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Mononuclear $Ni^{III}-$Alkyl Complexes (Alkyl = Me and Et): Relevance to the Acetyl-CoA Synthase and Methyl-CoM Reductase

Chien-Ming Lee,[*,†] Chien-Hong Chen,[‡] Fu-Xing Liao,[§] Ching-Han Hu,[§] and Gene-Hsiang Lee[||]

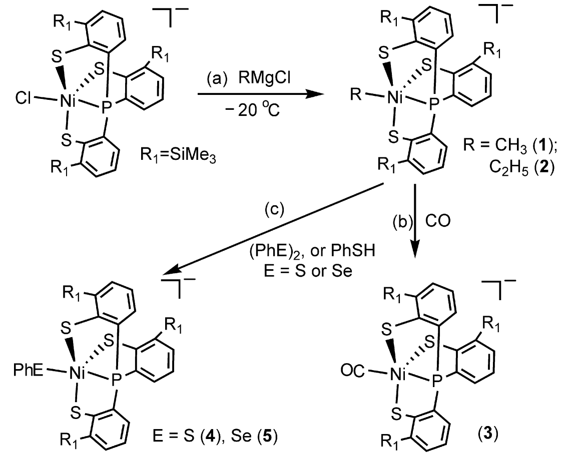
Department of Applied Science, National Taitung University, Taitung City 95092, Taiwan, School of Applied Chemistry, Chung Shan Medical University, Taichung City 40201, Taiwan, Department of Chemistry, National Changhua University of Education, Changhua 50058, Taiwan, and Instrumentation Center, National Taiwan University, Taipei 10764, Taiwan

Received March 24, 2010; E-mail: cmlee@nttu.edu.tw

Abstract: Mononuclear, distorted trigonal bipyramidal [PPN][Ni^{III}(R)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)] (R = Me (**1**); R = Et (**2**)) were prepared by reaction of [PPN][Ni^{III}Cl(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)] and CH_3MgCl/C_2H_5MgCl, individually. EPR, SQUID studies as well as DFT computations reveal that the Ni^{III} in **1** has a low-spin d^7 electronic configuration in a distorted trigonal bipyramidal ligand field. The Ni−C bond lengths of 1.994(3) Å in **1** and 2.015(3) Å in **2** are comparable to that in the $Ni^{III}-$methyl state of MCR (~2.04 Å) (Sarangi, R.; Dey, M.; Ragsdale, S. W. *Biochemistry* **2009**, *48*, 3146). Under a CO atmosphere, CO triggers homolytic cleavage of the $Ni^{III}-CH_3$ bond in **1** to produce $Ni^{II}-$thiolate carbonyl [PPN][Ni^{II}(CO)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)] (**3**). Additionally, protonation of **1** with phenylthiol generates $Ni^{III}-$thiolate [PPN][Ni^{III}(SPh)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)] (**4**).

The chemistry of Ni−alkyl complexes has been actively pursued, motivated primarily by the development of inexpensive catalysts for selective hydrocarbon activation[1] and, in particular, the relevance of $Ni^{II/III}-$alkyl intermediates (alkyl = methyl) to the catalytic chemistry of two enzymes, acetyl-CoA synthase (ACS) and methyl-coenzyme M reductase (MCR).[2,3] ACS is a nickel-based enzyme responsible for the assembly of CO, CH_3, and the coenzyme A to generate acetyl-CoA;[4] MCR is also a nickel-containing enzyme which catalyzes the conversions of methyl-coenzyme M (CH_3-SCoM) and coenzyme B (CoB−SH) to methane and heterodisulfide (CoM−S−S−CoB).[5] Recently, the crystal structures of ACS and MCR systems have been elucidated.[6,7] The active sites of two enzymes are associated with nickel ion which is believed to be selected for biological processes due to its unique redox and coordination properties. Although several groups have employed various spectroscopic and theoretical methods to characterize the intermediates formed during catalytic reactions, there has been a lot of debate about the catalytic mechanisms in both ACS and MCR systems.[8,9] For instance, an intense discussion in MCR is whether reactions of the MCR_{red1} (Ni^{I}) state with CH_3-SCoM results in the formation of a $Ni^{III}-CH_3$ intermediate (Mechanism I)[9a] or a $CH_3^{\bullet}$ radical and $Ni^{II}-$thiolate species (Mechanism II).[9c] In ACS, the central metal ion of the active state is in the Ni^{I} valence state according to the paramagnetic proposal,[8b] but it is in the Ni^{0} valence state based on the diamagnetic proposal.[8a] Therefore, upon reacting with CH_3^{+} donated from a corrinoid iron−sulfur protein, the $Ni^{III}-CH_3$ intermediate will be generated for the paramagnetic mechanism, and it will form the $Ni^{II}-CH_3$ intermediate in the diamagnetic pathway.

Scheme 1



Inspired by Liaw's recent work in the synthesis of a series mononuclear $Ni^{III}-$L complexes (L = OMe, OPh, SePh, SEt, SPh, and Cl) supported by ligand [P(C_6H_3-3-R-2-S)$_3$]$^{3-}$ (R = H, $SiMe_3$)[10] and the biological significance, we are interested in the chemistry of Ni^{III} complexes containing an alkyl group. Herein, we report the syntheses and structural characterization of two trivalent alkylnickel complexes [PPN][Ni^{III}(R)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)] [PPN = bis(triphenylphosphoranylidene)-ammonium; R = Me, Et]. To the best of our knowledge, no example of a methyl group bonded to Ni^{III} has been structurally characterized.

When a CH_3CN-THF (1:4 v/v) solution of [Ni^{III}(Cl)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)]$^-$ was treated with 1.1 equiv of RMgCl (R = Me, Et) at −20 °C, an immediate change in solution from bright green to dark red-brown occurred (Scheme 1a). The reaction mixture led to the isolation of five-coordinate [Ni^{III}(R)(P(C_6H_3-3-$SiMe_3$-2-S)$_3$)]$^-$ (R = Me for **1**, Et for **2**) as a dark-red solid after recrystallization from THF−CH_3CN/Et_2O (yield: 70% for **1**, 50% for **2**). Both **1** and **2** are soluble in CH_3CN-THF (1:4 v/v) and display thermal sensitivity in solution. Compared with the spectrum of **1** having absorption bands at 500 and 825 nm, the bands of **2** coordinated by a stronger electron-donating ethyl ligand exhibit a blue shift to 490 and 815 nm, respectively (see Supporting Information, Figure S1). The ^{1}H NMR spectra of **1** and **2** at ambient temperature show diagnostic signals with phenyl protons well removed from the diamagnetic region. The proton resonances shifted to downfield at δ 14.29 (br) and 12.73 (br) and to upfield at −1.86 (br) for **1** (14.94 (br), 12.33 (br), and −0.86 (br) for **2**) are assigned to Ni^{III}-bound

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[†] National Taitung University.
[‡] Chung Shan Medical University.
[§] National Changhua University of Education.
[||] National Taiwan University.

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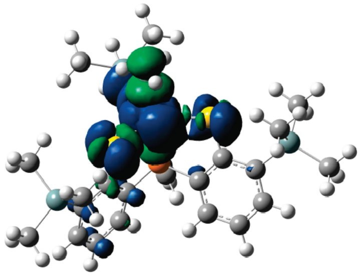

Figure 1. Plot of the spin density of **1**. Orbital and atomic contributions to the spin densities of **1** are shown in Supporting Information (Table S1). Selected computed structural data (Å): Ni−C_{Me} 1.949, Ni−S_{av} 2.329, Ni−P 2.175 (B3LYP/6-31G*).

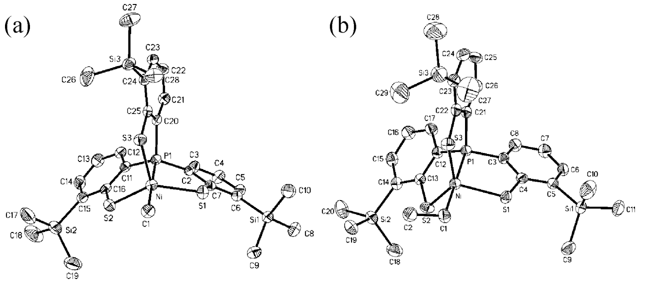

Figure 2. ORTEP drawings of $[Ni^{III}(CH_3)(P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3)]^-$ (a) and $[Ni^{III}(CH_2CH_3)(P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3)]^-$ (b) with thermal ellipsoids drawn at the 50% probability level. Selected bond distances (Å): Ni−C(1) 1.994(3) for **1**; Ni−C(1) 2.015(3) for **2**.

ligand $[P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3]^{3-}$ (Figure S2). Attempts to identify resonances of α hydrogens in **1** and **2** were unsuccessful, presumably due to paramagnetic broadening, but the peak at δ −45.07 (br) is most likely due to β hydrogens of **2** (Figure S2b).

The 77 K EPR spectrum of **1** exhibits rhombicity with three principal g values of 2.44, 2.00, and 1.96 (2.44, 1.99, 1.93 for **2**, Figure S3). The average g value of **1** ($g_{av} = 2.13$) indicates that the unpaired electron is primarily associated with the nickel ion.[10a] Indeed, the spin density result from density functional theory computation reveals that the unpaired electron resides predominantly in the d_{xy} and $d_{x^2-y^2}$ orbitals of Ni.[11] The spin density plot of **1** is shown in Figure 1 (Figure S4 for **2**). According to the figures, the atomic spin densities are 0.98 on nickel and −0.08 on methyl carbon, respectively. Similarly, for **2** the atomic spin densities are 0.99 on nickel and −0.09 on ethyl carbon (Table S1). These results are comparable to that of the EPR-active state of MCR ($g_\perp = 2.10$, $g_\parallel = 2.22$), in which the unpaired electron is primarily located in the $d_{x^2-y^2}$ orbital.[12] Furthermore, the effective magnetic moment of **1** in the solid state by SQUID magnetometer is 1.85 μ_B which is consistent with the Ni^{III} having a low-spin d^7 electronic configuration in a distorted trigonal bipyramidal ligand field (Figure S5).

Figure 2 displays the thermal ellipsoid plot of the anionic complexes **1** and **2**, respectively, and selected bond distances are given in the figure caption. The geometry of the Ni center in **1** and **2** adopts a distorted trigonal bipyramid with C(1) and P(1) occupying the axial positions. The average Ni−S distance of 2.2538(9) Å in **1** (2.2584(9) Å in **2**) is within the range of known five-coordinate Ni−thiolate complexes (2.21−2.31 Å).[10,13] It is noted that Ni−C bond lengths of 1.994(3) Å in **1** and 2.015(3) Å in **2** are slightly longer than the average bond length (∼1.98 Å) observed for synthetic $Ni^{I/II}$−alkyl complexes,[14] and close to the long Ni−C bond distance of ∼2.04 Å based on EXAFS data analysis and TD-DFT calculations of the Ni^{III}−methyl state in MCR.[9b] The results may suggest that the Ni^{III}−alkyl bond of **1** and **2** is much easier to cleave homolytically. To test this hypothesis, we treat the CH_3CN−THF (1:4 v/v) solution of **1** with CO at room temperature.

The insertion of CO into the Ni^{II}−methyl bond in monomeric or dimeric alkylnickel model complexes producing the NiC(O)Me species was described in the literature.[2c,e,15] In contrast, the reaction between CO and **1** leads to Ni^{II}−thiolate carbonyl $[Ni^{II}(CO)(P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3)]^-$ (**3**),[10b] as shown in Scheme 1b. The lack of observation of the acylnickel species from the reaction of CO with **1** but isolation of **3** may imply that the formation of the proposed $[(CO)Ni^{III}(CH_3)(P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3)]^-$ intermediate followed by Ni−CH_3 homolytic cleavage seems preferable to methyl migration or CO migratory insertion.

The methyl group of **1** can undergo alkyl-for-chalcogenate exchange with diphenyl dichalcogenide or protonation with phenylthiol.[15e] When **1** and $(PhE)_2$ (E = S or Se) or PhSH are mixed in solution at ambient temperature, $[PPN][Ni^{III}(EPh)(P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3)]$ (E = S (**4**); Se (**5**)) are isolated in high yield (Scheme 1c) (Figure S6).[10]

In summary, we succeeded in the syntheses and structural characterization of thermally unstable high-valent Ni^{III}−alkyl species (alkyl = Me (**1**), Et (**2**)) with tetradentate ligand $[P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3]^{3-}$, although a high redox potential of the Ni^{III}−alkyl state might be expected to undergo spontaneous reduction and polymerization. The stability of **1** and **2** might be attributed to the tunable electron-donating functionalities of ligand $[P(C_6H_3\text{-}3\text{-}SiMe_3\text{-}2\text{-}S)_3]^{3-}$, which shares similar characteristics with the noninnocent factor of the F_{430} in MCR.[9b] Additionally, the results obtained from this work may lend support to the intermediacy of Ni^{III}−CH_3 species proposed in both ACS and MCR catalytic cycles. We also note that **1** and **2** are capable of being used in reagents for alkyl transfer. Detailed investigations are ongoing.

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Supporting Information Available: Crystallographic data in CIF format and additional figures and experimental details (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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