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Interactions of Vanadium(IV) with Amidoxime Ligands: Redox Reactivity

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The use of amidoxime-functionalized polymer fibers as a sorbent for uranium has attracted recent interest for the extraction of uranium from seawater. Vanadium is one of the main competing ions for uranium sorption as V(V) species, however, vanadium is also present as V(IV) in seawater. In the present study, the interactions of V(IV) with amidoxime and similar ligands was explored. Attempts were made to synthesize V(IV) complexes of glutarimide-dioxime, a molecular analogue of polymer sorbents. However, V(IV) was found to react irreversibly with glutarimide-dioxime and other oxime groups, oxidizing to the V(V) oxidation state. We have explored the reactions and propose mechanisms, as well as characterized the redox behavior of the vanadium-glutarimide-dioxime complex.

Introduction

The world's oceans contain over 4.5 billion tons of uranium, over 1,000 times more than all known terrestrial sources, and it is therefore a promising source of uranium for nuclear energy.¹ The extraction technique receiving the most interest makes use of polymer sorbents functionalized with amidoxime groups, with significant improvements being made over the past 6 years that have more than doubled the sorbents' uranium capacity.^{1,2} Solution-state studies have generally involved several molecular analogues of these groups (Figure 1). Glutarimide-dioxime (**L^A**) has received the most attention due to its high affinity for uranium.³ It does have a significant drawback, which is its relatively low selectivity, forming strong complexes with several other metals including iron, copper,⁴ and notably vanadium, forming a very unusual, strong non-oxido complex in that case (Figure 1).^{5,6}

Vanadium is present in seawater at approximately 0.5–2 ppb (10–40 nM)⁷, which is similar to that of uranium at 3.3 ppb (13 nM)⁸, and indeed is the second most abundant transition metal in seawater after molybdenum.^{8,9} It is mainly present in the V(V) oxidation state due to slow oxidation of V(IV) by aerated water; nonetheless, approximately 10–15% of vanadium is present in the V(IV) state.⁷ This naturally occurring mixture of oxidation states, which is subject to seasonal and geographical variation, is a consequence of biological uptake

and use of vanadium in marine environments.^{7,9,10} Vanadium is an essential element for many organisms, although typically in very small amounts. *In vivo*, vanadium is present in several chemical environments in oxidation states ranging from V(III) – V(V), often V(IV), and when marine organisms die they release vanadium in those varying oxidation states.¹¹

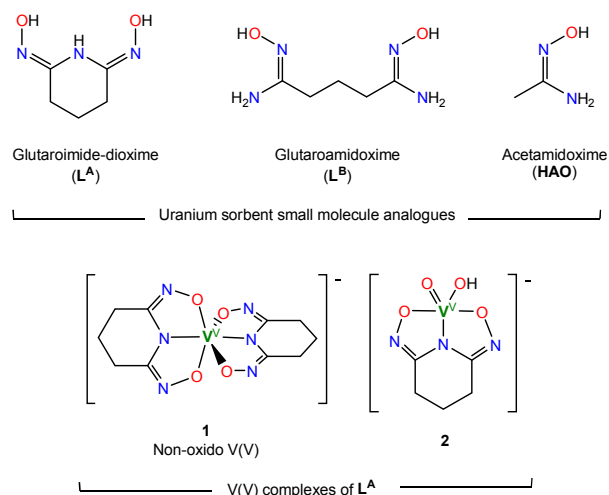


Figure 1. Ligands investigated for V(IV) reactivity and their known V(V) complexes.

Although the coordination chemistry of V(V) has been studied recently with glutarimide-dioxime,⁵ as well as its interactions with polymer sorbents,^{6,12} the analogous chemistry of V(IV) has not yet been investigated. Our initial work sought to study the interactions of V(IV) with seawater-relevant amidoxime ligands (Figure 1) in the same manner as U(VI), Fe(III), V(V) and other metals.^{3,5,13} In this way, we would understand the role of V(IV) in determining uranium sorption selectivity attempt to synthesize the non-oxido vanadium in the V(IV) oxidation state in the same way as V(V). However,

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† Footnotes relating to the title and/or authors should appear here.

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while doing so we discovered that V(IV) reacts with amidoxime ligands in conditions relevant to seawater, oxidizing to V(V) in the process. This type of reactivity has previously been observed with hydroxamic acids, a similar class of ligands with N-OH groups, where the O atom is abstracted upon complexation with V(III), V(IV), and Mo(V), forming the corresponding amide and oxidized metal-oxo complexes.¹⁴ One previous report of V(IV) reacting with salicylaldoxime leads to the V(V)-salicylaldoxime complex as the major product along with smaller amounts of other complexes arising from coupled small organic molecules.¹⁵ Other low oxidation state metal ions have also been observed to react similarly, including Mo(II)¹⁶ and U(IV),¹⁷ although in seawater uranyl is present exclusively as uranyl(VI) carbonate complexes.¹⁸

In our attempts to prepare and characterize V(IV) complexes of the model oxime ligands and reagents shown in Figure 1, we found that they invariably reacted to form V(V) complexes under the conditions tested. Cyclic voltammetry was performed on the 2:1 glutaroimide-dioxime V(V) complex **1** and, surprisingly, it was found to undergo reduction at a strongly negative potential. We also attempted to synthesize a V(IV) complex in non-aqueous solvents both directly and through chemical reduction of the V(V) complex, however, no stable complexes could be isolated, suggesting a V(IV) analogue may be inherently unstable towards ligand reactivity or disproportionation to V(V) and reduced species.

Methods

Synthesis

Acetamidoxime (HAO) was synthesized by stirring equal volumes of a 50% aqueous hydroxylamine solution, acetonitrile, and ethanol (5 mL each) at room temperature for 24 hours, followed by warming to 40°C in a glass Petri dish until all the volatiles evaporated and a white solid remained. It was then dissolved in water (5 mL) and evaporated again to remove any remaining acetonitrile. The resulting solid was redissolved in approximately 10 mL of water and its concentration was determined by ¹H NMR spectroscopy and protonation titration.

Tetraethylammonium vanadium(V) bis(glutaroimide-dioxime) ([NEt₄][1]) was prepared by adding glutaroimide-dioxime (290 mg, 2.1 mmol), ammonium metavanadate (117 mg, 1.0 mmol), and tetraethylammonium bromide (168 mg, 0.80 mmol) to a mixture of water (10 mL) and methanol (5 mL). The mixture was stirred vigorously for 30 minutes at room temperature, during which the mixture turned dark brown and the solids completely dissolved. The mixture was transferred to a glass Petri dish and warmed at 40°C overnight, during which all the solvent evaporated to leave a dark brown solid. The solid was extracted with dichloromethane (5×10 mL), dried over magnesium sulphate, filtered, and the solvent removed to give a brown oil. This was crystallized from dichloromethane (20 mL) layered with an equal volume of THF. Large dark brown-black blocks of [NEt₄][1] formed over several days. It is very soluble in chloroform, dichloromethane,

alcohols, and most other polar solvents, has trace solubility in THF, and is insoluble in all low-polarity solvents. The same product can be obtained in similar yield by using sodium orthovanadate instead of ammonium metavanadate, adjusting the pH to 6-8. Yield: 230 mg (0.50 mmol, 63%). ¹H NMR (CDCl₃): 1.23 ppm (t, 12H, ³J_{HH} = 7.4 Hz, N(CH₂CH₃)₄), 1.95 ppm (quintet, 4H, ³J_{HH} = 6.3 Hz, CH₂CH₂CH₂), 2.62 ppm (t, 8H, ³J_{HH} = 6.3 Hz, CH₂CH₂CH₂), 3.18 ppm (t, 8H, ³J_{HH} = 7.4 Hz, N(CH₂CH₃)₄); ¹³C NMR (CDCl₃, 126 MHz): 7.7 ppm (4C, N(CH₂CH₃)₄), 21.4 ppm (2C, CCH₂CH₂CH₂C), 21.6 ppm (4C, CCH₂CH₂CH₂C), 52.5 ppm (4C, t, ¹J_{CN} = 3.0 Hz, N(CH₂CH₃)₄), 154.0 ppm (4C, C=N-O-V); ⁵¹V NMR (CDCl₃, 132 MHz): 739 ppm.

Glutaramidoxime (**L^B**)¹⁹ and vanadyl toluenesulfonate²⁰ were synthesized according to literature procedures. Glutaroimide-dioxime (**L^A**) was synthesized according to literature procedure and recrystallized twice from methanol before use.²¹ Vanadyl (oxyvanadium, V(IV)) solutions were prepared by reducing a solution of acidified V₂O₅ with excess hydroxylamine hydrochloride. V(IV) was precipitated as VO₂ by the addition of sodium hydroxide, then redissolved in hydrochloric acid. The concentration of V(IV) was determined by titration with a solution of KMnO₄ of known concentration.

All other chemicals were obtained from commercial sources and used as received.

Cyclic voltammetry

Cyclic voltammetry experiments were performed on a Gamry Instruments Reference 600 potentiostat and data acquired with Gamry Framework software. Experiments in acetonitrile and DCM were performed in an inert atmosphere glovebox using dry solvent with 0.1 M [NBu₄][PF₆] electrolyte, with a Pt disc working electrode, Pt gauze counter electrode and Pt wire quasi-reference electrode. Experiments in water and methanol were performed with a Pt disc working electrode, Pt wire counter electrode and Ag/AgCl reference electrode, with 0.2 M KCl as the electrolyte in water and 0.2 M [NEt₄][Cl] in methanol. Ferrocene was added as an internal standard to non-aqueous solutions (Fc⁺/Fc at 0 V) and potassium ferricyanide was added as an internal standard to aqueous solutions ([Fe(CN)₆]³⁻/[Fe(CN)₆]⁴⁻ at +0.04 V) to reference experiments.

NMR

An internal standard of approximately 1 mM *t*-butanol (the exact concentration calculated per experiment based on stock solution volumes) in D₂O/H₂O mixtures was used as the solvent for quantitative experiments. ¹H NMR spectra in water or H₂O/D₂O mixtures were acquired on a Bruker AV-500 instrument (500 MHz) with a WATERGATE solvent suppression pulse sequence. ⁵¹V NMR spectra were acquired on a Bruker DRX-500 instrument (132 MHz).

Results and discussion

Attempts to prepare a reduced L^A-vanadium(IV) complex

In order to study the complexation behaviour of vanadium(IV) with L^A, we initially attempted a direct synthesis from L^A and aqueous vanadyl (oxyvanadium(IV)) under a variety of reaction conditions, varying the pH over the range of approximately 4–10, as well as the stoichiometry, rate, and order of addition of reagents. However, in water, only known V(V) species were identified as products: **1**, **2**,⁵ and mixtures of free vanadates, with the exact speciation of the latter dependent on concentrations and final pH.²² Regardless of the conditions used, V(V) complexes **1** and **2** and free V(V) species were invariably produced, confirmed by ⁵¹V NMR and visually, with the reaction changing to the amber-brown colour of **1**. To preclude the role of oxygen in these reactions, water degassed by boiling or sparging with nitrogen was used, with no change in outcome. This indicates that V(IV) oxidation in water is not caused by oxygen but rather by the ligand itself.

When the same reaction was performed in dry, degassed methanol, the reaction mixture turned a deep red colour within seconds, followed by a slow change to dark amber, indicating the formation of **1**. If the reaction is carried out under argon and the solvent removed rapidly just after the onset of the reaction, colourless crystals of toluenesulphonic acid form, and a deep red oil containing polyoxovanadates (V(V)) remains.²² When water is added to the red solution or oil, the vanadium clusters hydrolyse immediately and form the V(V) complex **1** with its characteristic dark amber colour. If the reaction is performed in basic methanol (sodium methoxide) or methanol with a drop of added water, the red colour was not observed, instead forming **1** directly, due to hydrolysis of vanadium clusters.¹⁰

The reaction of V(IV) with glutarimide-dioxime was also tested in aprotic solvents. Vanadyl acetylacetonate was dissolved in dry acetonitrile and excess L^A. Due to the low solubility of L^A, the reaction proceeded slowly, and the solution first turned green and then amber, also forming a brown-black precipitate. Small amounts of **1** were present in solution (determined by ⁵¹V NMR spectroscopy), and the insoluble black product could not be extracted into any solvent including methanol and water, likely caused by some irreversible decomposition process. Disproportionation of a V(IV)-L^A species formed initially could be occurring to form insoluble, reduced metal oxides. Based on these results, cyclic voltammetry was performed to determine the accessibility of the V(IV) oxidation state from **1** and establish possible conditions for this reaction.

Cyclic voltammetry of complex **1**

In order to solubilize **1** in non-aqueous solvents to perform nonaqueous reductions, a cation exchange reaction was performed to synthesize the organic-soluble tetraethylammonium complex. The extraction of **1** in the presence of tetralkylammonium salts from water into immiscible organic solvents failed and all compounds remained in the aqueous phase. However, the tetraethylammonium salt of **1** was successfully isolated by

synthesizing **1** in the presence of tetraethylammonium bromide in a water/methanol mixture, evaporating the solution to dryness, then extracting into dichloromethane. [NEt₄][**1**] was obtained as very dark brown-black block crystals by layering a dichloromethane solution with THF. [NEt₄][**1**] was used in all cyclic voltammetry experiments (Figure 2) due to its exact stoichiometry and higher purity, unlike the sodium salt isolated from water which may contain excess reagents and salts.

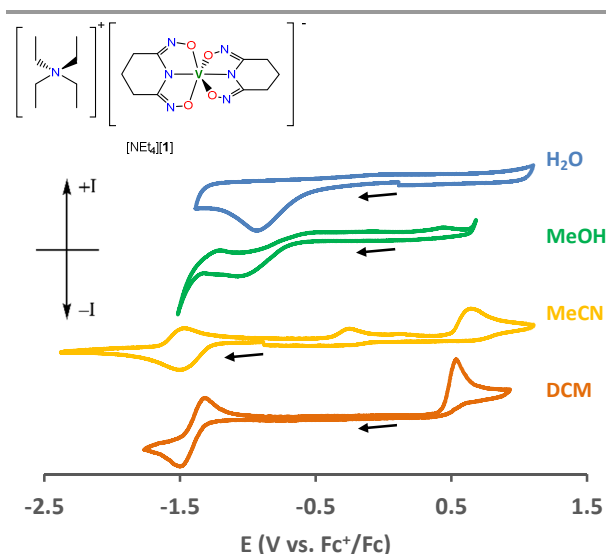


Figure 2. Cyclic voltammograms of **1** in several solvents, all measured at a scan rate of 100 mV/s against a Pt working electrode.

In water (pH 7), one irreversible reduction occurs at E_p^c - 920 mV vs. Fc⁺/Fc, which we assign to the reduction of V(V) to V(IV), followed by subsequent reaction. This is significantly more negative than free V(V)/V(IV) redox potentials (-600 mV for [V^VO₂]⁺/[V^{IV}O]²⁺ in acid or -400 mV for [V^VO₄]³⁻/[H₂V^{IV}O₄]²⁻ in strong base, relative to ferrocene),²³ consistent with the vanadium atom being more electron rich due to binding of the strongly electron-donating amidoxime ligand. Solid was observed plated onto the electrode, likely VO₂ since the V(IV) complex that is formed is not stable. Decomposition could conceivably proceed through ligand dissociation and subsequent vanadium hydrolysis to form VO₂.

Cyclic voltammetry was also performed in non-aqueous solvents to investigate if water precludes the isolation of a V(IV) complex. In methanol, the same irreversible behaviour was observed, with an irreversible reduction at a similar potential of E_p^c -1000 mV. The similarity of the electrochemical behaviour and chemical reactions (see above) suggest that a similar process may be taking place in both cases, with the V(IV) complex that is transiently formed reacting with the

ligand and then dissociating and forming VO₂ or kinetically inert polyoxovanadates.

Different electrochemical behaviour was observed in the aprotic solvents acetonitrile and dichloromethane. In the former, an irreversible reduction occurs at E_p^c -1.5 V, a more negative potential than in water or methanol. The initial reduction likely occurs in the same manner as in the protic solvents, but without a proton source for the ligand to dissociate completely and the V(IV) complex to hydrolyse, the acetonitrile coordinates then reacts, leading to a V(IV) complex that remains soluble. An oxidation occurs on the return scan, but is a different process and not a reverse wave (also at E_p^c -1.5 V with no peak-to-peak separation), likely this new V(IV) complex reoxidizing to V(V), with other oxidations of reacted ligands or other complexes observed at more positive potentials as well. In dichloromethane, the same reduction occurs at at E_p^c -1.41 V ($E_{1/2}$ -1.32 V), but shows reversible behaviour, with a peak-to-peak separation of 190 mV. Although this value is relatively large, the square root law is linear (see Supplemental Information, Figures S1, S2) and the large separation is therefore attributed to uncompensated resistance from the solvent. We attribute this process to the same initial reduction as in acetonitrile. However, the V(IV) complex is stable in DCM, since the solvent is noncoordinating and generally less reactive, making it reversible on the CV timescale.

We attempted the chemical reduction of **1** in both aqueous and nonaqueous solvents; to target a reduction at $E_{1/2}$ (-1.32 V) we used cobaltocene as a reducing agent (-1.33 V for [Cp₂Co]⁺/[Cp₂Co]) which would be a mild reaction if it were irreversible.²⁴ This was attempted in both acetonitrile and DCM, and in both cases, no reaction was observed initially, but within an hour an intractable black solid started to form in the same manner as the direct reaction with vanadyl acetylacetonate (above), and no products could be isolated, implying that a possible V(IV) complex is inherently unstable in these conditions, with this decomposition in aprotic solvents being caused by a lack of hydrolysis reaction pathways.

The reduction of **1** in protic solvents was also attempted with a variety of reducing agents in water (pH 6-8) or water-methanol mixtures before performing cyclic voltammetry experiments. Several common reducing agents were tested, including hydroxylamine, hydrazine, sodium thiosulfate, and zinc metal, spanning reduction potentials between -0.29 V and -1.16 V vs. ferrocene,^{24,25} and in all cases, no reaction was observed. Although any V(IV) products would be paramagnetic and not necessarily observable by NMR spectroscopy, all ¹H and ⁵¹V NMR spectra as well as absorption spectra remained unchanged. This lack of reactivity suggests that the presence of the two amidoxime ligands on vanadium greatly stabilizes the complex against reduction compared to other V(V) complexes, which have reduction potentials in the range of +0.6 V vs. ferrocene (for [VO]²⁺/[VO₂]⁺), +0.1 to +0.75 V for non-oxido *cis*-inositol complexes²⁶ or -0.25 to +0.49 V for Amavadin derivatives, with the lower end of the range occurring in organic solvents (discussed below).²⁷ Since the ligands are strongly electron-donating, such that they displace all oxido

groups on the metal upon coordination, they are poor ligands with respect to stabilizing the lower oxidation state on vanadium.

The unusual redox behaviour of **1** and its reluctance to be reduced is not a direct consequence of the rare non-oxo environment, as several other air-stable non-oxo V(IV) complexes are known. One of them is Amavadin, a natural product that is found in the hyperaccumulating fungus *Amanita muscaria* (Figure 3, left).²⁸ In contrast to **1**, vanadium is present exclusively in the V(IV) oxidation state in naturally-occurring Amavadin as well as synthetic derivatives, and although the V(V) form is readily accessible by chemical oxidizing agents such as hydrogen peroxide, it will slowly revert to the stable V(IV) oxidation state over time with no apparent decomposition.¹⁰ In some organic solvents, however, the V(V) form is favoured, turning red, indicating an easily accessible redox couple. This is notable because the ligand in Amavadin, 2,2'-(hydroxyimino)dipropionate, contains a central N-OH hydroxylamine group that is deprotonated in the complex, similar to the four N-O groups in **1**, yet it is inert when directly bonded to V(IV). A limited number of other non-oxido V(IV) complexes are known, including a complex with a *cis*-inositol derived ligand and other similar compounds (Figure 3, right) that are also unstable when oxidized to V(V).^{26,29}

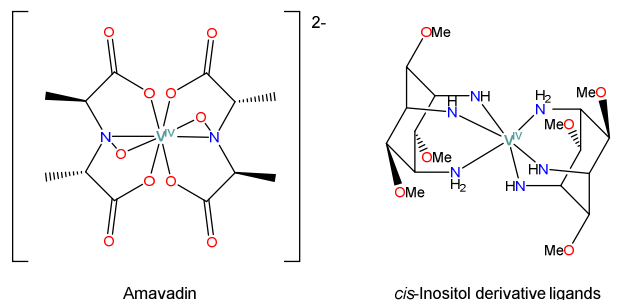


Figure 3: Stable non-oxido V(IV) complexes.

Vanadium(IV) reactivity with amidoximes and oximes

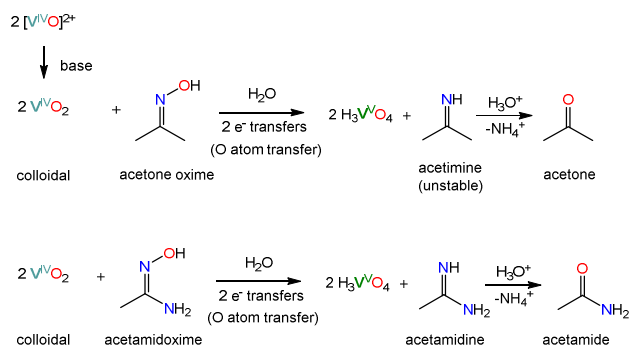
In addition to L^A (glutaroimide-dioxime), the reactions of other amidoximes and oximes with V(IV) were also monitored by ¹H and ⁵¹V NMR spectroscopy. We tested glutaramidoxime (amidoxime B, L^B)¹⁹ and acetamidoxime (HAO)³⁰ as models for other functional groups on uranium sorbents. Acetone oxime was also tested as it is the simplest ketoxime which should react to form a single product, acetone (substrates shown in Figure 1). For these substrates, only free V(V) species were observed in the products instead of metal complexes, as the substrates and probable products are expected to be poor ligands (see Supplemental Information, Figures S6 – S11).^{6,19} The presence of any ⁵¹V NMR signals is indicative of oxidation from V(IV) to V(V) since V(IV) is NMR-silent.²² Small amounts of VO₂ precipitation is observed, especially in the reactions of L^B, although no attempts were made to quantify this. Table 1 shows the products produced at different vanadium/oxime ratios.

Table 1. Product mixtures of V(IV) and amidoxime and oxime substrates.

| Substrate (S) | [S] | [V]:[S] | Unreacted [S] | [product] | [decomp.] |
|----------------------|-----|---------|---------------|-----------|-----------|
| L^B | 1 | 6:1 | 0 | | 0.85 |
| | 6 | 1:1 | 2.4 | | 3.2 |
| | 20 | 1:3 | 11.0 | | 9.0 |
| HAO | 2 | 3:1 | 0 | 1.2 | 0.2 |
| | 12 | 1:2 | 6.1 | 2.4 | 0.01 |
| | 36 | 1:6 | 32 | 1.8 | 4.3 |
| acetone oxime | 2 | 3:1 | 1.1 | 0.97 | |
| | 12 | 1:2 | 9.3 | 5.6 | |
| | 36 | 1:6 | 32 | 2.9 | |

Note: $[VO_2^{2+}] = 6 \text{ mM}$ for all reactions. All concentrations are in mM. Product is acetamide for **HAO**, acetone for acetone oxime. Decomposition (decomp.) is all other signals that are not product or unreacted substrate. Precipitate was present in the reactions of **L^B** and small amounts were present in reactions of **HAO**.

For these substrates, the formation of a heterogeneous mixture by the addition of base was necessary for any reaction to occur. This could indicate that the formation of a hydrated or colloidal vanadium(IV) oxide VO_2 or $VO(OH)_2$ is needed and the free vanadyl ion is inert.³¹ These reactions transiently turn a blue-grey colour with the formation of a colloid, as observed by the Tyndall effect (see Supplemental Information Images 1 and 2) which then reacts with the substrates (Scheme 1). The heterogeneous nature of this reaction also explains its slow and variable kinetics, taking hours to days to react fully. The reaction mixtures remain slightly acidic, around pH 4-6, so vanadium oxidation is not caused by strong base, and the substrates are not reactive towards hydrolysis due to low pH.³²



Scheme 1. Reaction of acetone oxime (upper) or acetamidoxime (lower) with V(IV) and base. Similar reactions take place with **L^B**. The exact composition of the V(IV) colloid is unknown, and the product V(V) species depend on concentration and pH.

The formation of the vanadium dioxide colloid *in situ* appears to be necessary for reactivity of the substrates other than **L^A**. With multiple vanadium centres in close proximity, this can allow for two-electron processes and oxygen atom abstraction. This type of reactivity is well known with vanadium oxides, notably in the contact process that is used on an industrial scale to produce sulfuric acid.³³ To confirm its reactivity, the colloidal material was isolated as a dark blue solid by centrifugation and decanting of the solution, after

allowing a reaction involving acetone oxime to proceed for one hour. When a fresh solution of oxime was added to the solid the reaction proceeded, producing the expected amount of acetone, almost 0.5 equivalents.

VO_2 prepared in the absence of acetone oxime was also tested for its reactivity, either as a wet solid after isolation by centrifugation and decanting of the solution, or after it had been heated to dryness. Both forms did react, although much smaller amounts of acetone were produced than when the VO_2 was formed in the presence of acetone oxime. Solid VO_2 was still present in the reactions, especially when the VO_2 was dried (Table 2). The large difference in reactivity can be attributed to the nature of the colloid and its surface. When the colloid is formed, acetone oxime or other substrate may act as a surfactant enhancing its reactivity, while hydrated VO_2 formed in the absence of substrate shows much lower reactivity and dried VO_2 lower still.

Table 2. Vanadium dioxide reactivity resulting from preparation method.

| VO_2 precipitation | Equivalents of acetone produced (relative to V) |
|---------------------------------------|-------------------------------------------------|
| With acetone oxime, decanted | 0.49 |
| Without acetone oxime | 0.16 |
| Without acetone oxime, dried at 120°C | 0.12 |

Note: all with $[acetone \text{ oxime}] = 20 \text{ mM}$, $[VO_2]^{2+} = 20 \text{ mM}$. Ideal = 0.5 equivalents.

When the reaction of **L^B** was performed at higher concentrations and on a larger scale in an attempt to isolate products, VO_2 precipitated which slowly settled over one week, during which the solution turned from blue to green to yellow-brown. The supernatant was then decanted and allowed to slowly evaporate, upon which brown crystals of glutaramidinium decavanadate, $[(H_2N)_2C(CH_2)_3C(NH_2)_2]_6 \cdot [V_{10}O_{28}]_2$, were obtained. The structure was confirmed by single crystal X-ray diffraction (see Supplemental Information Figure S14, Table S1). Decavanadate formation is observed as a consequence of an acidic solution, high vanadium concentration, and a poor ligand that does not interact directly with vanadium at all.²²²² Although the amidinium ion was isolated in the crystal structure, hydrolysis can occur to form the more stable amide, as seen previously in amidoxime reactivity.³⁴ Therefore, in many cases the ammonium ion was observed in the 1H NMR spectra of these reactions as a distinctive 1:1:1 triplet at $\delta = 7.16 \text{ ppm}$ due to $^1H-^{14}N$ coupling ($^1J_{HN} = 52 \text{ Hz}$), along with the formation of amides or carboxylic acids.

This type of reductive deoxygenation of amidoximes has been reported previously with transfer hydrogenation reactions³⁵ and enzyme activity.³⁶ In the latter case, O-substituted amidoximes were used as prodrugs for relatively reactive and less bioavailable amidines *in vitro* and *in vivo* after deoxygenation by liver enzymes. A somewhat similar deoxygenation reaction of amidoximes and imide-dioximes has been reported with nitrous acid, although in that case the amine portion of the amidoxime also reacts, as the reaction produces nitrous oxide and the amide.^{34,37,38} Similar reactivity has been observed with hydroxamic acids, although only when

N-substituted, reacting with reduced V(III), V(IV), Mo(IV), and Mo(V).¹⁴ In contrast, stable hydroxamate complexes are known with all of these oxidation states without *N*-substitution. Limited examples of V(IV) reacting with salicylaldehyde and salicylamidoxime have also been reported, where the V(V) complex was isolated in low yield.¹⁵ The low yield reported is consistent with 2 equivalents of V(IV) reacting with each ligand, in a one-electron process on the metal and two-electron process abstracting an oxygen atom from the ligand, resulting in at least half of the ligand remaining intact.

Vanadium(IV) reactivity with glutaroimide-dioxime (L^A)

After exploring the reactivity of V(IV) with simple oximes and amidoximes, we then looked the reaction of L^A with V(IV) by NMR to explain our observations described earlier. Unlike the other substrates, the reactions remained homogeneous throughout the reaction and no added base was needed. We attribute this difference in reactivity between L^A and the other substrates to the effectiveness of L^A as a ligand, where a transient V(IV) complex forms in solution.

In order to determine if O-atom transfer or other reactivity was occurring between V(IV) vanadyl and L^A , quantitative NMR experiments were performed. When the two reagents were mixed, the reaction mixtures turned dark brown and reactions started within seconds as observed previously. Spectra were acquired after approximately 6 hours to allow the reaction mixture to equilibrate; a sample spectrum is shown below (Figure 4). In these reactions, the ⁵¹V NMR spectra contained the known 1:1 and 2:1 complexes as well as free vanadium when excess vanadium is present.⁵ The initial pH of the vanadium solutions was 3-4 and glutaroimide-dioxime solution 8, and when mixed the final pH was in the range of 6-7 due to buffering by the ligand and complexes formed. Glutaroimidoxime was identified as one decomposition product by comparison with an NMR spectrum of the pure compound (see Supplemental Information Figures S4, S5) although the major decomposition product, likely arising from further reaction of glutaroimidoxime, was not able to be identified, not matching any known product or intermediate of hydrolytic decomposition.³²

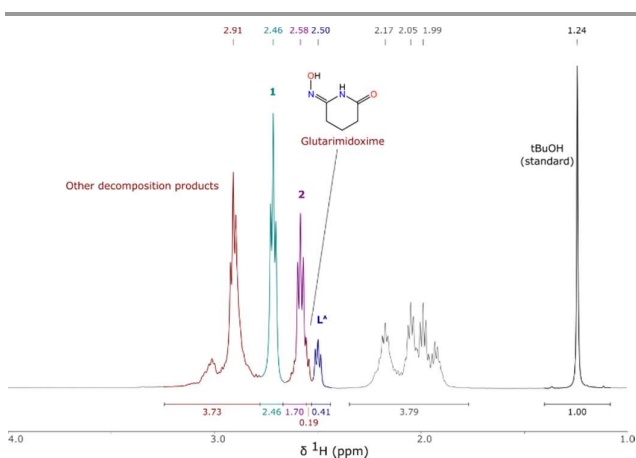


Figure 4. ¹H NMR spectrum of product mixture of L^A and V(IV) after 6 hours. Major decomposition product at $\delta = 2.91$ ppm unidentified. Conditions. 18 mM L^A , 6 mM VO^{2+} .

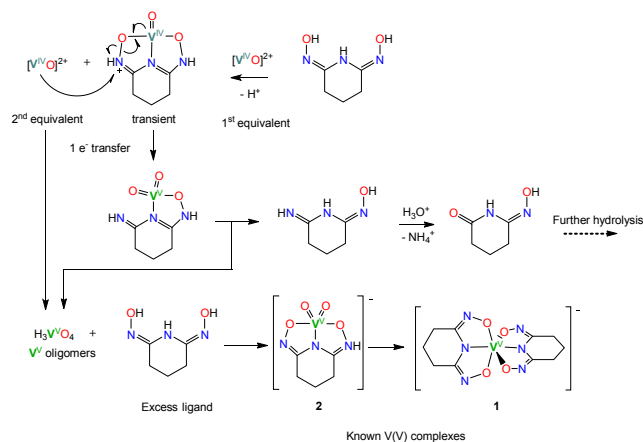
The concentrations of products vary depending on the ratio of reagents used, shown in Table 3. Here we can see that more than one equivalent of vanadyl reacts with one molecule of L^A , as the concentration of decomposition products exceeds the vanadium concentration when excess L^A is used. Additionally, if excess ligand remains after the V(IV) is oxidized to V(V), it forms the complexes **1** and **2**, which are the products observed previously.

Table 3. Product mixtures of V(IV) and glutaroimide-dioxime (L^A).

| [L^A] | V: L^A ratio | Unreacted [L^A] | [L^A] in 1 | [L^A] in 2 | [decomp.] |
|-----------|----------------|---------------------|-----------------------|-----------------------|-----------|
| 1 | 6:1 | 0 | 0 | 0.24 | 0.69 |
| 12 | 1:2 | 0.23 | 1.7 | 2.0 | 8.6 |
| 18 | 1:3.3 | 1.0 | 3.0 | 4.1 | 9.1 |

Note: all concentrations are in mM. $[VO^{2+}] = 6$ mM for all reactions. Multiple decomposition products ([decomp.]) were observed that could not be identified or quantified separately. Spectra acquired 6 hours after mixing.

We propose that the rapid homogeneous reaction of L^A with vanadyl occurs through the formation of a transient V(IV) complex followed by reaction with another equivalent of V(IV) (Scheme 2). This effectively amounts to disproportionation of the vanadium, but rather than being reduced to V(III), the ligand is reduced instead to form a second equivalent of V(V). This mechanism is also consistent with the lack of sensitivity to oxygen (see above), making a free radical mechanism very unlikely. Without complexation to form a transient L^A -V(IV) complex or the presence of organic radicals, a third-order reaction would be needed, which is not consistent with the rapid reaction and is relatively rare.



Scheme 2. Proposed reaction mechanism of glutaroimide-dioxime with V(IV). The mixture of V(V) product species formed varies depending on concentrations and pH.

Conclusions

In this study we have investigated the reactivity taking place between vanadium(IV) and amidoxime ligands. Rather than form stable V(IV) complexes with glutaroimide-dioxime (L^A), the ligand reacts to oxidize the vanadium to V(V), resulting in the formation of the known non-oxido V(V) complex of L^A , **1**. Based on the observed stoichiometry of the reaction and products observed, we propose that a V(IV) complex is formed transiently due to the strong chelating ability of L^A , but this then reacts with more reduced vanadium to form V(V) in solution. The reductive reaction of V(IV) was also explored with ligands and substrates that are similar to L^A ; glutaramidoxime (L^B), acetamidoxime, and acetone oxime. These three substrates required the precipitation of VO_2 as a colloid, followed by the same oxygen transfer reaction to form V(V) with an observed vanadium/oxime stoichiometry.

Cyclic voltammetry was performed on the non-oxido V(V) complex of glutaroimide-dioxime, $[NEt_4][1]$, to investigate whether reduction of this complex is possible, and we found that reduction is possible electrochemically but at a very reducing potential ($E \approx -1.0$ to -1.5 V vs. ferrocene), and is generally irreversible. Only in dichloromethane was it found to be reversible electrochemically, but upon attempted chemical reduction no products could be isolated. We attribute this to slow reaction of a transient V(IV) complex and lack of available hydrolysis pathways in an aprotic, relatively inert solvent. In protic solvents, no V(IV) complex could be formed either through reduction of **1** or direct reaction of L^A with V(IV) sources, and only V(V) complexes were obtained.

The ligands explored in this study (L^A , L^B , and **HAO**) are analogues of functional groups on polymer sorbents for the extraction of uranium from seawater. The extraction is generally performed with polymer sorbents, with the amidoxime functional groups resembling the binding sites used. Vanadium in particular is a major competitor for binding sites, but past work has focused on V(V), which makes up the majority of vanadium in seawater. However, vanadium also naturally occurs as V(IV) due to biological redox activity, and V(IV) composes a small but non-negligible amount of total dissolved vanadium in the ocean. Due to the prompt and irreversible reaction of V(IV) with L^A and other analogues in seawater-relevant conditions, V(IV) will react to permanently damage amidoxime-functionalized polymer sorbents, which is a potentially greater concern than the reversible, albeit strong, binding of V(V) which simply competes with U(VI) for binding and extraction.

Conflicts of interest

The authors declare no conflicts of interest.

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