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Ligand-Based Reduction of CO₂ to CO Mediated by an Anionic Niobium Nitride Complex

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There are several motivations for producing chemicals from CO₂ whenever possible, and in particular, CO is a promising target being both a versatile chemical precursor and a fuel.1 Reducing metal complexes capable of O-atom abstraction from CO₂ typically lead to the formation of strong metal-oxygen bonds that represent a challenge to catalytic turnover.2

In a special case for which the binding of CO₂ evidently involves insertion into a Cu–B linkage, catalytic turnover producing CO was accomplished by taking advantage of the ultimate delivery of oxygen into a stable B–O–B reservoir.3 This is to be compared with electrocatalytic methods for CO₂ reduction to CO in systems that likely involve a direct interaction between CO₂ and the metal center at some point in the catalytic cycle.4 Another commonly observed trend in metal-mediated CO₂ reduction is disproportionation reactivity leading to the formation of CO and CO₂,5 highlighted by the reaction of Li₂[W(CO)₅] with CO₂ to give W(CO)₆ and Li₂CO₃. With regard to organic systems, conversion of CO₂ to CO has recently been achieved with an N-heterocyclic carbene serving as the catalyst, activating the CO₂ through nucleophilic attack, and a variety of aldehydes serving as the oxygen acceptors to form carboxylic acids.6 Taking a different approach, we have sought to develop a ligand-based CO₂ reduction protocol in which the initial binding event is to a terminal nitrido nitrogen atom, rather than directly to the redox-active metal itself; this approach avoids the formation of strong oxometal bonds while ultimately making possible oxide ion transfer to variable externally added acceptors. This paradigm suggested itself through the twin discoveries of facile CO₂ uptake by a terminal vanadium nitride anion complex and corresponding niobium nitride anion synthesis via isocyanate decarbonylation.7,8 Accordingly, herein we present a sequence of reactions constituting a cycle for CO₂ reduction to CO using a terminal niobium nitride anion complex as a stable platform that is maintained throughout.

Complex [Na][Nnb(NtBuAr)₂] ([Na][I], Ar = 3,5-C₆H₄(CH₃)₂) reacts with 1 equiv of CO₂ at 0 °C to give the carbamate complex [Na][O₂CNNb(NtBuAr)₂] ([Na][O₂-C-I]) in 81% isolated yield (A, Scheme 1). Complex [Na][O₂-C-I] is isolated solvate free and has limited solubility in hydrocarbon solvents. Complex [Na][O₂-C-I] has been characterized using ¹H and ¹³C NMR and IR (νOCO = 1598 cm⁻¹) spectroscopies. When ¹³CO₂ was used in the reaction, the ¹³C chemical shift of the carbamate group was definitively identified at 161 ppm, and the νOCO stretch shifts to 1537 cm⁻¹. Although a closely related vanadium complex has been reported,9 structural data have not been disclosed previously for an N-bound carbamate complex. Crystals of [Na][O₂-C-I] suitable for single-crystal X-ray diffraction studies were grown by encapsulating the sodium cation with 2 equiv of 12-crown-4 and cooling a saturated solution of [(12-crown-4)Na][O₂-C-I] in 1:1 toluene:diethyl ether to −35 °C. The solid-state structure of the complex anion reveals a terminal N-bound carbamate functional group with the oxygen atoms extended away from the niobium metal center (Fig. 1). The short Nb–N₉ distance (1.764(2) Å) is comparable to other structurally characterized niobium imido groups and is characteristic of a niobium nitrogen triple-bond.10 The C–O distances (avg. 1.236(4) Å) show significant elongation when compared to free CO₂ (1.17 Å),11 but are slightly shorter than those found for organic carbamate functional groups.12 Although we refer to the N–CO₂ functionality as an N-bound carbamate, it may be thought of as an imido ligand bearing a CO₂ substituent and is closely related to the acylimido functional group, for which a number of examples have been synthesized and structurally characterized.13 Complex [Na][O₂-C-I] is stable indefinitely as a solid or in solution under high vacuum and at 23 °C. At higher temperatures, [Na][O₂-C-I] gives rise to the oxo complex ONb(NtBuAr) (80 h, 70 °C, THF) and sodium cyanate as the co-product (confirmed by ¹³C NMR spectroscopy).14 An analogous intramolecular metathesis has been observed in the reaction of Cs₂ with [Na][NV(NtBuAr)] to give sodium thiocyanate and the terminal sulfide complex SV(NtBuAr).15 This reactivity is also consistent with previous observations that acylimido complexes can extrude organic nitriles.16 The reactivity of [Na][O₂-C-I] has been studied with the goal of deoxygenating the carbamate carbon. The adopted strategy was derivatization with an electrophile to incorporate a carbamate oxygen into a good leaving group, thus rendering a C–O bond susceptible to reductive cleavage.17
In order to generate the isocyanate complex (OCN)Nb(N[12-BuC6]Ar)3 (3), the precursor to [Na][I], from Me-2, the one-electron reduction of Me-2 would have to result in selective dissociation of acetate ion over isocyanate ion. The cyclic voltammogram (CV) of Me-2 contains three observable features (Fig. 3). When scanning cathodically, the first redox event (I) is an irreversible reduction that occurs at −2.0 V vs. Fe/Fe⁺ (Fc = (C6H5)2Fe), assigned as the Nb[5+/4+] couple. If the cathodic scan is reversed after this event, a new irreversible anodic event (II) is observed at −0.9 V and is assigned to a Nb[4+/3+] couple. If the cathodic scan is allowed to continue beyond −2.0 V, a third redox event (III) is observed at −2.8 V and is assigned to the Nb[4+/3+] couple. The potentials of II and III agree with the previously reported CV of complex 3.27 We take this observation as support for the hypothesis that the cathodic event I is a 1e reduction of the niobium metal center that results in rapid dissociation of the acetate ligand to generate 3. In comparison, the CVs of F,C-2 and 1-Bu-2 contain three similar features.22 For F,C-2, event I is shifted to −1.7 V, this shift representing the most pronounced difference between the three CVs. Events II and III are nearly identical for all three complexes, again consistent with the idea that carboxylate dissociation occurs rapidly upon one-electron...
Although the overall process represented in Eq. 1 is two-electron reduction of CO₂ to CO with an anhydride serving as the oxide ion acceptor, an essential component of the system is the coupling of sequential metal-based one-electron steps (Scheme 1C, D) to bond-making and -breaking processes taking place at the nitrido ligand.

In conclusion, we have developed a synthetic cycle for CO₂ to CO conversion where the transformation is mediated by an anionic niobium nitride complex. These findings expand the field of CO₂ reduction chemistry and illustrate the promise of ligand-based approaches. Furthermore, this work, in conjunction with previously reported nitride transfer cycles, demonstrates the versatile chemistry available to terminal nitride ligands. To make feasible a catalytic version of the Scheme 1 chemistry, means must be developed such that the nitride nucleophile is able to discriminate between the CO₂ and the oxide ion acceptor electrophiles.

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Supporting Information Available: Complete experimental, spectroscopic, electrochemical, and crystallographic details. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(11) A search of the Cambridge Structural Database for niobium imidos revealed an average Nb-N distance of 1.779 Å.
(13) A search of the Cambridge Structural Database of carbamate fragments revealed an average C-O distance of 1.275 Å.
(22) See Supporting Information.
The terminal nitride anion complex [Na][N≡Nb(N[t-Bu]Ar)₃] ([Na][1], Ar = 3,5-Me₂C₆H₃) reacts quantitatively with CO₂ to give the carbamate complex [Na][O₂C-N≡Nb(N[t-Bu]Ar)₃] ([Na][O₂C-1]). The structure of [Na][O₂C-1] as the bis-12-crown-4 solvate, as determined by X-ray crystallography, displays a unique N-bound carbamate ligand without any metal-oxygen interactions. When treated with organic acid anhydrides or acid chlorides, complex [Na][O₂C-1] reacts via salt-elimination to give the five-coordinate complexes (RC(O)O)(OCN)Nb(N[t-Bu]Ar)₃ (R-2, R = Me, t-Bu, F₃C). We show that complexes R-2 yield the starting complex [Na][1] with concomitant release of CO upon two-electron reduction. This series of reactions constitutes a closed cycle for the conversion of CO₂ to CO mediated by a terminal nitride anion complex.