole, *ortho*-aryl C−H bond activation rapidly takes place to quantitatively afford the alkylidene aryl (PNP)Ti═CH^{t}Bu(C_6H_4-2-OCH_3) (**2**) (Scheme 1).[7] Complex **2** likely forms via the hypothetical intermediate (PNP)Ti≡C^{t}Bu($CH_3OC_6H_5$), 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.[4] 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^{t}Bu(C_6H_3-2-F-3-OCH_3) (**3**). Only traces of the regioisomer having C−H bond activation adjacent to the OMe group is observed (<3% by ^{31}P NMR spectroscopy).[7]

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^{t}Bu($C_6F_2H_2OCH_3$) (**4**) (Scheme 1).[7] 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^{t}Bu(C_6H_3-2-F-5-OCH_3) (**5**) and (PNP)Ti═CH^{t}Bu(C_6H_3-5-F-2-OCH_3) (**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,[7] respectively. This result implies that intermediate **A** is somewhat discriminative for ortho C−H activation next to the fluoride group.[8] 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.[5] Complexes **2**−**6** have been characterized by ^{1}H, ^{13}C, ^{31}P, and in some certain cases ^{19}F (**3**−**6**) NMR spectroscopy. Regioselectivity, in certain cases, was further scrutinized by single-crystal X-ray diffraction (XRD) studies (compounds **2** and **4**).[7]

Aryl C−H bonds are not the only linkages amenable to 1,2-addition reactions. Hence, C−O bond cleavage occurs when **1** is treated with $CH_3OC_6F_5$, concurrent with formation of the disubstituted alkylidene complex (PNP)Ti═C[^{t}Bu(C_6F_5)](OCH_3) (**7**) in 59% yield (Scheme 2).[7] Complex **7** displays NMR spectroscopic signatures consistent with a Ti−OCH_3 group (^{1}H: 3.72 ppm), an alkylidene functionality (^{13}C: 310.2 ppm),[9] 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.[7]

It is well-known that the C−F linkage in C_6F_6 has a much higher enthalpic dissociation energy (154 kcal/mol) than the C−H bond

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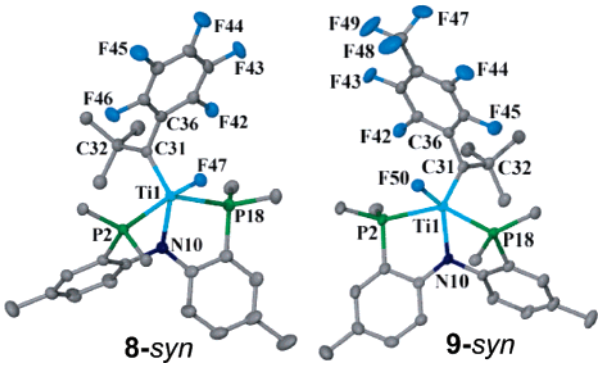

Figure 1. Molecular structures of **8-*syn*** and **9-*syn*** depicting thermal ellipsoids at the 50% probability level (right). Hydrogen atoms, solvent molecules, and isopropyl methyls on phosphorus have been omitted for clarity. Selected metrical parameters are reported in the Supporting Information.

in benzene (110 kcal/mol).[10] Despite this, complex **1** transforms (48 h, 50 °C, 78% isolated yield), in neat C_6F_6, to a pentafluorophenyl-substituted alkylidene (PNP)Ti=C[^{t}Bu(C_6F_5)](F) (**8**) (Scheme 2).[7] Interestingly, the ^{13}C NMR (323.5 and 317.0 ppm) and ^{31}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 ^{t}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($C_6F_4CF_3$)](F) (**9**) as the major and isolable product (Scheme 2).[7] Examination of the crude mixture by ^{19}F NMR spectroscopy reveals at least five C−F activation products to be generated.[7] As observed with **8**, predominately two rotamers are present in solution (^{13}C 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 ^{t}Bu groups (Ti=C: 1.949(8) Å), as well as a terminal fluoride ligand (Ti−F: 1.829(1) Å). The $C_6F_4CF_3$ 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.[5] 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.[7] The Ti=C linkage is comparable to the *syn* rotamer (1.951(7) Å), which is also reflected by similar Ar_F−C−^{t}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,[5] we propose that complexes **7**−**9** are likely formed via 1,2-CO and -CF bond addition across the transient Ti≡C^{t}Bu bond. However, as observed in the ring-opening metathesis of pyridines with **A**,[12] [2 + 2] cycloaddition could refute our original proposed mechanism and facilitate the formation of a strong Ti−X bond through a β-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^{t}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.

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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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