Organometallic Chemistry

Deutsche Ausgabe: DOI: 10.1002/ange.201607899
Internationale Ausgabe: DOI: 10.1002/anie.201607899

Carbon–Nitrogen Bond Cleavage by a Thorium-NHC-bpy Complex

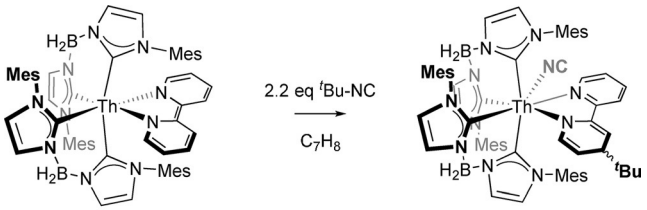
Mary E. Garner, Stephan Hohloch, Laurent Maron, and John Arnold**

Abstract: *Actinide complexes demonstrate unparalleled reactivity towards small molecules. However, utilizing these powerful transformations in a predictable and deliberate manner remains challenging. Therefore, developing actinide systems that not only perform noteworthy chemistry but also demonstrate controllable reactivity is a key goal. We describe a bis(NHC)borate thorium-bpy complex (**1**) that is capable of reductively cleaving the R–NC bond in a series of organic isocyanides. In contrast to most actinide-mediated bond activations, the dealkylation event mediated by **1** is remarkably general and yields very well-defined products that assist in mechanistic elucidation. Synthesis of the rearranged but-3-enyl product from the reaction of **1** and cyclopropylmethyl isocyanide supports the notion of a radical-based mechanism.*

Organometallic chemistry of the actinide elements has blossomed over the past decade.[1–3] The rich reaction chemistry of thorium has been most developed in metallocene-supported systems, outside of which relatively few alternative supporting ligand frameworks have been explored. Our interest in utilizing new ligand platforms[4–6] recently led to the discovery of a useful bis(NHC)borate motif that stabilizes reactive thorium compounds.[7] Upon also incorporating a redox-active bipyridine ligand into the coordination sphere, the NHC-thorium-bpy complex (**1**) was found to engage in a range of chemical transformations and support an unusual open-shell singlet electronic structure ($f^1\pi^{*1}$). Preliminary reactivity studies with organic azides and carbonyls established its redox non-innocence.[7]

To probe the effect of the unique electronic structure of **1** in single- and multi-electron transformations, we turned our attention to organic isocyanides. It has been shown that highly reducing metals (e.g., Sm^{II} and alkali metals) promote C–N bond cleavage in isocyanides, presumably through one-electron processes.[8–10] However, the very negative reduction potentials of the $Th^{IV/III}$ and Th^{III}/Th^{II} couples[11–13] often prohibit this type of reductive behavior by thorium compounds. Therefore, all previous reports discussing the interaction of isocyanides and thorium complexes have described conventional redox-innocent ($2e^-$ donor or insertion) reactivity.[14,15] In this work, we utilize the redox non-innocence of **1** to expose an additional facet of thorium-bpy mediated reactivity and report the first examples of reductive R–NC bond cleavage by a thorium complex.

Treatment of **1** with tert-butyl isocyanide results in reductive bond cleavage of the R–NC single bond, new $C(sp^3)$–$C(sp^3)$ bond formation between the tert-butyl fragment and the bpy ligand, and a terminally bound dealkylated isocyanide ligand (Scheme 1).



1 **2**

Scheme 1. Reaction of **1** with tert-butyl isocyanide to generate **2**.

Evidence for this unusually bound dealkylated isocyanide ligand is provided first by infrared spectroscopy. Dealkylation of an isocyanide dramatically alters the electronic environment within the CN moiety.[16,17] Indeed, comparing the strong ν_{CN} stretch of **2** (2046 cm^{-1}) to that of free tert-butyl isocyanide (2125 cm^{-1}) reveals a 79 cm^{-1} shift to lower energy.

Single-crystal X-ray diffraction studies support an N binding mode for the dealkylated isocyanide and a Th1–N11 bond length of 2.494(5) Å (Figure 1). This rare N-terminus binding mode has been seen for other f-block elements[18–20] and is rationalized by a combination of density functional theory

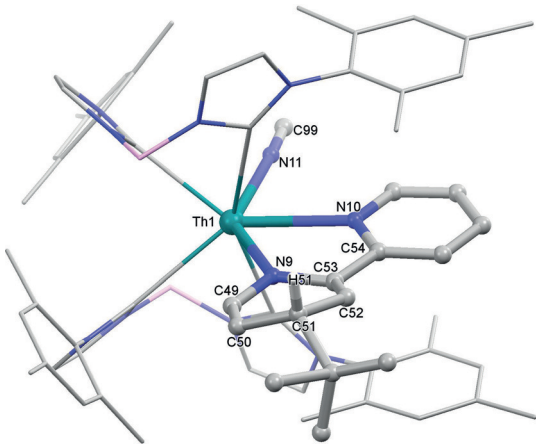


Figure 1. A ball and stick representation of **2**. Hydrogen atoms are omitted and the bis(NHC)borate ligands deemphasized for clarity.

[*] M. E. Garner, Dr. S. Hohloch, Prof. Dr. J. Arnold
Department of Chemistry, University of California, Berkeley
Berkeley, CA 94720 (USA)
E-mail: arnold@berkeley.edu
Prof. Dr. L. Maron
LPCNO, Université de Toulouse
135 Avenue de Rangueil, 31077 Toulouse (France)
E-mail: laurent.maron@irsamc.ups-tlse.fr

Supporting information and the ORCID identification number(s) for the author(s) of this article can be found under http://dx.doi.org/10.1002/anie.201607899.

(DFT), X-ray crystallography, and hard soft acid base theory (HSAB). Accordingly, DFT calculations performed on **2** agree with the experimentally determined solid-state structure, showing that the N-bound isocyanide product is 5.6 kcal mol^{-1} more stable than a C-bound cyanide complex (see the Supporting Information). Additionally, refinement of the X-ray diffraction data of **2** as a hypothetical C-bound cyanide complex yields an ORTEP diagram with irregularly sized and shaped thermal ellipsoids within the CN moiety (Figure S27). In contrast, refinement as an N-bound isocyanide complex yields well-behaved thermal ellipsoids.

Furthermore, X-ray diffraction studies reveal that the newly substituted bpy ligand is asymmetrically bound to the thorium center as a result of the coupling event. One of the bpy rings is re-aromatized and datively bound to the metal center with a Th1–N10 bond length of 2.669(4) Å, while the other ring is formally monoanionic, with a Th1–N9 bond length of 2.394(4) Å. Notably, the substituted ring resembles a 1,4-dihydropyridine-type structure (Figure 2) comprised of localized single and double bonds.

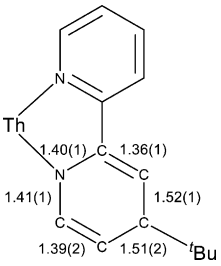


Figure 2. A representation of the 1,4-dihydropyridine structure of the substituted bpy ligand in **2**.

To date, thorium complexes are only known to form simple adducts or insertion products when treated with isocyanides.[15,20] Although this work is the first example of thorium-mediated reductive cleavage of an R–NC bond, the bond activation by **1** advances that seen previously in transition metals and lanthanides.[8,9,21,22] Evans[9] and Schulten[10] introduced Sm^{II}-mediated R–NC bond cleavage and concluded that single-electron chemistry was probable in the formation of Sm–(CN) derivatives. Our system goes beyond that, demonstrating that the open-shell singlet ($f^1\pi^{*1}$) electronic structure of **1** promotes clean R–NC bond scission chemistry and furnishes a very well-defined product in which both fragments of the cleaved isocyanide are retained.

Notably, this bond-cleavage reactivity is not limited to tert-butyl isocyanide. Complex **1** also reductively cleaves the R–NC bond in benzylic, 1°, and 2° alkyl isocyanides (Figure 3). However, despite forcing conditions (72 h, 90 °C), **1** does not react with aryl isocyanides. The coupling is highly regioselective (> 99 %), affording products in which the alkyl fragment adds to the 4′ position of the bpy ligand. However, only moderate stereoselectivity is achieved at this position when bulkier cyclohexyl (**4**) and tert-butyl (**2**) isocyanides are used (d.r. 70:30 and 80:20, respectively). When less bulky isocyanides are used (e.g., n-butyl and benzyl) the resulting diastereomers are formed in approximately equal amounts, as judged by NMR spectroscopy. Similar to **2**, the IR spectra of products **3**, **4**, and **5** contain strong ν_{CN} stretching bands at 2045, 2044, and 2046 cm^{-1}, respectively, and are consistent with terminally bound dealkylated isocyanide compounds.[20] Modifications at both the metal and the bpy ligand (i.e., Th–NC and bpy–R) as a result of the R–NC bond activation, may point to the involvement

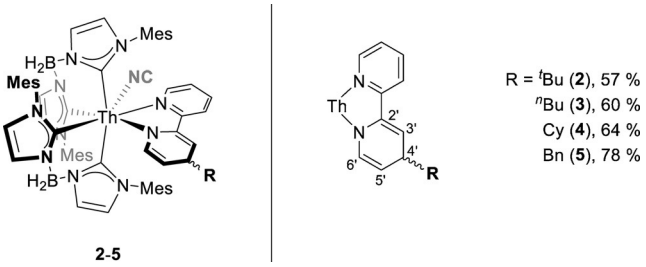


Figure 3. A general representation of coupled products **2**–**5**.

of metal–ligand cooperativity during the transformation.[23] However, a dinuclear process cannot be ruled out.

Coupled products **2**–**5** display a characteristic set of peaks in the centers of their ^{1}H NMR spectra. The 4′-H of the bpy ligand appears as a complex multiplet between 3.06–3.81 ppm. The 5′-H resonance appears further downfield between 3.82–4.11 ppm and shows strong *cis*-vicinal coupling ($^3J = 7.5$–7.8 Hz) to the 6′-H, which resonates consistently between 6.85 and 6.90 ppm. Finally, the 3′-H peak appears as a multiplet between 4.66–4.88 ppm.

The asymmetry of the products (**2**–**5**) and the formation of two diastereomers concurrently in each coupling reaction hamper a quantitative kinetics investigation by NMR spectroscopy. However, the qualitative rate of reaction is clearly benzylic > 3° ≫ 2° > 1°. Treating **1** with benzyl isocyanide at room temperature instantaneously causes a dramatic color change from dark green to orange-brown, but reaction of **1** with *n*-butyl isocyanide requires heating to 50 °C and 48 h to reach full conversion to **3**. These qualitative observations correlate with carbon radical stabilities and suggest a radical-type mechanism is operative.[24] Further evidence for this notion comes from treating **1** with cyclopropylmethyl isocyanide, which affords the rearrangement product **6**. This implies the formation of a cyclopropylmethyl radical, which is known to rearrange to the but-3-enyl moiety.[25–27] As with products **2**–**5**, the generated radical couples to the bpy ligand of **1** to provide **6** in 62 % yield (Figure 4).

NMR spectroscopy verifies the identity of the rearranged but-3-enyl product (**6**). The distinctive upfield ^{1}H (0.0–0.7 ppm) and ^{13}C resonances (0–10 ppm) characteristic of

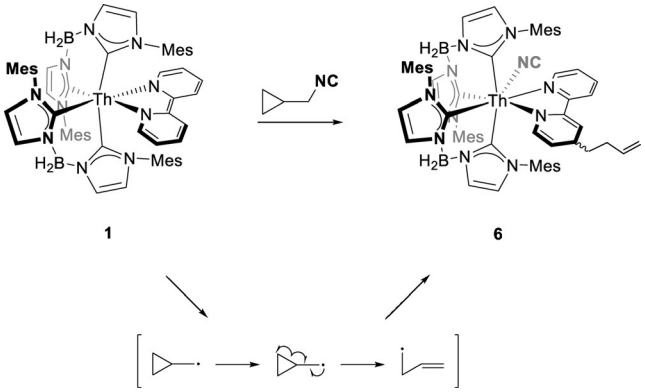


Figure 4. Rearrangement of the cyclopropylmethyl radical to the but-3-enyl radical and formation of **6**.

the cyclopropyl moiety are not observed in the NMR spectra of **6**.[28,29] Rather, along with the diagnostic multiplet pattern seen in products **2**–**5** (see above), the ^{1}H NMR spectrum of **6** contains multiplets with strong vicinal coupling ($^3J = 17.1$ and 10.2 Hz) corresponding to the alkenyl protons of the but-3-enyl substituent. Additionally, 2D NMR studies corroborate the connectivity of the but-3-enyl fragment to the 4′-C of the bpy ligand (Figures S16 and S17 in the Supporting Information).

X-ray diffraction studies unambiguously confirm the structure of **6** (Figure 5). The terminal C61–C62 bond

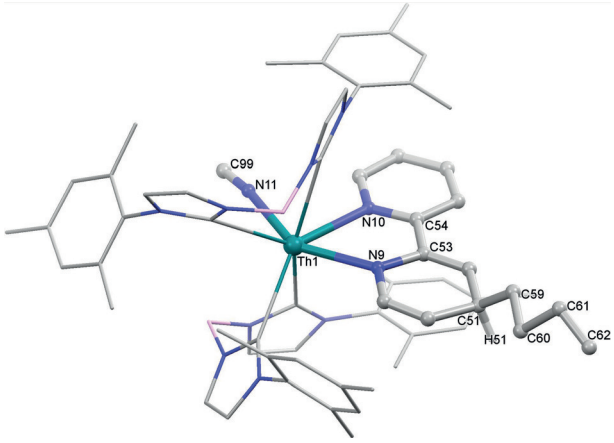


Figure 5. A ball and stick representation of **6**. Hydrogen atoms are omitted and the bis(NHC)borate ligands deemphasized for clarity.

length, at 1.35(2) Å, falls in the range expected for a C(sp^2)–C(sp^2) bond and supports the assignment of a but-3-enyl substituent. As seen for **2**, the bpy ligand is asymmetrically bound to the metal center, with a Th1–N10 bond length of 2.62(5) Å and a Th1–N9 bond length of 2.38(6) Å. Remaining metrical parameters of **6** are similar to those found in **2** (Figure 1), **3**, and **4** (Figures S25 and S26, respectively).

Although **1** demonstrates consistent bond cleavage reactivity towards alkyl isocyanides, no such trend is observed with organic nitriles. Instead, the interaction of **1** with benzyl cyanide immediately leads to an intractable mixture of products, while treatment of **1** with pivalonitrile yields no reaction (determined by NMR spectroscopy). Furthermore, screening the reactivity of **1** with different nitriles (benzonitrile, propionitrile, acetonitrile) still did not provide a congruent mode of reactivity. We believe that competing insertion chemistry,[14,15] along with the more endergonic bond cleavage event required for nitriles (C–C vs. C–N), prevents **1** from effecting similar dealkylation chemistry to that observed for isocyanides.

In conclusion, the ability of **1** to perform reductive R–NC bond cleavage highlights the role of metal–ligand synergism in accessing new reactivity in the organoactinide regime. The unique electronic structure of **1** allows the complex to behave like a highly reducing metal. However, unlike transformations by such metals, the dealkylation mediated by **1** is controlled, predictable, and remarkably general across a series of isocyanides. The interaction of **1** with R–NC affords well-defined products (**2**–**6**), which assists mechanistic elucidation. The isolation of **6** provides additional evidence for a radical-based mechanism. Moreover, the uncommon N binding mode of the dealkylated isocyanide fragment is consistently observed among the coupled products **2**–**6** and is supported by X-ray diffraction experiments (Figures S24–S27) and DFT calculations. Incorporating redox-active moieties not only leads to unique electronic structure, but also underscores the importance of metal–ligand cooperativity as a means to control remarkable chemical transformations. Efforts to expand the ability of **1** to mediate single- and multi-electron transformations, as well as activate other C–X bonds, are underway.

Acknowledgements

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences, and Biosciences Heavy Element Chemistry Program of the U.S. Department of Energy (DOE) at LBNL under Contract No. DE-AC02-05CH11231. MEG acknowledges the NSF-GRFP for a graduate research fellowship (DGE 1106400) and SH acknowledges the German Academic Exchange Service (DAAD) for a postdoctoral scholarship. We acknowledge the NIH Shared Instrument Grant (S10-RR027172) for X-ray diffraction instrumentation. We thank Prof. Robert Bergman for helpful discussion.

Keywords: bipyridine · cooperativity · isocyanide · N-heterocyclic carbenes · thorium

How to cite: *Angew. Chem. Int. Ed.* **2016**, *55*, 13789–13792
Angew. Chem. **2016**, *128*, 13993–13996

[1] M. Ephritikhine, *Organometallics* **2013**, *32*, 2464–2488.
[2] C. J. Burns, M. S. Eisen, *The Chemistry of the Actinide and Transactinide Elements*, Dordrecht, The Netherlands, **2006**.
[3] F. T. Edelmann, *Coord. Chem. Rev.* **2014**, *261*, 73–155.
[4] A. L. Ward, H. L. Buckley, W. W. Lukens, J. Arnold, *J. Am. Chem. Soc.* **2013**, *135*, 13965–13971.
[5] A. L. Ward, W. W. Lukens, C. C. Lu, J. Arnold, *J. Am. Chem. Soc.* **2014**, *136*, 3647–3654.
[6] C. Camp, N. Settineri, J. Lefèvre, A. R. Jupp, J. M. Goicoechea, L. Maron, J. Arnold, *Chem. Sci.* **2015**, *6*, 6379–6384.
[7] M. E. Garner, S. Hohloch, L. Maron, J. Arnold, *Organometallics* **2016**, acs.organomet.6b00467.
[8] V. P. Boyarskiy, N. A. Bokach, K. V. Luzyanin, V. Y. Kukushkin, *Chem. Rev.* **2015**, *115*, 2698–2779.
[9] W. J. Evans, D. K. Drummond, *Organometallics* **1988**, *7*, 797–802.
[10] M. G. Gardiner, A. N. James, C. Jones, C. Schulten, *Dalton Trans.* **2010**, *39*, 6864–6870.
[11] L. J. Nugent, R. D. Baybarz, J. L. Burnett, J. L. Ryan, *J. Phys. Chem.* **1973**, *77*, 1528–1539.
[12] R. J. M. Konings, L. R. Morss, J. Fuger, *The Chemistry of the Actinide and Transactinide Elements*, Springer, The Netherlands, **2010**.
[13] R. R. Langeslay, M. E. Fieser, J. W. Ziller, F. Furche, W. J. Evans, *Chem. Sci.* **2015**, *6*, 517–521.

[14] P. Yang, E. Zhou, B. Fang, G. Hou, G. Zi, M. D. Walter, *Organometallics* **2016**, *35*, 2129 – 2139.
[15] A. C. Behrle, J. R. Walensky, *Dalton Trans.* **2016**, *45*, 10042 – 10049.
[16] J.-C. Berthet, P. Thuéry, N. Garin, J.-P. Dognon, T. Cantat, M. Ephritikhine, *J. Am. Chem. Soc.* **2013**, *135*, 10003 – 10006.
[17] K. Nakamoto, *Infrared and Raman Spectra of Inorganic and Coordination Compounds. Part B: Applications in Coordination, Organometallic, and Bioinorganic Chemistry*, Wiley, New York, **1997**.
[18] W. Ren, G. Zi, D. Fang, M. D. Walter, *J. Am. Chem. Soc.* **2011**, *133*, 13183 – 13196.
[19] A. Hervé, Y. Bouzidi, J.-C. Berthet, L. Belkhiri, P. Thuéry, A. Boucekkine, M. Ephritikhine, *Inorg. Chem.* **2014**, *53*, 6995 – 7013.
[20] J. Berthet, P. Thuéry, M. Ephritikhine, *Dalton Trans.* **2015**, *44*, 7727 – 7742.
[21] W. D. Jones, W. P. Kosar, *Organometallics* **1986**, *5*, 1823 – 1829.
[22] C. L. Tennent, W. D. Jones, *Can. J. Chem.* **2005**, *83*, 626 – 633.
[23] J. R. Khusnutdinova, D. Milstein, *Angew. Chem. Int. Ed.* **2015**, *54*, 12236 – 12273; *Angew. Chem.* **2015**, *127*, 12406 – 12445.
[24] E. V. Anslyn, D. A. Dougherty, *Modern Physical Organic Chemistry*, University Science Books, Sausalito, CA, **2006**.
[25] D. Griller, K. U. Ingold, *Acc. Chem. Res.* **1980**, *13*, 317 – 323.
[26] V. W. Bowry, J. Lusztyk, K. U. Ingold, *J. Am. Chem. Soc.* **1991**, *113*, 5687 – 5698.
[27] D. C. Nonhebel, *Chem. Soc. Rev.* **1993**, *22*, 347 – 359.
[28] M. Baranac-Stojanović, M. Stojanović, *J. Org. Chem.* **2013**, *78*, 1504 – 1507.
[29] E. Pretsch, P. Bühlmann, M. Baderstscher, *Structure Determination of Organic Compounds*, Springer, Heidelberg, **2009**.

Received: August 13, 2016
Revised: September 5, 2016
Published online: September 28, 2016

