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Title: Synthesis and Preliminary Reactivity of Redox-Active Aluminum-Nitroxide Complexes

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Synthesis and Preliminary Reactivity of Redox-Active Aluminum-Nitroxide Complexes

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Bachelor of Sciences

Submitted in partial fulfilment of the requirements for

College Honors

Departmental Distinction in Biochemistry

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Synthesis and Preliminary Reactivity of Redox-Active Aluminum-Nitroxide Complexes

INTRODUCTION

There are reasons why developing cheaper metal catalysts is an attractive idea for the whole field of chemistry including its high abundance, low cost and sustainability. Aluminum metal is one of the most abundant elements in the Earth (about 8% of the Earth's crust), [1] which drives down its price to about \$2.00/kg of Al. [2] The commonly used metals for catalysis, i.e. palladium, platinum, iridium among others, are much less abundant in the earth and drive their purchase price to greater than \$30,000/kg. The development of new aluminum complexes for catalytic applications is therefore desirable. Aluminum complexes have seen wide success in Lewis acid catalysis. [3] Unfortunately, aluminum only has one stable oxidation state [Al(III)], and cannot participate alone in redox processes, thereby limiting the application of aluminum complexes for chemical reactions where oxidation and reduction of molecules. The aim of the Grave's group is to synthesize aluminum complexes with redox active ligands. The ligands themselves act as electron reservoirs that can facilitate reaction chemistry at the metal center. Therefore the metal itself maintains a constant electron configuration while the ligand provides the redox states necessary to accomplish the redox activity.

The work herein has specifically been investigating the coordination chemistry of nitroxide ligands to aluminum. The N-O functional group is known to exist across three oxidation states: The fully reduced form of the nitroxide group, the aminoxyl anion (NO^-), can be oxidized by one electron to the neutral, radical form (NO^0) which in turn can be further oxidized to the give the oxoammonium cation (NO^+) (Figure 1) [4].

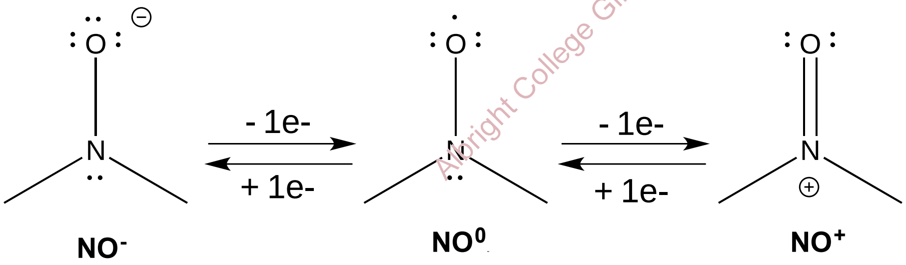
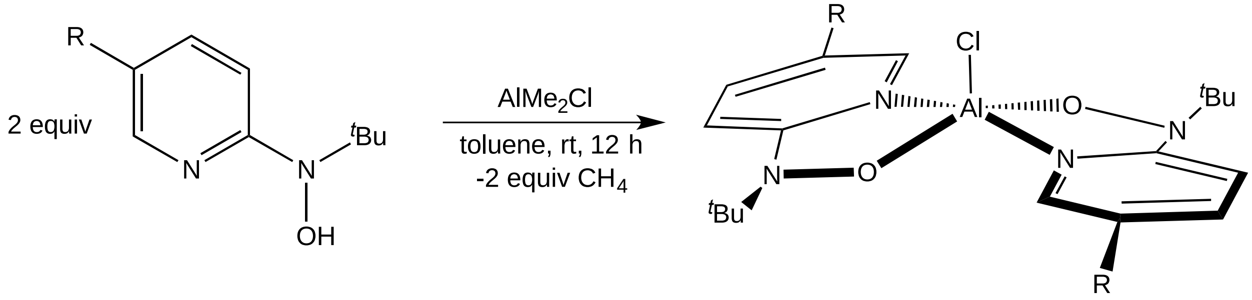


Figure 1: The three different oxidation states of the nitroxide functional group [4].

Previously, Albright student Andrew Poitras worked with various pyridylhydroxylamine ligands and reported the synthesis of their complexes with aluminum. [5] He synthesized a series of aluminum-nitroxide ligand complexes, including $[2\text{-}^t\text{BuNO})\text{py}]_2\text{AlCl}$, $[2\text{-}^t\text{BuNO})\text{py}^{\text{CH3}}]_2\text{AlCl}$

and [2-^{t}BuNO)py^{CF3}]$_2$AlCl (Figure 2). These complexes were characterized by ^{1}H NMR and x-ray crystallography. The cyclic voltammograms of the complexes showed that the complexes were redox active, however the processes were not reversible and suggested that the compounds were not stable to oxidation.



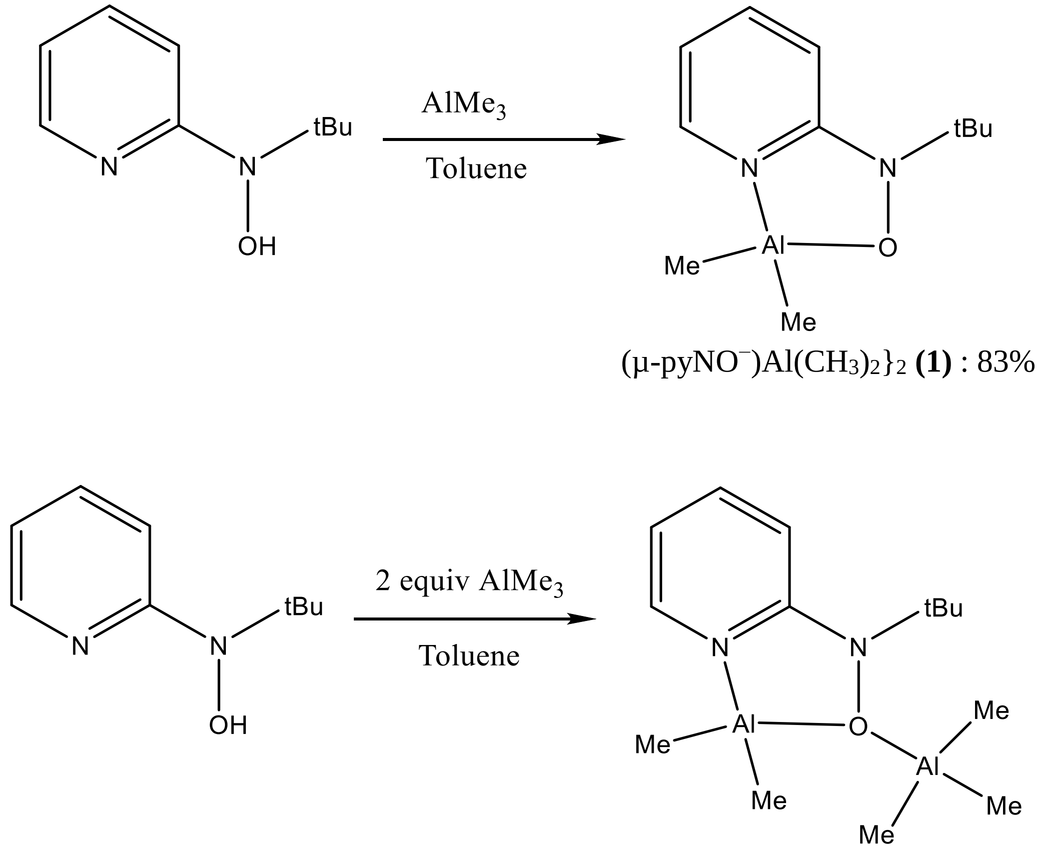
R = H **[(2-^{t}BuNO)py]$_2$AlCl**
R = CH$_3$ **[(2-^{t}BuNO)pyCH$_3$]$_2$AlCl**
R = CF$_3$ **[(2-^{t}BuNO)pyCF$_3$]$_2$AlCl**

Figure 2: The synthesis of previously made aluminum nitroxide complexes.

In order to continue in the previous work that had been done, a different approach to creating more stable complexes was proposed. To expand upon the original complexes, the pyridylnitroxide ligands would be attached to a different aluminum compound source to see if that would change the electrochemical behavior. This would be the goal of the first part of the project. The second part of the research investigated changing the ligands attached to aluminum in order to have achieve a higher chelate number (more bonds) to see if that would create a more stable complex that could stand up to the oxidation conditions.

PART 1

The first part of my research dealt with expanding upon the work that was previously done with the pyriyl nitroxide ligands (pyNOH) compounds by creating aluminum-ligand complexes with different starting materials, in this case AlMe$_3$. The first complex (μ-pyNO$^-$)Al(CH$_3$)$_2$}$_2$ **(1)** was made by a reaction of one equivalent of 2-(*tert*-butyl-hydroxylamine) pyridine (pyNOH) with AlMe$_3$ in toluene which gave a 83% yield (Figure 3). The ^{1}H NMR spectra showed that the deprotonation reactions occurred with virtually no side products. The second compound (pyNO$^-$)Al(CH$_3$)$_2$•Al(CH$_3$)$_3$ **(2)**, a colorless monomeric, dinuclear aluminum complex was made when two equivalents of AlMe$_3$ was added to one equivalent of (^{R}pyNOH). Complex **(2)** was prepared in a 70% yield. A ^{1}H-NMR was taken of compound **(2)** was taken and was consistent with the structure. It showed the aromatic peaks along with the t-Buytl and aluminum methyl peaks. The structure of the crystalline solids of both compounds **1** and **2** were found by x-ray crystallography (Figures 4 and 5).



$(\mu\text{-pyNO}^{-})Al(CH_3)_2\}_2$ **(1)** : 83%

$(\text{pyNO}^{-})Al(CH_3)_2{\bullet}Al(CH_3)_3$ **(2)** : 70%

Figure 3: Synthesis of the Al-pyridyl nitroxide complexes 1 and 2.

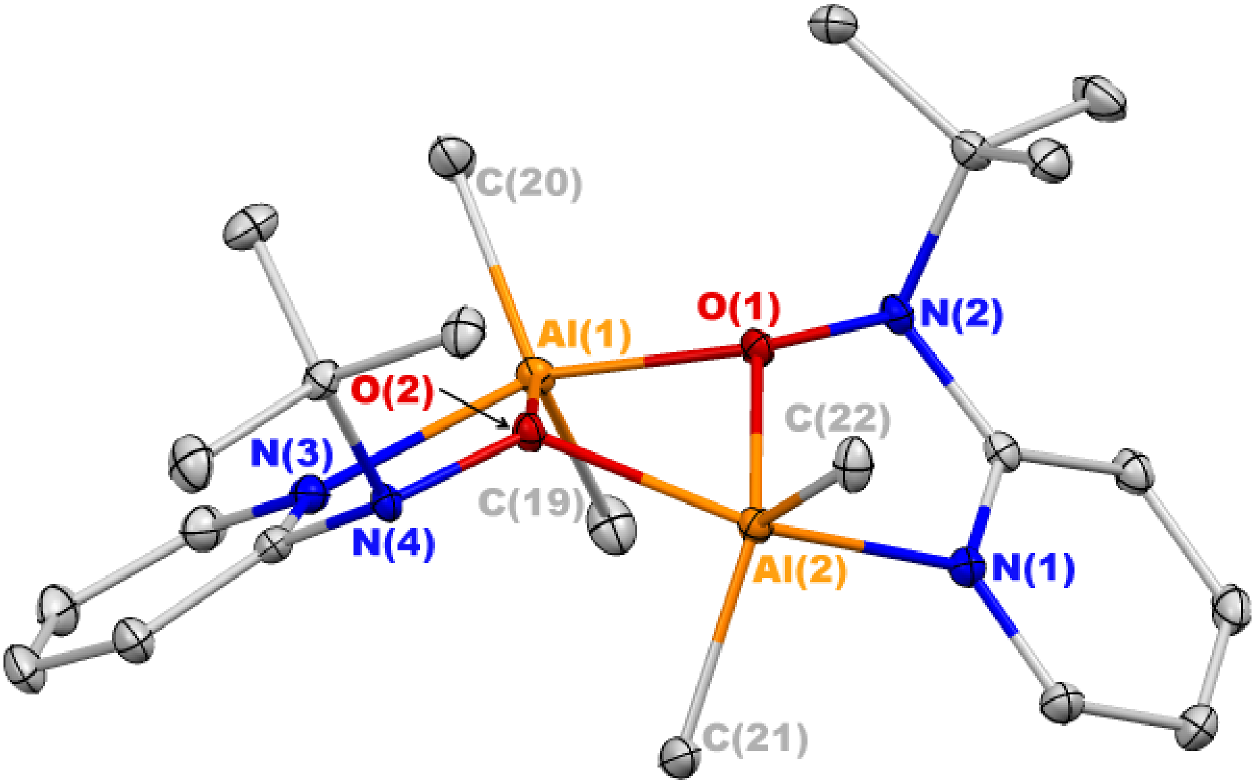


Figure 4. Solid state structure of $\{(\mu\text{-pyNO}^{-})\text{Al}(\text{CH}_3)_2\}_2$ (**1**). [6]

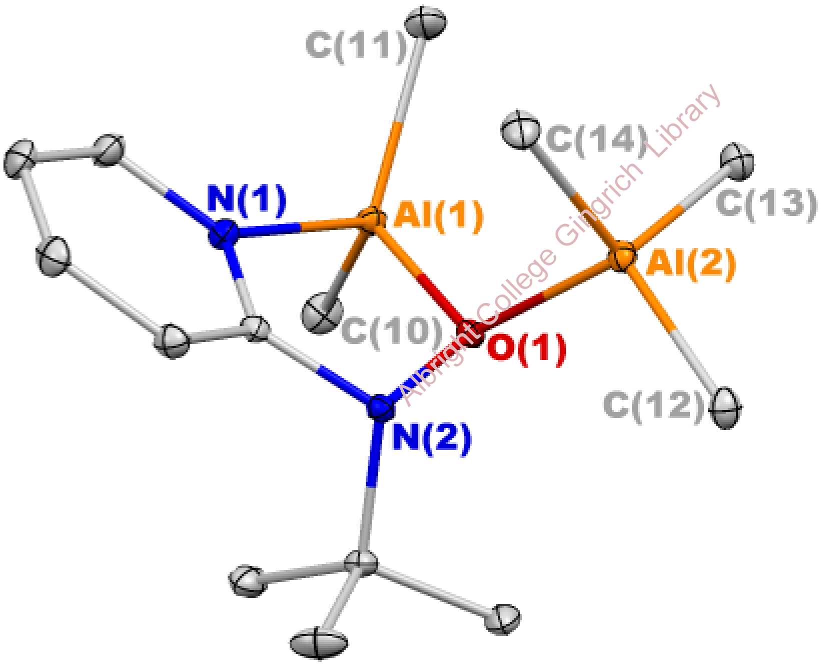


Figure 5: Solid state structure of (pyNO)Al(CH$_3$)$_2$•Al(CH$_3$)$_3$ (**2**). Ellipsoids are projected at 30% probability and H atoms are omitted for clarity [6].

The cyclic voltammogram of **1** was collected in THF (Figure 6). The CV of **1** exhibits two features, which we assign as sequential one-electron oxidation processes corresponding to the N–O^{-}/N–O$^{\cdot}$ couples of each pyNO^{-} ligand in the dimer. We do not observe the other two oxidation processes corresponding to the N–O$^{\cdot}$/N=O^{+} couples in the electrochemical window. In this complex, the first oxidation process is irreversible with the return reduction features essentially absent. The second oxidation is quasi-reversible with diminished return reduction waves.

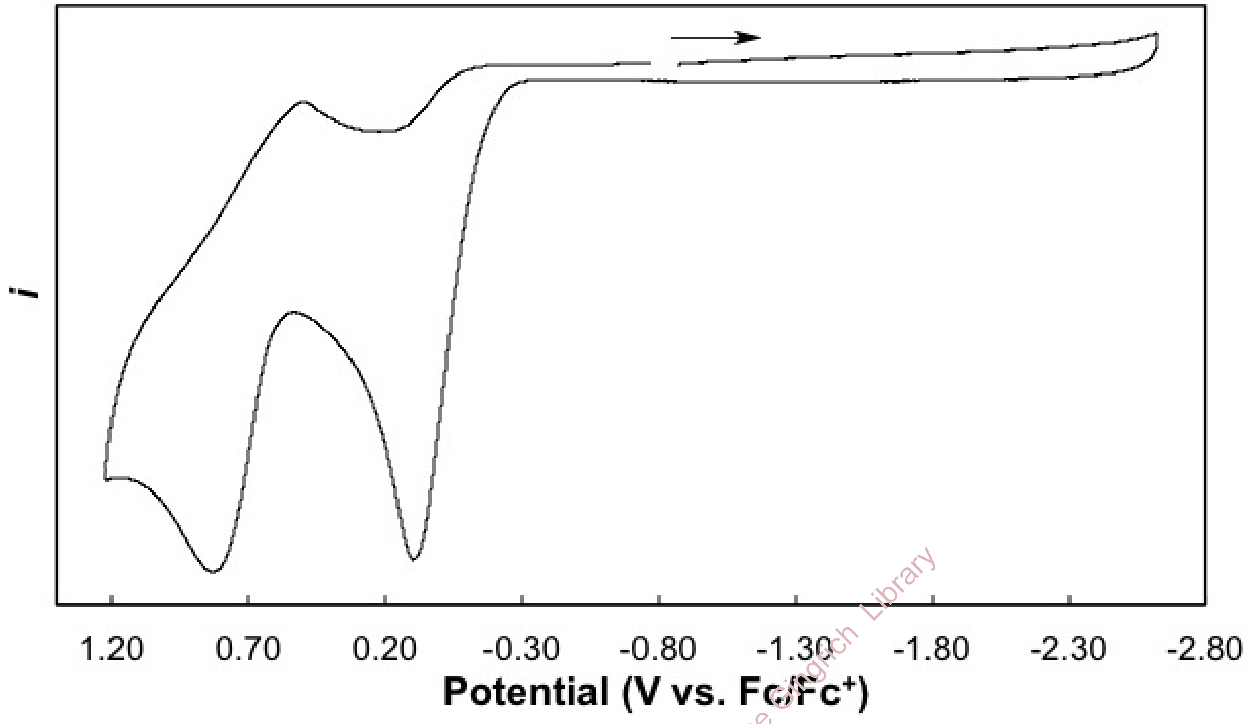


Figure 6: Cyclic voltammogram of compound **1** recorded in 0.1 M [n-Pr$_4$N][BAr^F] THF solution [5].

The whole basis upon the second part of this research is based upon finding an aluminum-ligand nitroxide complex that not only is oxidized, but is stable upon oxidation and has good, reversible electrochemical behavior. Even though the goal of part of the research was to change the identity of the central aluminum in order to create a more stable complex, the CV showed that a different route would have to be taken in order to achieve this. Instead of changing the source of aluminum, a complex synthesized with a new ligand utilizing the nitroxide functional group would possibly create a more stable complex.

PART 2

I have also been working on synthesizing more robust Al-nitroxide complexes and have been focusing on the multidentate tripodal nitroxide ligand [(2-^{t}BuNO)$C_6H_4CH_2)_3$N] (TriNOX). This ligand should form four bonds to the central aluminum ion and ultimately provide additional stability in the redox chemistry. We have also begun exploring the reactivity of the (TriNOX)Al complex with various oxidizing agents.

The first task in this part of the research was to prepare the [(2-^{t}BuNO)$C_6H_4CH_2)_3$N] ligand (**3**) (Figure 7. This was done following a literature procedure. [7] The identity of the ligand was confirmed by ^{1}H NMR which shows the OH peak at around 7.5 ppm and the CH_2 groups around 3.7 ppm (Figure X). Both of these signals were a key to look at to determine if the coordination chemistry to aluminum was successful. (

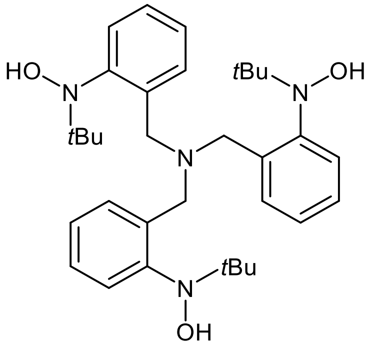


Figure 7: The (TriNOX)H_3 ligand **(3):**

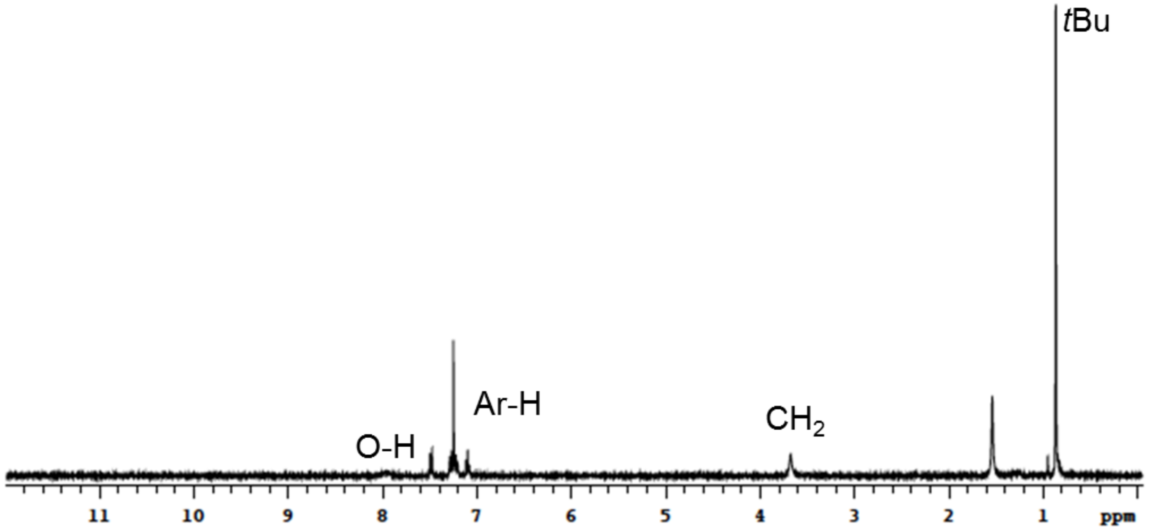
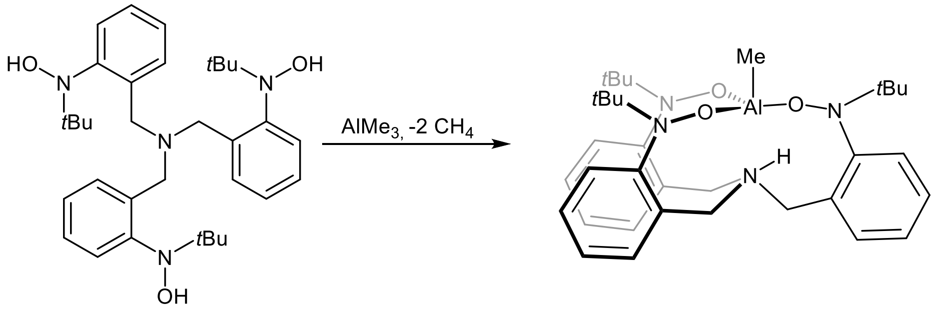


Figure 8: The ^{1}H NMR of the (TriNOX)H_3 ligand

Synthesis of H(TriNOX)AlMe

Once the (TriNOX)H_3 ligand was prepared the next goal was to coordinated the ligand to a central aluminum atom. The first approach that was used to generate this complex was to react the (TriNOX)H_3 ligand **(3)** with $AlMe_3$ in a one to one layered reaction with compound **(3)** dissolved in THF and $AlMe_3$ dissolved in hexane (Figure 9). Rather than the (TriNOX)Al complex **(6)**, the deprotonation did not occur and a proton shift resulted in the protonation of the ligand nitrogen and resulted in one remaining methyl group on the central aluminum. This was shown by the ^{1}H NMR with the presence of and N-H peak around 11.1 ppm and the Al-Me peak which is <0 ppm (Figure 10). The solid state of these white crystals of compound **(4)** was elucidated by x-ray crystallography (Figure 11).



H(TriNOX)AlMe **(4):**

Figure 9: The reaction diagram of the synthesis of H(TriNOX)AlMe

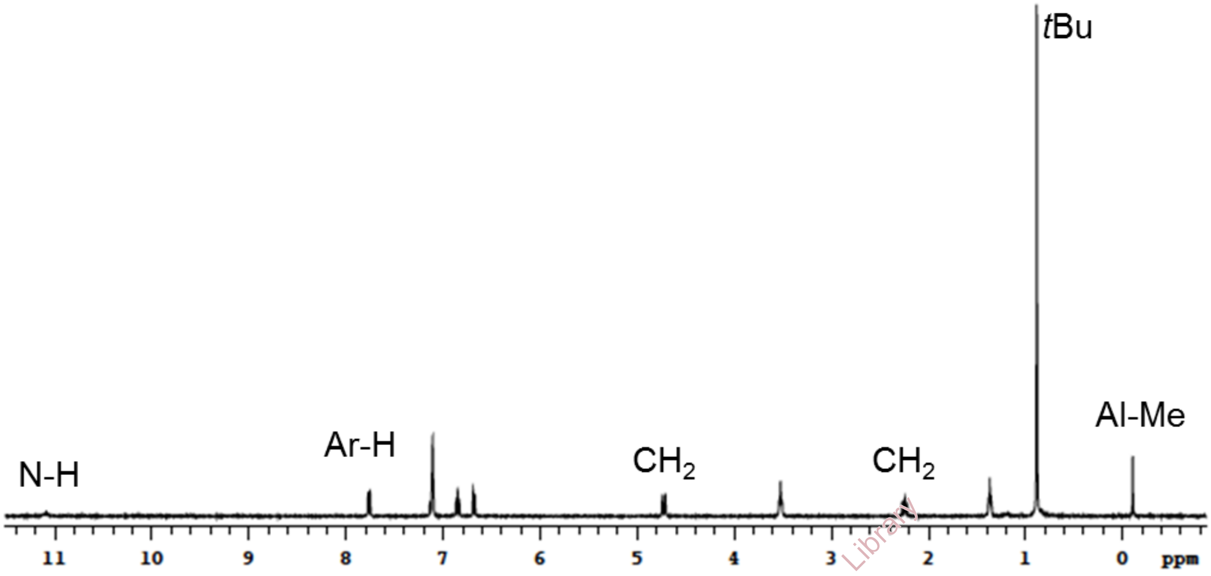


Figure 10: The ^{1}H NMR spectra of H(TriNOX)AlMe

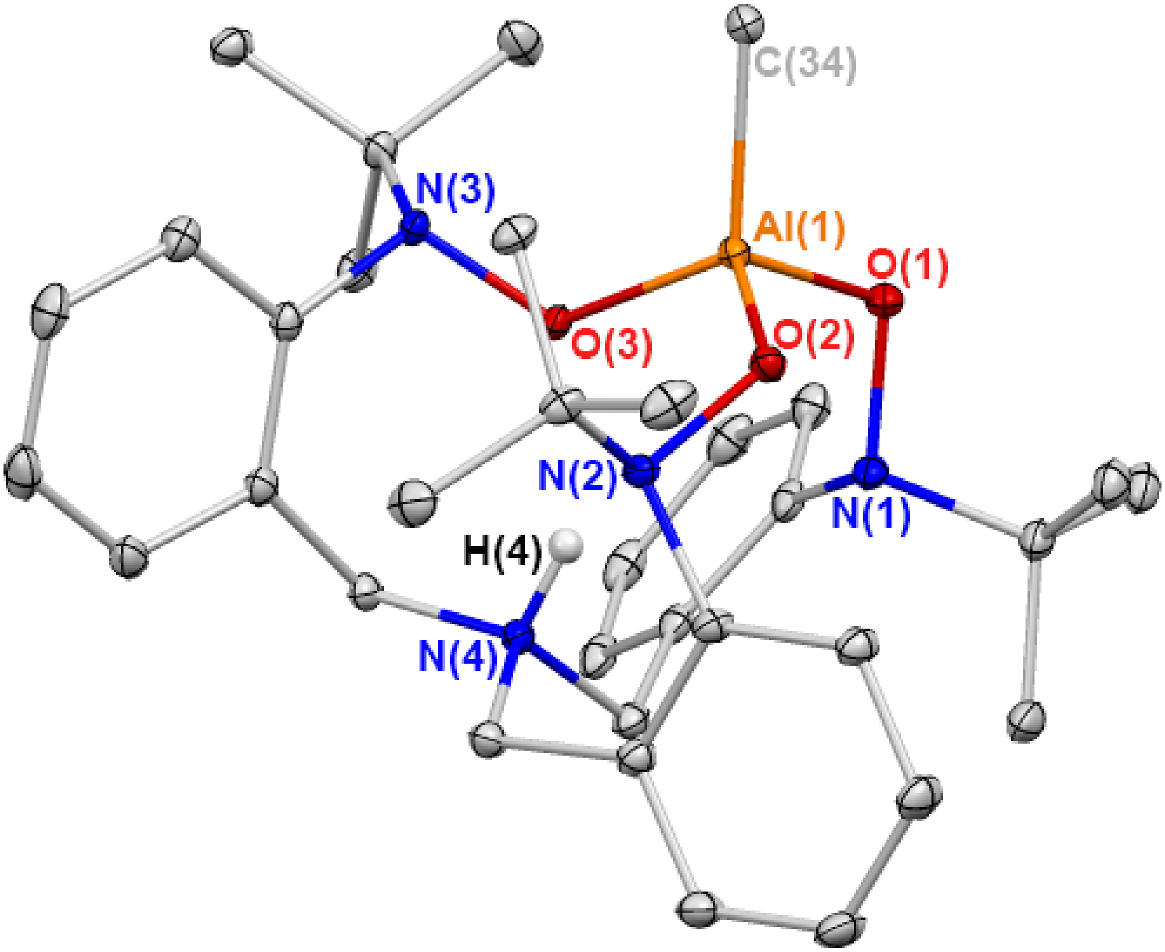
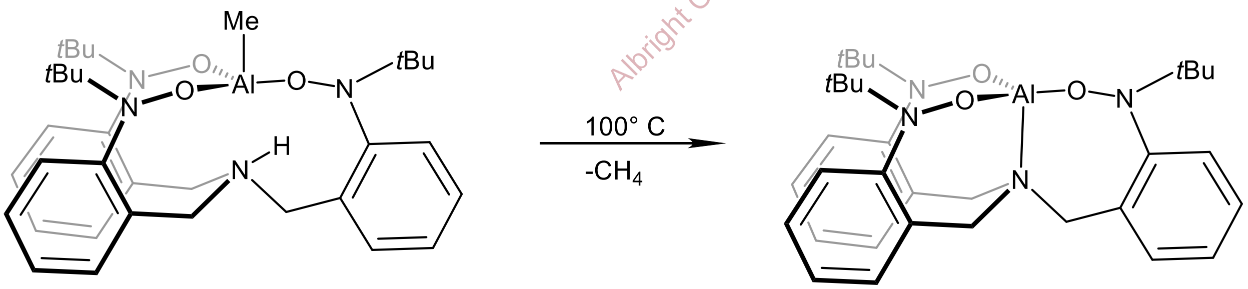


Figure 11: Solid state structure of H(TriNOX)AlMe **(4)**.

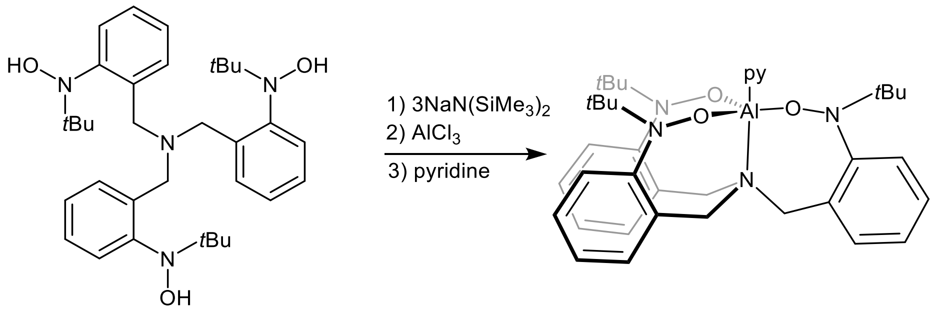
When compound **(4)** was heated to 100 °C for 24 hours in C_6D_6, there was a color change from colorless to yellow, and when the ^{1}H NMR was taken the N-H peak at 11.1 ppm was gone along with the Al-Me peak at 0 ppm. The proposed reaction that is thought to have occurred in given in Figure X and involves the deprotonation of the nitrogen accompanied with a loss of a methyl group.



(4) **(6)**

Figure 12: The loss of the methyl group that occurred during the heating of the H(TriNOX)AlMe changing to the (TriNOX)Al complex.

A more direct synthesis of the Al(TriNOX) complex was proposed by instead using a strong base to deprotonate the (TriNOX)H_3 ligand and then in the second step using $AlCl_3$ as the source of aluminum. This technique would require fewer steps to synthesize compound **(6)** than the previous synthesis. In order to get crystal structures of this complex, it was necessary to dissolve the compound in pyridine, so it was deduced that the complex made actually had a 5th bond to aluminum which came from a pyridine ring. Indeed the results of x-ray crystallography proved that compound **(5)** had been made in a 79% yield. The ^{1}H-NMR also confirms this result by showing only the two CH_2 peaks, methyl peaks from the t-Butyl groups and the aromatic hydrogens.



(TriNOX)Al-py **(5):**79%

Figure 13: The synthesis of the (TriNOX)Al-py complex **(5)**

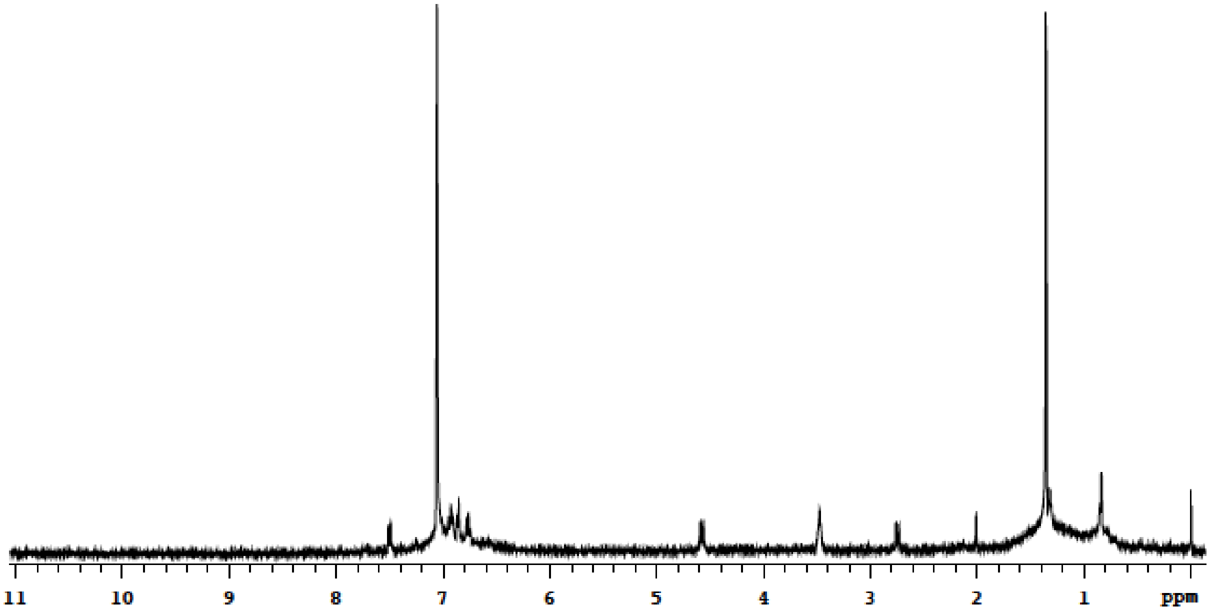


Figure 14: The ^{1}H NMR of the (TriNOX)Al complex

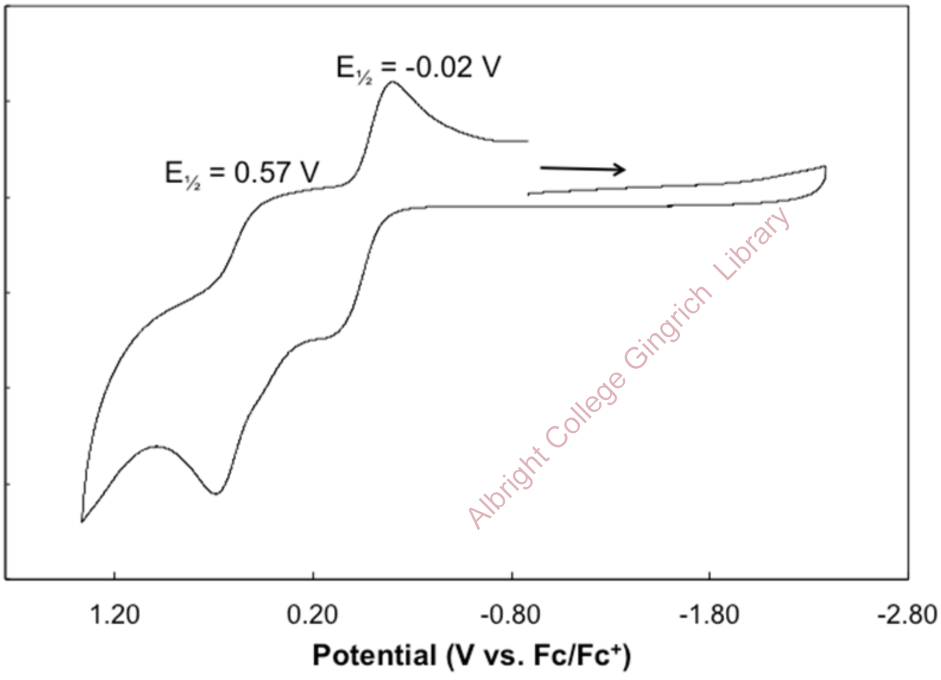


Figure 15: Cyclic voltammogram of compound **5** recorded in 0.1 M [*n*-Pr_4N][BAr^F] THF solution.

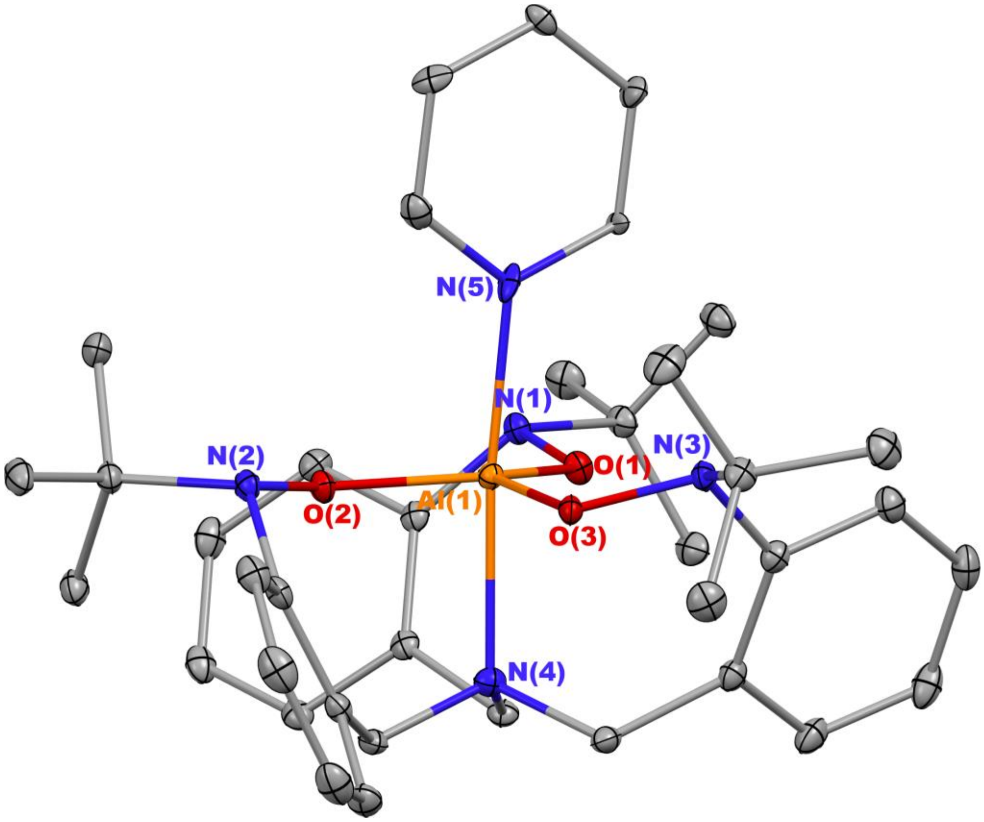


Figure 16: The crystalline structure of compound **(5)**

PART 3

Preliminary Reactivity

In this part of the project, preliminary oxidation reactions were conducted onto compound **(6)** in order to find the potential of this complex to change its oxidation state. The following oxidizing agents were used and found to react with compound **(6)**: I_2, CuCl, Py-O (heated to 100°C), XeF_2, Me(OTf), Trityl Br, Ag(OTf), and finally $N(C_6H_4Br)_3SbCl_6$. The proposed structures for all of the reactions are given in Figure 16.

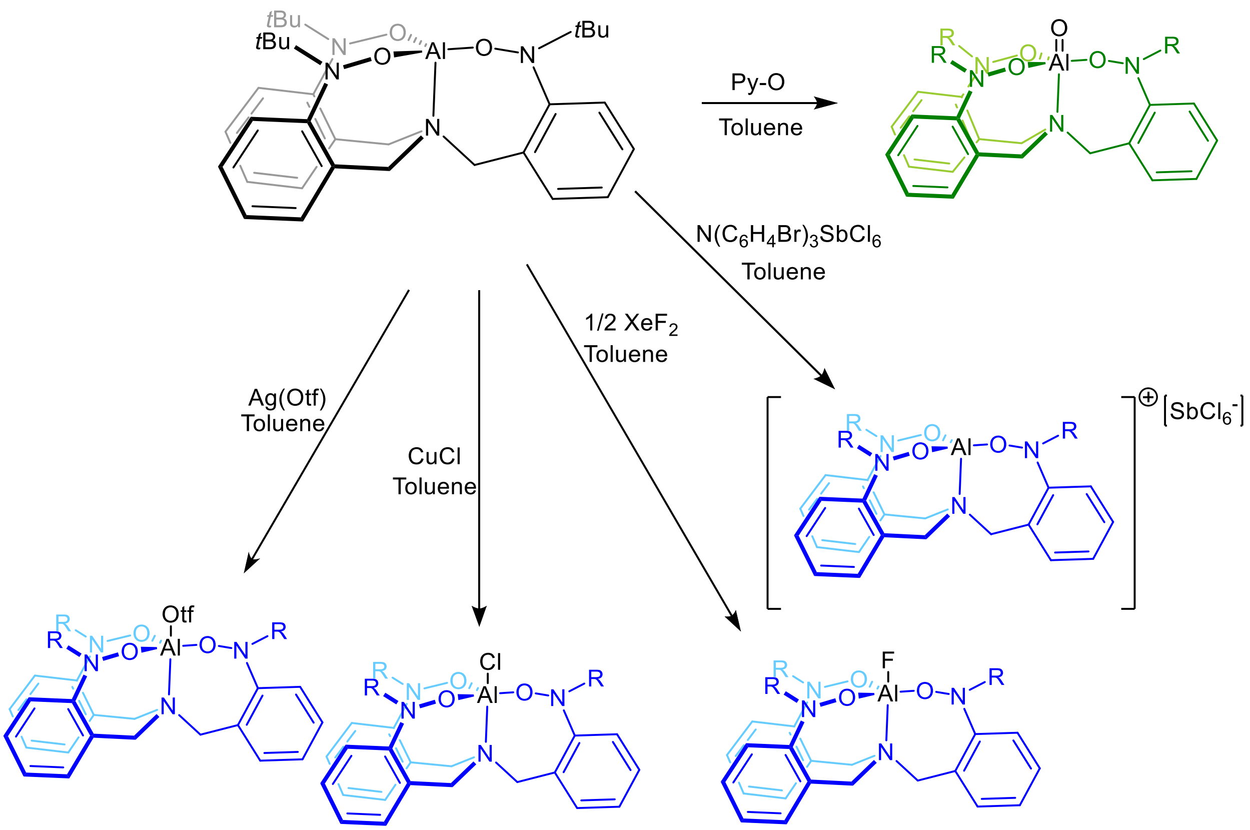


Figure 17: The oxidation chemistry performed on the (TriNOX)Al **(6)** complex. Two electron oxidations are in green and one electron oxidations are in blue.

Procedure for all:

25-100 mg of (TriNOX)Al was weighed out and dissolved in toluene (orange solution) Then 1 equivalent of the oxidizing agent was added and the reaction was stirred overnight. The reactions with precipitates had to be filtered through a filter pipet. The following color changes were observed:

Oxidizing agent	Physical Change Observed
I_2	Red solution
CuCl	Brown solution with brown precipitate
Py-O*	Yellow Color
XeF_2 (only had to use ½ equivalent)	Black solution
Me(OTf)	Pale yellow solution
Ag(OTF)	Brown solution (with precipitate)

*(Had to be heated to 100°C before reaction took place)

Figure 18: The observed physical, including color, changes that occurred during the oxidation of (TriNOX)Al **(6)** with various oxidizing agents.

EXPERIMENTAL

All reactions were performed under an inert atmosphere (N_2) or on the Schlenk line or in a Vacuum Atmospheres, Inc. Nexus II drybox equipped with molecular sieves 13X/Q5 Cu-0226S catalyst purifier system. The C_6D_6 that was used was for NMR experiments was purchased from Sigma Aldrich and stored with potassium metal before use. All other solvents that were used were sparged with dry argon for 20 minutes dried using a commercial two-column solvent purification system.

Synthesis of {(μ-pyNO$^-$)Al(CH$_3$)$_2$}$_2$ (1): *N-tert*-Butyl-*N*-(2-pyridyl)hydroxylamine (0.10 g, 0.60 mmol) was added to a flask equipped with a magnetic stir bar and was dissolved in toluene (~25 mL). A 2.0 M solution of trimethylaluminum in heptane (0.30 mL, 0.60 mmol) was added to the solution and the resulting mixture was stirred at room temperature. After 12 h, the reaction was filtered over a Celite-padded frit and the volatiles were removed from the filtrate under reduced pressure. The resultant oily solid was triturated with pentane (3 x 10 mL) and dried under reduced pressure to give **1** as a yellow solid. Yield: 0.11 g, 0.25 mmol (83%). ^{1}H NMR (C_6D_6): δ 7.45 (bs, 2H), 6.63 (t, *J* = 1.2 Hz, 2H), 6.44 (d, *J* = 8.8 Hz, 2H), 5.93 (t, *J* = 6.0 Hz, 2H), 1.27 (s, 18H, $C(CH_3)_3$), −0.24 (s, 12H, Al-CH_3). ^{13}C NMR (C_6D_6): δ 159.5, 143.0, 137.5, 115.5, 114.0, 62.6($C(CH_3)_3$), 28.6 ($C(CH_3)_3$), −6.3 ($AlCH_3$). Anal. Calcd. for $C_{22}H_{38}Al_2N_4O_2$: C, 59.44; H, 8.62; N, 12.60. Found: C, 59.34; H, 8.46; N, 12.55. UV−vis spectrum (CH_2Cl_2), λ_{max} (λ_M): 284 (24,400), 355 (5430).

Synthesis of (pyNO$^-$)Al(CH$_3$)$_2$•Al(CH$_3$)$_3$ (2): *N-tert*-Butyl-*N*-(2-pyridyl)hydroxylamine (0.10 g, 0.60 mmol) was added to a flask equipped with a magnetic stir bar and was dissolved in toluene (~25 mL). A 2.0 M solution of trimethylaluminum in heptane (0.60 mL, 1.20 mmol) was added to the stirring solution and the resulting mixture was stirred at room temperature. After 12 h, the reaction was filtered over a Celite-padded frit and the volatiles were removed from the filtrate under reduced pressure. The resultant oily solid was dissolved in hexane, filtered over a Celite-padded frit, and dried under reduced pressure to give 3 as a colorless solid. Yield: 0.12g, 0.41 mmol (68%). ^{1}H NMR (C_6D_6): δ 6.97 (dm, 1H, *J* = 5.6 Hz), 6.57 (td, 1H, *J* = 8.4 Hz, *J* = 1.6 Hz), 6.34 (dm, 1H, *J* = 8.4 Hz), 5.94 (tm, 1H, *J* = 5.6 Hz) 1.06 (s, 9H $C(CH_3)_3$), −0.20 (s, 6H, $AlCH_3$), −0.27 (s, 9H, $AlCH_3$). ^{13}C NMR (C_6D_6): δ 161.6, 141.9, 140.8, 119.6, 116.5, 65.4 ($C(CH_3)_3$), 28.5 ($C(CH_3)_3$), −5.8 ($AlCH_3$), −7.0 ($AlCH_3$). Anal. Calcd. for $C_{14}H_{28}Al_2N_2O$: C, 57.13; H, 9.59; N, 9.52. Found: C, 57.09; H, 9.65; N, 9.76. UV−vis spectrum (CH_2Cl_2), λ_{max} (λ_M): 284 (12,508), 351 (3025).

Synthesis of (TriNOX)H$_3$ (3): The synthesis of this ligand has been previously reported [7].

Synthesis of H(TriNOX)AlMe (4): 100 mg (0.182 mmol) of the tripodal nitroxide ligand [(2-^{t}BuNO)$C_6H_4CH_2)_3N$] was dissolved in THF. 0.9 mL of trimethylaluminum was dissolved in a pipet of hexanes. A layered reaction was performed to layer hexanes/trimethyaluminum over (TriNOX)H_3/tetrahydrofuran. White crystals formed on the bottom of the solution and collected by decanting the solvent, washing with hexane and then drying on the vacuum line. 0.0473 g of product was recovered (44.12% yield). An ^{1}H NMR and ^{13}C NMR were taken in C_6D_6.

Synthesis of (TriNOX)Al-py (5): 500 mg (0.91 mmol) of the white solid tripodal nitroxide ligand [(2-^{t}BuNO)$C_6H_4CH_2)_3N$] was weighed out and dissolved in THF. 500 mg of solid sodium bis(trimethylsilyl)amide was added and stirred for ~ 2 hours at room temperature. 121 mg of aluminum chloride was added and left stirring overnight. (orange/yellow solution). The solution was then filtered over a Celite-padded frit and the volatiles were removed from the filtrate under reduced pressure. The solid was then dissolved in pyridine and stirred for about 30 minutes, and then solvents were removed under reduced pressure. The orange solid was dissolved back in toluene and then filtered over a Celite-padded frit and the volatiles were removed from the filtrate under reduced pressure.. The solid was triterated 3 times with pentane and then 0.411g of solid was collected. ^{1}H-NMR and ^{13}C-NMR was taken of the sample.

Synthesis of (TriNOX)Al (6): The H(TriNOX)AlMe was dissolved in THF and heated at 100°C and stirred overnight. The solution had a color change from clear to yellow overnight. An ^{1}H NMR was taken in C_6D_6. The peaks on the NMR were consistent with (TriNOX)Al.

CONCLUSION

In part 1 of the project, two complexes were successfully synthesized that utilized different aluminum sources then previously used in order to create more stable complexes. The complexes were made from the $AlMe_3$ source (compounds **1** and **2**), but the complex did not seem to be reversible when the CV was taken. It seemed as though switching out the aluminum source was not enough to create a complex stable enough for the oxidative conditions. The (TriNOX)H_3 ligand was synthesized in part 2 of the project which was used to attach to aluminum in two different ways to synthesize compounds **(5)** and **(6)**. The CV of compound **(6)** was taken, and showed the reversibility of the complex, which shows that this ligand successfully created a more stable complex than previously made through the use of nitroxide ligands. Part 3 of the project demonstrated the preliminary reactivity of complexes **(5)** and **(6)** by reacting them with various oxidizing agents and monitoring the results through color change and ^{1}H-NMR.

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