

Synthesis and Characterization of $V^V(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$, a d^0 Metal Complex with Dioxygenase Catalytic Activity

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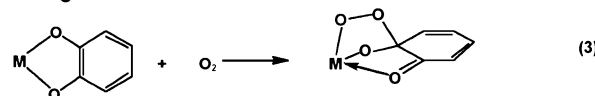
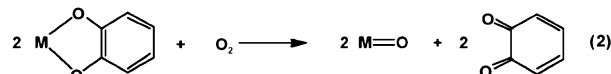
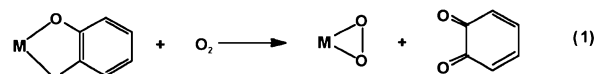
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Transition-metal complexes containing redox-active quinoid ligands are of interest because of their catalytic capabilities in multielectron, substrate-activation reactions such as dioxygenase catalysis using O_2 . The new catecholate complex $V^V(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$ (where 3,6-DBSQ = 3,6-di-*tert*-butylsemiquinone and 3,6-DBCat = 3,6-di-*tert*-butylcatecholate) was synthesized by combining $VO(\text{acac})_2$ with 1 equiv of 3,6-DBBQ (where 3,6-DBBQ = 3,6-di-*tert*-butylbenzoquinone) and 2 equiv of $H_2(3,6\text{-DBCat})$ in dry methanol under an inert atmosphere. The resultant complex was characterized by single-crystal X-ray diffraction, elemental analysis, near-IR, UV/vis, and electron paramagnetic resonance (EPR) spectroscopy. The crystallography as well as the near-IR and EPR studies suggest that the radical spin is localized on the 3,6-DBSQ ligand at room temperature, making $V^V(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$ a type 1 mixed-valence complex. Initial dioxygenase catalysis studies reveal that $V^V(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$ is a good dioxygenase precatalyst for the substrate $H_2(3,6\text{-DBCat})$ with O_2 in ca. 600 total turnovers to >93% intra- and extradiol products with only 1–2% of the undesired benzoquinone autoxidation product.

Studies on the coordination chemistry of transition-metal complexes containing redox-active quinoid ligands have recently been focused on multielectron substrate-activation reactions that use the electron density derived from the ligands without a change^{1–4} in the metal oxidation state.⁵ By far the most common substrate is O_2 , which is well-known to add to nucleophilic metal complexes; O_2 also adds to complexes containing α -diamide and catecholate ligands

without a change in the oxidation state at the metal.^{2,3} Reactions of this type are relevant to the mechanism of oxygen activation in enzymatic and synthetic catechol oxidation reactions.⁴ For example, peroxosemiquinonate complexes, proposed as intermediates in catechol oxidation reactions, have been formed reversibly for catecholate complexes of antimony(V), demonstrating that O_2 reduction is mediated by the catecholate ligand.⁶

In much earlier work with tris(catecholato) complexes of molybdenum(VI) and vanadium(V), it was observed that O_2 addition leads to the formation of oxobis(catecholato) species with the release of *o*-benzoquinone.^{7,8} These reactions demonstrate that there are three potential products that may be formed by the addition of O_2 to a d^0 metal complex containing a reduced quinoid (catecholate) ligand without a change in the metal oxidation state, namely, reactions and products (1)–(3).



These reactions can be taken a step further with the insertion of O_2 into a catechol C–C bond to give the ring-opened products associated with the intra- and extradiol dioxygenase enzymes and related synthetic systems.⁴ Recent structural characterization on an extradiol dioxygenase enzyme at various stages in the catalytic cycle has provided evidence for an iron peroxosemiquinonate intermediate.⁹

The catechol used most frequently in reactions that model catechol dioxygenase catalytic activity is 3,5-di-*tert*-butyl-

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catechol [$\text{H}_2(3,5\text{-DBCat})$; note once deprotonated $\text{H}_2(3,5\text{-DBCat})$ becomes the catecholate $3,5\text{-DBCat}$]¹⁰ because of its commercial availability and the activating effect of the *tert*-butyl substituents. Reactions have been studied with a wide variety of metals, but the two metals studied most extensively are iron, because of its biological relevance, and vanadium, because of its catalytic efficiency.¹¹

Earlier reactions between either $\text{V}(\text{CO})_6$ and 3,5-di-*tert*-butyl-1,2-benzoquinone (3,5-DBBQ) or $\text{VO}(\text{acac})_2$ and $\text{H}_2(3,5\text{-DBCat})$ were both observed to form “ $\text{V}(3,5\text{-DBQ})_3$ ” under inert conditions (where 3,5-DBQ = 3,5-di-*tert*-butylquinoid).⁷ Electron paramagnetic resonance (EPR) characterization established that “ $\text{V}(3,5\text{-DBQ})_3$ ” had a ligand-based $S = 1/2$ spin ground state that might be associated with a $\text{V}^{\text{III}}(3,5\text{-DBSQ})_3$ (where 3,5-DBSQ = 3,5-di-*tert*-butylsemi-quinone) species with strong V–SQ antiferromagnetic spin coupling or with the redox isomer $\text{V}^{\text{V}}(3,5\text{-DBSQ})(3,5\text{-DBCat})_2$ and its mixed-charge ligands.⁷ In the presence of trace quantities of O_2 , the product was observed to form dimeric $[\text{V}^{\text{V}}\text{O}(3,5\text{-DBSQ})(3,5\text{-DBCat})_2]_2$.^{7a} In the presence of excess oxygen, $[\text{VO}(3,5\text{-DBSQ})(3,5\text{-DBCat})_2]_2$ reacts further to ultimately give V_2O_5 and 3,5-DBBQ,^{7a} but in the presence of excess $\text{H}_2(3,5\text{-DBCat})$, the dimeric complex serves as an exceptionally long-lived catalyst for catechol oxidation with $>10^5$ turnovers of $\text{H}_2(3,5\text{-DBCat})$ to produce well-characterized intra- and extradiol dioxygenase products.¹²

However, less investigated are metal complexes containing 3,6-DBCat ligands^{13,14} or catechol oxidation catalysis¹⁴ using $\text{H}_2(3,6\text{-DBCat})$. The symmetrical distribution of *tert*-butyl substituents should have the following advantages: (i) they should lead to a less complicated series of organic oxidation products, relative to $\text{H}_2(3,5\text{-DBCat})$; and (ii) monomeric metal precursors and possibly catalysts should be favored by the disposition of *tert*-butyl substituents adjacent to the catecholate oxygens which, in turn, should disfavor bridging interactions to a second metal center. However, these and other advantages (or disadvantages) of 3,6-DBCat remain less investigated in comparison to those of 3,5-DBCat.^{13,14}

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(10) Initial reductive activation of triplet O_2 by electron transfer from a spin singlet catecholate ligand would be spin-forbidden as an inner-sphere condensation reaction, yet basic solutions of 3,5-DBCat are notoriously oxygen-sensitive, giving ring-cleavage products upon exposure to air. Speier, G.; Tyeklar, Z. *J. Mol. Catal.* **1990**, *57*, L17–L19. (b) It therefore seems reasonable that the initial activating Cat $\rightarrow \text{O}_2$ electron-transfer step should take place with the formation of a quasi-outer-sphere intermediate that leads to one of the reduced oxygen species shown in eqs 1–3.

(11) In an earlier publication, we cited 28 literature 3,5-DBCat oxidation precatalyst systems based on vanadium (Yin, C.-X.; Finke, R. G. *J. Am. Chem. Soc.* **2005**, *127*, 9003–9013). By monitoring the O_2 uptake, we were able to establish that these precatalysts proceed with the initial formation of H_2O_2 and 3,5-di-*tert*-butyl-1,2-benzoquinone (3,5-DBBQ) in the presence of excess $\text{H}_2(3,5\text{-DBCat})$. The catalyst resting state, $[\text{VO}(3,5\text{-DBSQ})(3,5\text{-DBCat})_2]_2$, is formed in an autocatalytic step and then breaks in half to a monomeric dioxygenase catalyst according to the observed kinetics.¹²

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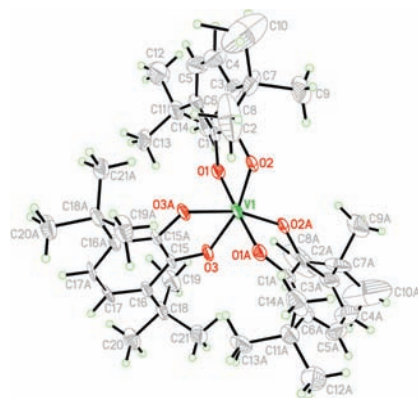


Figure 1. 50% probability thermal ellipsoid plot of $\text{V}(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$.

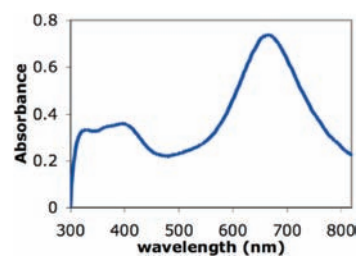
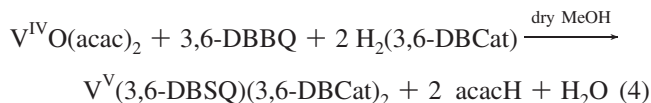


Figure 2. UV/vis spectra of 2.2×10^{-5} M $\text{V}(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$ in toluene and under an inert atmosphere at room temperature.

Herein we report that the reaction between $\text{VO}(\text{acac})_2$ and a 2:1 mixture of $\text{H}_2(3,6\text{-DBCat})$ and 3,6-DBBQ in dry methanol gives a new octahedral monomeric product of formula $\text{V}^{\text{V}}(3,6\text{-DBSQ})(3,6\text{-DBCat})_2$ (**1**). In addition, we find that **1** is a good $\text{H}_2(3,6\text{-DBCat})$ dioxygenase precatalyst,¹⁵ leading to ~ 600 total catalytic turnovers (TTO) to more than 93% intra- and extradiol dioxygenase products, with very little (1–2%) of the undesired benzoquinone autoxidation product, *vide infra*.

Complex **1** was synthesized according to eq 4. The bulk sample composition, verified by elemental analysis (Galbraith Laboratories, Inc., Knoxville, TN), is consistent with the formula $\text{V}(3,6\text{-DBSQ})(3,6\text{-DBCat})_2 \cdot \text{CH}_3\text{OH}$. Calcd [found]: V, 6.85 [6.58]; C, 69.43 [69.91]; H, 8.67 [8.90].



Crystallographic characterization¹⁶ is consistent with the bulk sample composition and reveals that **1** consists of charge-localized SQ and Cat ligands. Complex **1** is located about a crystallographic 2-fold axis that bisects the semi-quinonate ligand (Figure 1).

Relevant to the structure of **1** is that prior structure determinations of complexes containing mixed-charge SQ and Cat ligands, C–O lengths have been diagnostic of the

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(16) Unit cell data for $\text{C}_{43}\text{H}_{64}\text{O}_7\text{V}[\text{V}(3,6\text{-DBSQ})(3,6\text{-DBCat})_2 \cdot \text{CH}_3\text{OH}]$: orthorhombic, space group $Ccca$, $Z = 8$. $a = 19.9969(17)$ Å, $b = 23.740(2)$ Å, $c = 18.1741(16)$ Å. R (R_w) = 0.0540 (0.0840), GOF = 1.071.

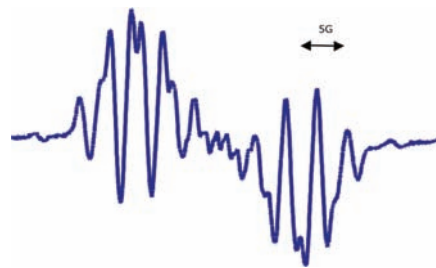
Table 1. Selected Bond Lengths (Å) for V(3,6-DBSQ)(3,6-DBCat)₂

Cat ligands		SQ ligands			
V–O1	1.868(2)	V–O2	1.898(2)	V–O3	1.971(2)
C1–O1	1.330(4)	C2–O2	1.326(4)	C15–O3	1.298(3)
C1–C2	1.421(5)			C15–C15A	1.466(6)
C3–C4	1.376(5)	C5–C6	1.373(6)	C16–C17	1.364(4)

reduction level of the quinone ligand.¹⁷ In this case as well, the C–O length for the ligand located along the 2-fold axis is at a SQ value, 1.298(3) Å, the C–O lengths for the independent Cat ligand are 1.330(4) and 1.336(4) Å, and the C–C length between ring C1 and C2 carbon atoms is significantly longer for the SQ ligand [1.466(6) Å] than for the Cat ligand [1.421(5) Å] (Table 1). The C–C lengths at the ring 3–4 and 5–6 positions are generally found to be contracted for SQ ligands (C16–C17 of the structure determination), and this is the case for the 3,6-DBSQ ligand with a value of 1.364(4) Å. However, lengths at these positions for the Cat ligand are found to be similarly contracted [1.376(5) and 1.373(6) Å; Table 1], suggesting some SQ character for this ligand that could result from either crystallographic disorder or a shift in the charge distribution to, conceivably, a V^{III}(3,6-DBSQ)₃ redox isomer.

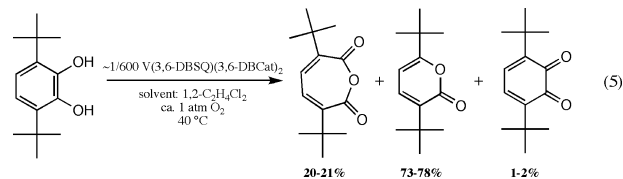
The related complex of manganese was found to undergo a shift in the charge distribution, from Mn^{III}(3,6-DBSQ)₃ at temperatures just above room temperature to Mn^{IV}(3,6-DBSQ)₂(3,6-DBCat) at lower temperatures.^{13c} This equilibrium could be monitored by the appearance of a ligand-to-ligand' intervalence transfer (LL'IT) transition at 2300 nm for the complex at low temperature. However, electronic spectra obtained for the vanadium complex **1** in solution (Figures 2 and S4 of the Supporting Information) and in the solid state (Figures S1–S3 of the Supporting Information) show no evidence for a shift in charge between the Cat and SQ ligands. Spectra recorded in both media show an intense absorption at 670 nm¹⁸ ($\epsilon = 33000\text{--}38000\text{ M}^{-1}\text{ cm}^{-1}$; concentrations = $2.2 \times 10^{-5}\text{--}9.4 \times 10^{-5}\text{ M}$ in toluene), similar to that of the 668 nm band ($\epsilon \sim 27000\text{ M}^{-1}\text{ cm}^{-1}$) observed for [VO(3,5-DBSQ)(3,5-DBCat)]₂ in toluene.¹¹ No other absorptions at lower energy that might be associated with a precedented^{13a–c} type 2 mixed-valence complex (where the region is $\sim 2100\text{ nm}^{13a–c}$) are observed for **1**, at least at room temperature.

The isotropic EPR spectrum recorded for V^V(3,6-DBSQ)(3,6-DBCat)₂ in toluene confirms the charge-localized nature of the complex at room temperature. The spectrum, shown in Figure 2, is that of the 3,6-DBSQ radical, weakly coupled with the $I = 7/2$ ⁵¹V center, with additional coupling from the two SQ ring protons at carbon atoms C4 and C5 (C17 and C17A of the structure determination). The spectrum is centered about a $\langle g \rangle$ value of 2.0058, and a reasonable simulation could be obtained with $A(^{51}\text{V})$ of 3.47 G and $A(^1\text{H})$ of 4.53 G. This is in contrast to the nine-line spectrum with $\langle g \rangle$ value of 2.004 along with $A(^{51}\text{V})$ and $A(^1\text{H})$ of 2.85 and 0.35 G, respectively, observed for [VO(3,5-DBSQ)(3,5-DBCat)]₂.^{8a} Together, the

**Figure 3.** EPR spectrum of V(3,6-DBSQ)(3,6-DBCat)₂ in toluene and under an inert atmosphere at 23 °C.

electronic and EPR spectra of **1** point to a charge-localized type 1 mixed-valence formulation for V^V(3,6-DBSQ)(3,6-DBCat)₂ with no contribution from, for example, V^{III}(3,6-DBSQ), again at room temperature. Studies of other temperatures would be valuable and are in progress.

Preliminary studies examining the catalytic activity of **1** plus the substrate H₂(3,6-DBCat) under O₂ show that the products and yields shown in eq 5 are obtained according to gas chromatography–mass spectrometry (GC–MS) identification and GC quantitation. Importantly, as eq 5 summarizes, >93% dioxygenase products are obtained with **1** along with only 1–2% of the undesired autoxidation product, benzoquinone (the ranges of the products shown represent the small variability in three repeat catalytic runs). In addition, even these initial catalytic results demonstrate the catalytic dioxygenase capability derived from **1** of ca. 600¹⁹ TTOs for the substrate H₂(3,6-DBCat). Additional studies of the dioxygenase activity derived from **1** are currently underway.¹⁵



To summarize, herein we have described the synthesis of the catecholate complex **1** and its characterization by single-crystal X-ray diffraction, elemental analysis, near-IR, UV/vis, and EPR. The data reveal that **1** is a type 1 mixed-valence compound at room temperature with a localized radical spin on the 3,6-DBSQ ligand. Catalysis of H₂(3,6-DBCat) plus O₂ plus **1** as the precatalyst gives intra- and extradiol dioxygenase products along with 1–2% of the autoxidation product benzoquinone in ca. 600 TTOs of catalysis. Future studies and a full report on the dioxygenase catalytic activity of **1** as well as other vanadium and molybdenum catecholate complexes will be reported in due course.¹⁵

Acknowledgment. We gratefully acknowledge NSF Grant CHE 9531110 to R.G.F.

Supporting Information Available: Full experimental section including materials and methods and the synthesis of H₂(3,6-DBCat), 3,6-DBBQ, and V(3,6-DBSQ)(3,6-DBCat)₂, tables of X-ray crystallographic information, atomic coordinates, isotopic displacement, bond length, and bond angle, near-IR and IR spectra of V(3,6-DBSQ)(3,6-DBCat)₂, solid-state and solution UV/vis spectra of V(3,6-DBSQ)(3,6-DBCat)₂, and X-ray crystallographic data in CIF format. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(18) The large intensity of the band at 670 nm leads one to wonder if this band is a LL'IT band. However, this band is higher in energy than expected and, to our knowledge, is unprecedented for LL'IT systems.

(19) TTOs were calculated by the formula $\sum[\text{oxygenated products (mmol)}] / [\text{V(3,6-DBSQ)(3,6-DBCat)}_2 \text{ (mmol)}]$.