BPTI protein, used for the parametrization of the Karplus equation.[15] The RMS difference between measured J couplings and the couplings calculated from the crystal structure refined with anisotropic B factors was slightly larger, 1.01 Hz. The major contributions to the RMS difference originate primarily from five residues, K70, K78, Y85, E135, and S141. Polar residues K70, Y85, and E135 are involved in intermolecular crystal contacts, K78 is in a sharp turn immediately adjacent to the major interprotein contact domain in the crystal, and S141 is the last residue observed in the crystal structure.[14]

Energy minimization of the crystal structure or a 100 ps molecular dynamics (MD) simulation of the fully hydrated protein significantly decreased agreement between measured and calculated J values. This occurred despite the small RMS deviation (1.50 Å for the backbone atoms, 2.06 Å for all atoms) between the crystal structure and the time averaged MD structure, suggesting that straightforward energy minimization of a good (1.65-Å) crystal structure can lead to false local minima and that 100 ps of dynamics simulation may be insufficient to cure this.

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Supplementary Material Available: Table containing the crystal structure ϕ angles of staphylococcal nuclease, complexed with pdTp and Ca^{2+}, the J couplings calculated on the basis of these ϕ angles, and the measured J couplings (3 pages). Ordering information is given on any current masthead page.

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Ligand-Mediated Reactivity of Niobium-Ketene Complexes

Saul E. Halfon, Maria C. Fermin, and Joseph W. Bruno*

Hall-Atwater Laboratories
Wesleyan University
Middletown, Connecticut 06457

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As part of a study of the chemistry of metal-bound ketenes,[1,2] we sought the preparation of niobocene-ketene complexes so as to extend our earlier work on vanadocene analogues. In the course of these studies, we have used unsymmetrically substituted ketenes to determine reaction stereoselectivities;[3] herein we describe some unprecedented ketene isomerizations as well as a novel synthesis of the first ketene-hydride complex.

Treatment of Cp'_2NbCl ($Cp' = \eta^5\text{-}C_5H_4SiMe_3$)[4] with ketenes gives rise to the desired ketene complexes (eq 1) in 70-80% yields.

$$Cp'_2NbCl + R^1R^2C{=}C{=}O \rightarrow Cp'_2Nb(Cl)(OCCR^1R^2) \quad (1)$$

$$\begin{array}{l} \mathbf{1},\ R^1 = R^2 = Me \\ \mathbf{2},\ R^1 = R^2 = Ph \\ \mathbf{3},\ R^1 = Me;\ R^2 = Ph \\ \mathbf{4},\ R^1 = Et;\ R^2 = Ph \end{array}$$

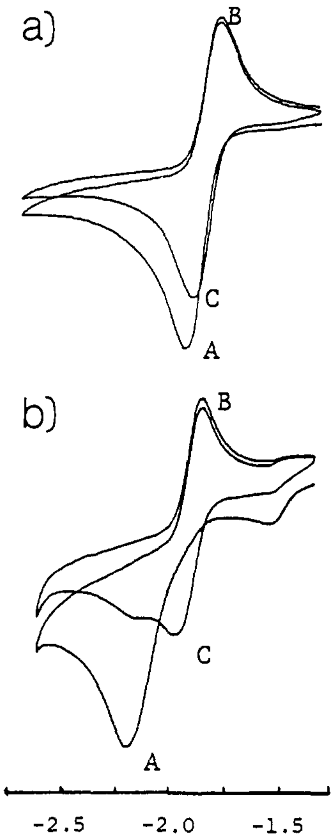
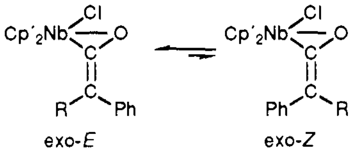


Figure 1. Voltammograms of compounds **2** (a) and **3** (b): 15 mM in THF/1.0 M $Bu_4N^+BF_4^-$. Platinum disk working electrode: potentials are in volts relative to a Ag/Ag^+ reference electrode. Scan rates = 100 mV/s.

This contrasts with Cp_2NbCl, which gives only reductive coupling of two ketene moieties. Although several isomers are possible, the symmetrically substituted ketenes yield only one complex isomer (C=O bound); thus, exo-endo isomerism is not a factor.[5] However, with unsymmetrical ketenes isomeric mixtures *are* observed (via ^1H NMR) due to E-Z isomerism about the C=C bond (eq 2).[6] For **3** the E:Z ratio is 81:19, while for **4** it is 70:30



(2)

(in C_6D_6); these assignments are based on variable-temperature NMR studies (the E-Z equilibrium shifts but remains slow on the NMR time scale up to 75 °C) and an X-ray diffraction study[7] of *exo*-(E)-**4**. Compounds **3** and **4** were allowed to equilibrate (toluene, 20 °C) in the presence of equimolar EtPhC=C=O and MePhC=C=O, respectively. In neither case was ketene exchange observed, so this isomerization constitutes the first example of an intramolecular C=C isomerization of a C=O bound ketene.

Voltammograms for **2** and **3** are presented in Figure 1. The sequential cathodic sweeps exhibit a form commonly associated with an ECEC mechanism (eq 3-5).[8] We suggest that wave A

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[6] Spectroscopic and analytical data are included as Supplementary Material.

[7] Crystal data for **4**: $C_{24}H_{33}NbClOSi_2$, MW = 522.05, monoclinic, $P2_{1/c}$, a = 7.938 (5) Å, b = 15.81 (2) Å, c = 21.61 (1) Å, $\alpha = \beta = 90°$, γ = 95.41 (6)°, V = 2700 (7) Å^3, Z = 4, d = 1.28 g cm^{-3}.

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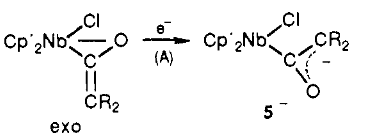


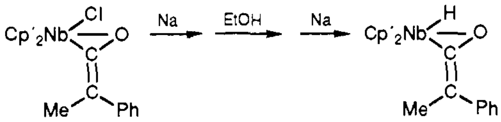
(3)

$$5^- \xrightarrow[(B)]{-e^-} \underset{6}{Cp'_2Nb(Cl)(O{=}C{=}CR_2)} \qquad (4)$$

$$6 \xrightarrow[(C)]{e^-} 5^- \qquad (5)$$

(Figure 1, first sweep) represents reduction and isomerization to endo metallaenolate (**5**$^-$), wave B represents oxidation of this to a ketene complex (**6**) which is an isomer of the starting material, and that wave C in the second sweep represents reduction of **6**. Possible formulations for **6** include *endo*-C=O or -C=C bound ketene complexes; this point is under study. The relative heights of waves A and C in the second sweep depend on ketene substituents and scan rate, suggesting that this ligand is involved in the isomerization process. We have also noted that added chloride (as LiCl) has no effect on the voltammetry, and that standardization with $Cp_2Fe^{0/+}$ indicates that the processes depicted in Figure 1 are one-electron events. The key observation, then, is that the ketene complexes undergo a one-electron reduction via a process which involves a structural change in the ketene ligand.

In an attempt to generate and trap a niobaenolate, **3** was treated with sodium amalgam (in ether) and quenched with added ethanol. Further investigation revealed that the one-pot process requires 2 equiv of reductant and that the proton source must be added in the presence of the second reducing equivalent. The resulting product is *exo*-(*E*)-Cp'$_2$Nb(H) (OCCMePh) (**7a**, eq 6), isolated as an off-white solid in 60% yield; in solution it undergoes slow equilibration to a 50:50 mixture of **7a** and *exo*-(*Z*)-**7b** (these assignments are corroborated by NOE experiments). These are the first metal complexes to contain both hydride and ketene ligands. We propose that the synthetic sequence involves reduction to a metallaenolate (as indicated by the voltammetric experiments, eq 3), which is protonated at carbon to give **8**.[9] This Nb(IV)



(6)

7a

$$3 \xrightarrow{Na} Na^+5^- \xrightarrow[-NaOEt]{EtOH} [Cp'_2Nb(Cl)\ (C({=}O){-}CR_2H)] \qquad (7)$$

$$8 \xrightarrow[-NaCl]{Na} \underset{7}{Cp'_2Nb(H)\ (OCCR_2)} \qquad (8)$$

acyl is rapidly reduced by the second equivalent of sodium, with loss of Cl$^-$. The resulting Nb(III) acyl then undergoes β-H elimination to give the ultimate product. Although Baird has observed acyl β-H elimination resulting in metal hydride and free ketene,[10,11] there is no example of such a process giving a ketene hydride complex. Consistent with the proposed mechanism, we note that (a) if niobaenolate **5**$^-$ is deliberately oxidized prior to addition of the proton source, **3** is regenerated; (b) if the initially formed intermediate **5**$^-$ is removed from the excess amalgam before it is treated with the proton source, a mixture of **3** and **7** results; and (c) the use of MeOD as quencher results in D incorporation only at the Nb-D site. These observations would seem to preclude alternate mechanisms involving loss of chloride in the first reduction step or an initial two-electron reduction (also, a reduced niobium center should react with ethanol to give H_2 and Nb-OEt; neither is observed).

Lastly, we note that the synthetic sequence of e$^-$, H$^+$, e$^-$ is equivalent to treatment with hydride. However, treatment of **3** with $LiAlH_4$ gave rapid conversion to $Cp'_2Nb(\mu\text{-}H)_2AlH_2$, while milder hydride sources (MBH_4) failed to react. Similarly, treatment of $Cp'_2Nb(BH_4)$ or $Cp'_2Nb(H)\ (PPh_3)$ with ketenes gave intractable products, suggesting niobium-hydride-induced ketene polymerization.[12] Thus, a ketene-mediated synthesis of **7** appears to be the only viable route, and it illustrates the fact that the complexed ketene can support chemistry with which free ketenes are incompatible. Further studies of the utility of the complexed ketenes are in progress.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, and Research Corp. for support and Gayle Schulte for performing the crystallographic study.

Supplementary Material Available: Spectral data (^{1}H NMR and IR) for **1**–**4** and **7** (3 pages). Ordering information is given on any current masthead page.

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Oxygen-Atom Transfer from Nitrous Oxide. Identification of Intermediates in the Oxidation of Diphenylacetylene at Group 4 Metal Centers and the Structural Characterization of $(\eta\text{-}C_5Me_5)_2Ti\{N(O)NCPh{=}CPh\}\cdot{}^1/_2C_7H_8$

G. Alan Vaughan, Chadwick D. Sofield, and
Gregory L. Hillhouse*

*Searle Chemistry Laboratory, Department of
Chemistry, The University of Chicago
Chicago, Illinois 60637*

Arnold L. Rheingold*

*Department of Chemistry, University of Delaware
Newark, Delaware 19716*

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Nitrous oxide is a thermodynamically potent oxidant for oxo-transfer reactions (ΔG_f° = 25 kcal/mol), but it is remarkably kinetically inert in the absence of a suitable activating center (usually a transition metal);[1,2] moreover, the sole byproduct of oxo transfer from N_2O, dinitrogen, is an innocent, unreactive one. For these reasons nitrous oxide is an attractive oxygen-atom source for effecting selective chemical oxidations. Other workers, most notably Bottomley's group, have exploited N_2O as a reagent for preparing unusual transition-metal-oxo clusters,[3,4] while Lunsford

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