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Dis-assembly of a Benzylic CF_3 Group Mediated by a Niobium(III) Imido Complex

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Supporting Information

ABSTRACT: All three C−F bonds in CF_3-substituted arenes are activated by a niobium imido complex, driven by the formation of strong Nb−F bonds. The mechanism of this transformation was studied by NMR spectroscopy, which revealed the involvement of Nb(III). Attempts to extend this chemistry to nonaromatic CF_3 groups led to intramolecular reactivity.

The thermodynamic stability of C−F bonds [bond dissociation energy (BDE) = 110−130 kcal mol^{-1}], combined with their inherent kinetic inertness, has allowed for many technical applications of fluorocarbons in medicinal chemistry as well as the synthesis of resistant polymers.[1−3] However, such strong bonding is also troublesome in view of the fact that these chemically inert compounds are persistent in the environment.[4,5] Therefore, in recent years, synthetic methods for the activation and functionalization of C−F bonds have attracted growing attention.[1,2,5−16] With increasing degree of fluorination at carbon, the C−F bond strength increases and the C−F bond length decreases, resulting in substantial steric shielding of the carbon site.[2] Because of this increased stability, fluorine abstraction from a CF_3 moiety is difficult and rare.[6,9,11,17−20]

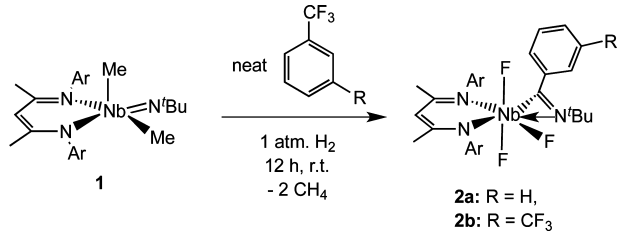
An even more challenging transformation is the functionalization of CF_3 groups via triple C−F activation. Recently, significant progress has been made in regard to reduction of the CF_3 group, leading to hydrodefluorination[16,21−24] and C−C coupling.[21,25] Interestingly, Ar−CF_3 reduction has been achieved with low-valent niobium Nb(0) generated in situ from $NbCl_5$.[19] However, to our knowledge, a reaction in which all three fluorine atoms of an organic CF_3 group, as well as the carbon fragment initially bound to them, are directly transferred to a single metal center has not been reported.

In our effort to develop new semihydrogenation catalysts,[26] we reported the efficiency of a trivalent niobium complex in selective semihydrogenation of alkynes.[27] The active catalyst in the mechanism, a transient tricoordinated "[BDI]Nb=N^{t}Bu" (BDI = 2,6-diisopropylbenzene-β-diketiminate), was trapped as an η^6-bound arene in the absence of CO. We then showed that this η^6-bound arene complex can be formed via hydrogenolysis of the niobium complex {[BDI]Nb(N^{t}BuN)$(CH_3)_2$} (**1**) in neat benzene or toluene.[28] These mono-η^6-bound arene species were found to undergo two-electron reduction chemistry and to form the corresponding bimetallic arene-bridged complexes via a dissociative mechanism.[28]

To probe the behavior of these mono- and bimetallic arene complexes further, the hydrogenolysis of complex **1** in fluorinated solvents was studied. This unexpectedly led to a new type of functionalization of a CF_3 group in which all three fluorines were transferred to the Nb center and a new C−N bond was formed between the remaining organic fragment and the *tert*-butylimido ligand.

The Hydrogenolysis of **1** in neat α,α,α-trifluoromethylarene proceeds as shown in Scheme 1.

Scheme 1. Hydrogenolysis of Complex 1 in Fluorinated Arene Solvents



As previously observed with benzene or toluene as the solvent, in $PhCF_3$ the solution quickly changed color from pale yellow to deep red upon H_2 addition at room temperature; after a few hours, the solution lightened to an orange-brown color. Evaporation of the solvent under reduced pressure followed by extraction and crystallization from Et_2O afforded orange blocks of complex **2a** in good yield (87%). Surprisingly, the ^{1}H NMR spectrum of **2a** in mesitylene-d_{12} did not show the expected characteristic resonances of a mono- or bimetallic arene-bound complex at 2−4 ppm. Additionally, ^{19}F NMR analysis revealed two broad downfield resonances in a 2:1 ratio (+162.4 and +92.2 ppm, respectively). Lowering the temperature to 243 K led to a sharpening of the two resonances and better resolution, allowing a doublet at 159.4 ppm [$^2J_{F-F}$ = 45(2) Hz] and a poorly resolved triplet at 85.1 ppm [$^2J_{F-F}$ = 48(5) Hz] to be observed. Despite the short relaxation time of these ^{19}F resonances (T_1 = 0.8−1.1 ms), ^{19}F−^{19}F nuclear Overhauser effect spectroscopy (NOESY) data obtained at both room and low temperature showed a correlation between the two sets of resonances. These data strongly indicated the formation of a niobium trifluoride complex rather than a $PhCF_3$-bound complex.

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Crystallographic analysis of **2a** confirmed the above conclusion, revealing the presence of a diketiminate niobium (V) trifluoride complex bearing an η^2-bound imine, {[BDI]-NbF_3(^{t}BuN=CC_6H_5)}, having a distorted capped-octahedral geometry with the three fluorines in the basal plane (Figure 1).

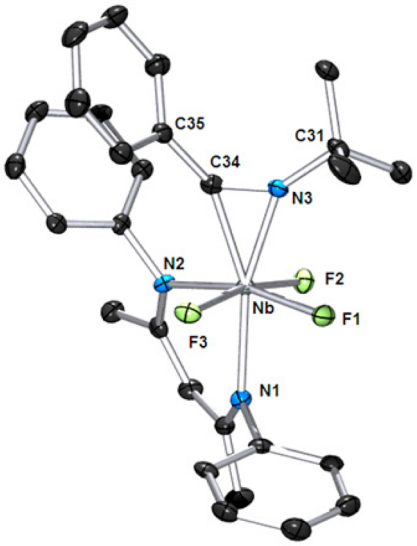


Figure 1. ORTEP diagram of complex **2a**. H atoms and iPr groups have been removed for clarity. Selected bond distances and angles are presented in Table S.2 in the SI.

The two trans fluorines show similar Nb−F distances [av 1.9095(16) Å]; the remaining fluorine is trans to one of the BDI nitrogens ligand, resulting in a slightly longer Nb−F distance [1.9386(16) Å]. One of the apical positions is occupied by the moiety formed by coupling between the imido group and the benzylic carbon of the $PhCF_3$ reactant. The C34−N1 bond distance of 1.261(4) Å suggests the presence of a C=N bond and therefore an imine fragment. The Nb−C and Nb−N bond distances to the imine moiety [Nb−C34 = 2.170(3) Å and Nb−N3 = 2.080(3) Å] are within the range of previously observed Nb−C_{alkyl} and Nb−N_{donor} bond lengths[29,30] and are consistent with the view shown in Scheme 1. The large angles observed within the imine moiety [C35−C34−N3 = 131.1(3)° and C34−N3−C31 = 137.5(3)°] imply sp^2 hybridization of both C1 and N3, further supporting the above description.

Conducting a similar experiment using 1,3-bis-(trifluoromethyl)benzene afforded dark-yellow crystals of **2b** in very good yield (91%). Both the NMR and X-ray diffraction analyses were analogous to those of complex **2a**, showing the formation of {[BDI]NbF_3(^{t}BuN=$CC_6H_4CF_3$)} [Figure S.2 in the Supporting Information (SI)]. The ^{19}F resonance of the remaining CF_3 group was found as a sharp singlet at −61.6 ppm. This result provides a second example of selective disassembly of one CF_3 moiety and supports an intramolecular activation mode.

Attempts to extend this transformation to nonaromatic CF_3 groups were made by performing the hydrogenolysis of **1** in neat 1,1,1-trifluoro-*n*-hexane or CH_3CF_3 dissolved in *n*-hexane. However, the reactivity observed was completely different from that seen with the aromatic CF_3 groups and led to the isolation of two products (Scheme 2). Upon H_2 addition, the solution of **1** quickly turned red, with the formation of a purple precipitate. After 12 h, evaporation of the solvent under reduced pressure deposited a purple/red powder. The red material was extracted and crystallized from hexane, affording red crystals of complex **3** in 52% yield. The remaining purple powder was extracted with and crystallized from tetrahydrofuran, forming dark-purple crystals of complex **4** in low yield (21%). A control experiment in which the hydrogenolysis of complex **1** was performed in hexane alone afforded the same product distribution. ORTEP views of **3** and **4** are presented in Figure 2.

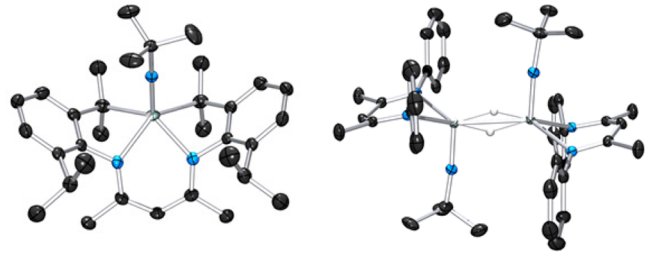
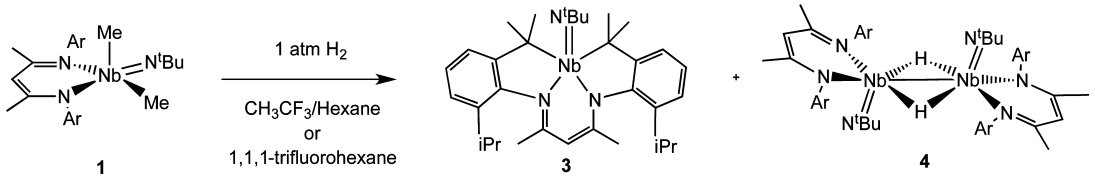


Figure 2. ORTEP diagrams of complexes **3** (left) and **4** (right). H atoms in both complexes and the iPr groups in **4** have been removed for clarity. Selected bond distances and angles are presented in Table S.3.

Complex **3** exhibits a pseudo-square-pyramidal geometry in which the BDI group has been transformed into a κ^4-*CNNC* ligand via activation of the two isopropylmethines. The Nb−C bond distances are on average 2.260(3) Å, which is within the range of previously reported Nb(V)−C bond lengths.[29] Complex **4**, on the other hand, was found to be a diamagnetic dihydride-bridged complex, with the hydride resonance observed as a broad singlet at −1.35 ppm in the ^{1}H NMR spectrum. The hydrides, which were located in the Fourier difference map and refined isotropically, display a Nb−H distance of 1.92(2) Å. The dimer possesses a center of inversion about a central {$Nb_2(\mu$-H)$_2$} core. The short Nb−Nb bond distance of 2.7846(4) Å supports metal−metal bonding and accounts for the observed diamagnetism of **4**.[31]

The reactivity observed in nonaromatic solvent suggested that (i) only benzylic CF_3 groups are activated by this system, (ii) arene coordination to Nb may be a key requirement for C−F activation, and (iii) high-valent niobium hydrides may be involved as intermediates during the hydrogenolysis. To investigate these hypotheses, the hydrogenolysis of **1** in the

Scheme 2. Hydrogenolysis of Complex 1 in Nonaromatic Fluorinated Solvents



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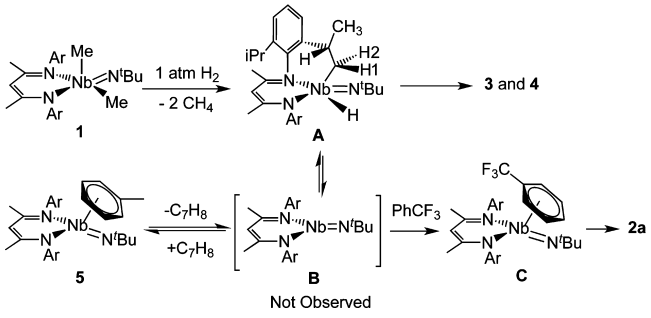
presence and absence of $PhCF_3$ was followed by ^1H and ^{19}F NMR spectroscopies. Since both benzene and toluene are known to compete strongly in arene coordination[28] and the use of neat $PhCF_3$ could interfere with the observation of intermediates, sterically hindered mesitylene-d_{12} was used as an NMR solvent.

First, hydrogenolysis of **1** alone resulted in the fast formation of **3** and **4**, implying that despite its aromatic character, mesitylene-d_{12} is too poor a π-acidic ligand to form a persistent arene-bound complex. Following the reaction by ^1H NMR spectroscopy showed the rapid formation and disappearance of an intermediate complex, **A**, for which a broad resonance at 9.2 ppm is consistent with the presence of a Nb−H bond.[32] To gain further structural insight, soon after H_2 addition the sample was placed in a spectrometer cooled to 243 K. The persistence of **A** at low temperature allowed for its characterization by NMR spectroscopy (see the SI). A DEPT-135 NMR experiment showed the presence of one CH_2 group, consistent with the formation of a metallacylic niobium hydride (complex **A** in Scheme 3).[32]

Scheme 3. Intermediates Observed by NMR Spectroscopies



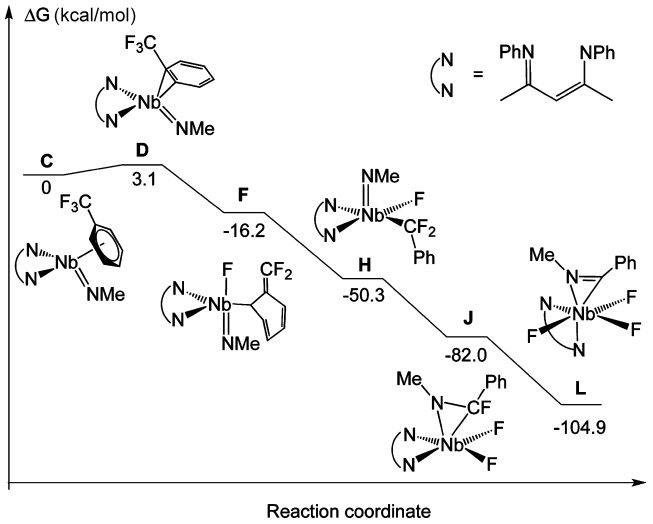
In an HSQC NMR experiment, the CH_2 carbon was found to bear two inequivalent protons. Additionally, a COSY NMR experiment showed that one of the methylene protons, H1, is weakly correlated to the niobium hydride only, while the other methylene proton, H2, is correlated to the methine proton. Finally, the NOESY NMR spectrum revealed that the methine proton is strongly correlated to H1 and the CH_3 group but only weakly to H2. These 2D NMR experiments further supported the assignment of **A** and also confirmed its stereochemistry, in which the hydride and the methine proton are cis to one another. When performed under an atmosphere of D_2, the hydrogenolysis of **1** in hexane formed **3** and **4** in which deuterium incorporation was observed at all positions of the isopropyl group. Such scrambling suggests a fast equilibrium between **A** and the transient "[BDI]Nb=N^{t}Bu" species **B** (Scheme 3) and/or successive σ-bond metathesis of **A**.

A similar experiment was then performed in the presence of 10 equiv of $PhCF_3$, and the same hydride intermediate **A** was observed at low conversion along with a new complex **C**. After 10 min at room temperature, a significant amount of **C** was formed; cooling the sample to 243 K allowed us to perform its complete NMR characterization. The structure of **C** is consistent with a complex containing an η^6-bound $PhCF_3$, in which the arene protons resonate between 4 and 3 ppm in a 2:3 ratio. Meanwhile, a new singlet in the ^{19}F NMR spectrum appears at −62.4 ppm, which is slightly upfield from that of free $PhCF_3$ (−61.4 ppm; see the SI). When the solution was allowed to warm to room temperature, **C** was quickly converted to the final product **2a**. Additionally, the formation of **2a** and intermediate **C** was observed when the niobium complex **5** was stirred with 10 equiv of $PhCF_3$ in C_9D_{12} at room temperature (Scheme 3 bottom).

Taken together, these experiments suggest that hydrogenolysis proceeds via intermediate **A**, which is in equilibrium with the transient tricoordinate Nb(III) species **B** as illustrated in Scheme 3. In the absence of trapping ligands, **A** reacts further to form **3** and **4**, whereas a π-acidic ligand such as $PhCF_3$ traps the low-valent species **B**, yielding d^2 arene intermediate **C**. This intermediate then reacts further to activate the CF_3 moiety.

While **C** was found experimentally to be a key intermediate in the triple C−F activation of $PhCF_3$, the mechanism of its conversion to the final product **2a** remained unclear. To address this, we turned to density functional theory (DFT) calculations for additional mechanistic information. These preliminary calculations showed the presence of a very exergonic overall stepwise C−F activation ($\Delta G_{C\rightarrow 2a}$ = −104.9 kcal mol^{-1}), consistent with the formation of strong Nb−F bonds (BDE_{Nb-F} = 137 kcal mol^{-1}).[33] Additionally, no concerted transition state consistent with an oxidative addition was found for the first C−F activation. Instead, the DFT calculations suggested a two-step process: an initial fluorine abstraction leading to sp^2 hybridization at the benzylic carbon (i.e., formation of a coordinated Ph=CF_2 group) with a Nb−C_{alkyl} bond (intermediate **F**) followed by a 1,3-shift (Scheme 4).

Scheme 4. Calculated Intermediates Involved in $PhCF_3$ Disassembly (Free Energies and Structures of Transition States Are Presented in Figure S.20)



Fluorine abstraction in the absence of arene coordination was found to be almost 10 kcal mol^{-1} higher in free energy (see the SI). Finally, the two remaining C−F bonds appear to be activated stepwise. In each step, C−F bond cleavage and nitrene transfer to the benzylic carbon take place in a concerted manner (Scheme 4).

To conclude, the selective dis-assembly of a benzylic CF_3 moiety has been observed in which three fluorine atoms and the resulting carbene fragment are transferred to a single Nb center, with concurrent formation of a new C−N bond. Evidence points to the formation of an η^6-arene-bound niobium complex as a key intermediate in this process. The involvement of arene coordination is apparently essential to stabilize the

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rate-determining transition state, since other saturated fluorinated substrates led to intramolecular attack upon other ligands. DFT calculations suggested that the d^2 species **C** undergoes stepwise C−F activation to yield the final d^0 niobium trifluoride/η^2-bound imine product.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures; analytical data; NMR spectra of intermediates **A** and **C**; crystallographic data and CIFs for complexes **2a**, **2b**, **3**, and **4**; and DFT calculation methods and results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Osterberg, C.; Richmond, T. G.; Kiplinger, J. L. *Chem. Rev.* **1994**, *94*, 373.
(2) Burdeniuc, J.; Jedicka, B.; Crabtree, R. H. *Chem. Ber.* **1997**, *130*, 145.
(3) Richmond, T. In *Activation of Unreactive Bonds and Organic Synthesis*; Murai, S., Ed.; Springer: Berlin, 1999; pp 243−269.
(4) Shine, K. P.; Sturges, W. T. *Science* **2007**, *315*, 1804.
(5) Amii, H.; Uneyama, K. *Chem. Rev.* **2009**, *109*, 2119.
(6) Uneyama, K.; Amii, H. *J. Fluorine Chem.* **2002**, *114*, 127.
(7) Torrens, H. *Coord. Chem. Rev.* **2005**, *249*, 1957.
(8) Clot, E.; Eisenstein, O.; Jasim, N.; Macgregor, S. A.; McGrady, J. E.; Perutz, R. N. *Acc. Chem. Res.* **2011**, *44*, 333.
(9) Braun, T.; Wehmeier, F. *Eur. J. Inorg. Chem.* **2011**, 613.
(10) Jones, W. D. *Dalton Trans.* **2003**, 3991.
(11) Klahn, M.; Rosenthal, U. *Organometallics* **2012**, *31*, 1235.
(12) Nova, A.; Mas-Ballesté, R.; Lledós, A. *Organometallics* **2012**, *31*, 1245.
(13) Yow, S.; Gates, S. J.; White, A. J. P.; Crimmin, M. R. *Angew. Chem., Int. Ed.* **2012**, *51*, 12559.
(14) Lv, H.; Cai, Y.-B.; Zhang, J.-L. *Angew. Chem., Int. Ed.* **2013**, *52*, 3203.
(15) Yang, X.; Sun, H.; Zhang, S.; Li, X. *J. Organomet. Chem.* **2013**, *723*, 36.
(16) Kuehnel, M. F.; Holstein, P.; Kliche, M.; Krüger, J.; Matthies, S.; Nitsch, D.; Schutt, J.; Sparenberg, M.; Lentz, D. *Chem.—Eur. J.* **2012**, *18*, 10701.
(17) Lentz, D. *J. Fluorine Chem.* **2004**, *125*, 853.
(18) Barrett, A. G. M.; Crimmin, M. R.; Hill, M. S.; Hitchcock, P. B.; Procopiou, P. A. *Angew. Chem., Int. Ed.* **2007**, *46*, 6339.
(19) Driver, T. G. *Angew. Chem., Int. Ed.* **2009**, *48*, 7974.
(20) Azhakar, R.; Roesky, H. W.; Wolf, H.; Stalke, D. *Chem. Commun.* **2013**, *49*, 1841.
(21) Fuchibe, K.; Akiyama, T. *J. Am. Chem. Soc.* **2006**, *128*, 1434.
(22) Douvris, C.; Ozerov, O. V. *Science* **2008**, *321*, 1188.
(23) Douvris, C.; Nagaraja, C. M.; Chen, C.-H.; Foxman, B. M.; Ozerov, O. V. *J. Am. Chem. Soc.* **2010**, *132*, 4946.
(24) Janjetovic, M.; Träff, A. M.; Ankner, T.; Wettergren, J.; Hilmersson, G. *Chem. Commun.* **2013**, *49*, 1826.
(25) Fuchibe, K.; Mitomi, K.; Suzuki, R.; Akiyama, T. *Chem.—Asian J.* **2008**, *3*, 261.
(26) La Pierre, H. S.; Arnold, J.; Toste, F. D. *Angew. Chem., Int. Ed.* **2011**, *50*, 3900.
(27) Gianetti, T. L.; Tomson, N. C.; Arnold, J.; Bergman, R. G. *J. Am. Chem. Soc.* **2011**, *133*, 14904.
(28) Gianetti, T. L.; Nocton, G.; Minasian, S. G.; Tomson, N. C.; Kilcoyne, A. L. D.; Kozimor, S. A.; Shuh, D. K.; Tyliszczak, T.; Bergman, R. G.; Arnold, J. *J. Am. Chem. Soc.* **2013**, *135*, 3224.
(29) Tomson, N. C.; Arnold, J.; Bergman, R. G. *Organometallics* **2010**, *29*, 2926.
(30) Tomson, N. C.; Arnold, J.; Bergman, R. G. *Organometallics* **2010**, *29*, 5010.
(31) Akagi, F.; Matsuo, T.; Kawaguchi, H. *Angew. Chem., Int. Ed.* **2007**, *46*, 8778.
(32) Figueroa, J. S.; Piro, N. A.; Mindiola, D. J.; Fickes, M. G.; Cummins, C. C. *Organometallics* **2010**, *29*, 5215.
(33) Drobot, D. V.; Pisarev, E. A. *Russ. J. Inorg. Chem.* **1981**, *26*, 1.