

Reactivity Investigation of Dinuclear Vanadium(IV,V)–Citrate Complexes in Aqueous Solutions. A Closer Look into Aqueous Vanadium–Citrate Interconversions

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Well-known vanadium(IV)– and vanadium(V)–citrate complexes have been employed in transformations involving vanadium redox as well as nonredox processes. The employed complexes include $K_2[V_2O_4(C_6H_6O_7)_2] \cdot 4H_2O$, $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$, $K_2[V_2O_2(O_2)(C_6H_6O_7)_2] \cdot 2H_2O$, $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$, $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$, $(NH_4)_4[V_2O_2(C_6H_4O_7)_2] \cdot 2H_2O$, and $(NH_4)_6[V_2O_4(C_6H_4O_7)_2] \cdot 6H_2O$. Reactions toward hydrogen peroxide at different vanadium(IV,V): H_2O_2 ratios were crucial in delineating the routes leading to the interconversion of the various species. Equally important thermal transformations were critical in showing the linkage between pairs of dinuclear vanadium–citrate peroxo as well as nonperoxo complexes, for which the important vanadium(V)–assisted oxidative decarboxylation, leading to reduction of vanadium(V) to vanadium(IV), seemed to be a plausible pathway in place for all the cases examined. FT-IR spectroscopy and X-ray crystallography were instrumental in the identification of the arising products of all investigated reactions. Collectively, the data support the existence of chemical links between different and various structural forms of dinuclear vanadium(IV,V)–citrate complexes in aqueous media. Furthermore, in corroboration of past studies, the examined interconversions lend credence to the notion that the involved species are active participants in the respective aqueous distributions of the metal ion in the presence of the physiological ligand citrate. The concomitant significance of structure-specific species relating to soluble and potentially bioavailable forms of vanadium is mentioned.

Introduction

Vanadium has been linked with a number of enzymic and nonenzymic systems relevant to physiological functions in lower and higher organisms.¹ In all of those cases, vanadium is either an indispensable part of an active site in a regulatory biomolecule or a necessary external inorganic cofactor directing catalytic actions.² Outstanding among the systems in which vanadium is an integral part of enzymic active sites are the alternative nitrogenases³ and haloperoxidases.⁴ Notable, on the other hand, are the roles that vanadium can exhibit in physiological pathways, including those in humans, reflecting mitogenic,⁵ antitumorogenic,⁶ inhibitory action toward phosphoglucomutases,⁷ and insulin mimetic activity.⁸

The latter action is one that has received considerable attention in recent years due to the extent and severity of the physiological aberration with which it is associated.

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Specifically, vanadium has been found to display insulin mimetic activity in cases of the heterogeneous metabolic syndrome of diabetes mellitus.^{9–11}

A number of epidemiological and related studies have shown a linkage between the disease and the phenotypic changes in insulin mimetic activity upon administration of vanadium.¹² The details, however, of how the metal ion acts, in what form(s), and what its targets are in biological fluids still remain research subjects in need of perusal. It is important to note that the two predominant oxidation states of the metal ion purported to play a biologically relevant role are V^{IV} and V^V. Aside, though, from this, the equally significant aspects of solubility and bioavailability of vanadium have been targets of scientific conjecture that is difficult to delineate.

Attempts to shed light onto these questions resulted over the years in a plethora of speciation studies for vanadium systems in the presence of physiological or physiologically relevant ligands.¹³ To the benefit of the proposed species, purported to exist in aqueous media as a function not only of concentration but also of pH, synthetic studies were carried out that targeted such species and their physicochemical

properties. A number of such complex vanadium(IV,V) synthetic complexes have since been synthesized and structurally characterized.^{14–17} Among those included are vanadium(IV,V)–citrate complexes, a series of which have been isolated from aqueous solutions and structurally characterized.^{16–18} The interconnections of all these complexes, however, in the context of reactivity patterns has remained a question, the answer to which could be related not only to their participation as components of distribution diagrams but also to their potential bioavailability in biologically relevant media.

The paucity of such studies at the synthetic level has prompted us to pursue a series of investigations targeting potential chemical relationships among different species in aqueous media. Hence, in the present study we report on the connections among well-known dinuclear vanadium(IV)– and vanadium(V)–citrate complexes in aqueous media and the types of transformations linking the various vanadium–citrate complexes containing two different oxidation states of the same metal ion. Key tools in the identification of the arisen species are FT-IR spectroscopy and X-ray crystallography. The investigated transformations include (a) nonredox chemistry, involving H₂O₂ addition to solutions of dinuclear vanadium(V)–citrate complexes as well as mild thermal treatment of solutions of vanadium(V)–peroxo–citrate complexes, followed by isolation of the arisen species; (b) oxidative action on vanadium(IV) complexes due to the presence of hydrogen peroxide; and (c) thermally induced vanadium(V)–assisted oxidative decarboxylations leading to reduction of vanadium(V) to vanadium(IV)–containing dinuclear species. Collectively, these effects appear to contribute significantly to the understanding of the reactivity of vanadium–citrate species in aqueous solution.

Experimental Section

Materials and Methods. All experiments were carried out in the open air. Nano pure quality water was used for all reactions. H₂O₂ 30% was purchased from Aldrich. Authentic samples of the

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well-characterized compounds $K_2[V_2O_4(C_6H_5O_7)_2] \cdot 4H_2O$,^{15a,16a} $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$,¹⁷ $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$,^{15a,16d} $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$,^{14a} $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$,^{14a} $(NH_4)_4[V_2O_2(C_6H_4O_7)_2] \cdot 2H_2O$,^{14a} and $(NH_4)_6[V_2O_4(C_6H_4O_7)_2] \cdot 6H_2O$ ¹⁸ were prepared as previously described. Ammonia and KOH were purchased from Fluka. In all cases of synthetic reactions employed in this work, use of the rotary evaporator was made at around 45 °C.

Physical Measurements. FT-infrared measurements were taken on a Perkin-Elmer 1760X FT-infrared spectrometer. X-ray crystallographic unit cell determination of derived compounds from chemical transformations was carried out on a Crystal Logic dual-goniometer diffractometer, using graphite monochromated Mo K α radiation. GC–mass spectroscopic measurements were taken on a Shimadzu GC-17A gas chromatograph equipped with a 50 m HP-5 column and a 5971A MS detector. Electron-impact (EI) ionization was employed.

Transformation Reactions. From $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$ to $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. A quantity of 0.10 g (0.13 mmol) of $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$ was placed in a 25 mL flask and dissolved in 2 mL of water, affording a bluish solution. To that solution, in an ice bath, was added slowly and under continuous stirring 0.27 mL (2.6 mmol) of a 30% hydrogen peroxide solution, further diluted with cold water 1:1. The resulting solution became orange-like and was allowed to stir on ice for about 1 h. At the end of this period, the solution was orange-like and stayed as such. Subsequently, the reaction flask was placed at 4 °C. Addition of ethanol resulted in the precipitation of a red crystalline material at the bottom of the flask a few days later. The red crystals were isolated by filtration and dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. The X-ray determination of the cell parameters for one of the isolated single crystals provided further evidence of the identity of the product. Yield: 0.050 g (55%).

From $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$ to $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. A quantity of 0.25 g (0.32 mmol) of $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$ was placed in a 25 mL flask and dissolved in 2 mL of water, affording a bluish solution. To that solution, in an ice bath, was added slowly and under continuous stirring 0.72 mL (7.1 mmol) of a 30% hydrogen peroxide solution, further diluted with cold water 1:1. The resulting solution became orange-like and was allowed to stir on ice for about 30 min. At the end of this period, the solution became orange and stayed as such. The pH of the solution was ~4. The reaction flask was placed in the refrigerator overnight. The following day the color of the solution was red. Addition of ethanol was added and the reaction flask was returned to 4 °C. A couple of days later red crystals formed at the bottom of the flask. The crystalline product was isolated by filtration and dried in vacuo. The FT-IR of the red product was identical to that of an authentic sample of $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. Yield: 0.10 g (45%).

From $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$ to $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$. A quantity of 0.10 g (0.13 mmol) of $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$ was placed in a 25 mL flask and dissolved in 2 mL of water, affording a bluish solution. To that solution, in an ice bath, was added slowly and under continuous stirring 0.09 mL (0.9 mmol) of a 30% hydrogen peroxide solution, further diluted with cold water 1:1. The resulting solution became orange-like and was allowed to stir on ice for about 30 min. Subsequently, the reaction flask was placed in the refrigerator. Addition of ethanol at 4 °C resulted in the deposition of yellow crystals at the bottom of the flask a few days later. The crystalline material was isolated by filtration and dried in vacuo. The FT-IR spectrum of the product

was identical to that of an authentic sample of $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$. Further identification of the product was afforded by the unit cell determination of a single-crystal probed by X-ray diffraction. Yield: 0.032 g (30%).

From $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$ to $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. A quantity of 0.26 g (0.32 mmol) of $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$ was placed in a 25 mL flask and dissolved in 2 mL of water, affording a yellowish solution with pH ~5. To that solution, in an ice bath, was added slowly and under continuous stirring 0.51 mL (5.0 mmol) of a 30% hydrogen peroxide solution, further diluted with cold water 1:1. The resulting solution became orange-like and was allowed to stir on ice for about 10 min. Concomitantly, ethanol was added and the reaction flask was placed at 4 °C. A few days later, a red crystalline material was deposited and was isolated by filtration and dried in vacuo. The FT-IR spectrum of the crystalline product was identical to that of an authentic sample of $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$. Yield: 0.071 g (32%).

From $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$ to $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$. A quantity of 0.20 g (0.29 mmol) of $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$ was placed in a 25 mL flask and dissolved in 8 mL of water, affording a reddish solution with pH ~3. The resulting solution was heated mildly to 50 °C for approximately 2 h, finally becoming yellowish in color. Subsequently, the solution was taken to dryness by means of a rotary evaporator. The resulting residue was redissolved in 2 mL of water. The pH of the solution was ~5. Then, the reaction flask was placed in the refrigerator. Addition of ethanol afforded a yellow crystalline material at the bottom of the flask after a few days. The crystalline product was isolated by filtration and dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$. The X-ray cell parameter determination for one of the isolated single crystals offered further evidence of the identity of the product. Yield: 0.20 g (86%).

From $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$ to $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$. A quantity of 0.18 g (0.26 mmol) of $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$ was placed in a 25 mL flask and dissolved in 3 mL of water, affording a reddish solution with pH ~3. The flask was heated to ~50 °C, in a water bath, for 1 day. The resulting green solution was filtered and the pH of the filtrate was adjusted to ~8 with aqueous KOH. The reaction solution was then heated to 50 °C for an additional 2 days. Then, the heat was turned off and the green-blue reaction mixture was allowed to return to room temperature. Subsequently, the reaction flask was placed in the refrigerator. Addition of 2-propanol afforded a blue crystalline material at the bottom of the flask after a few days. The crystalline product was isolated by filtration and was dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$. Yield: 0.020 g (20%).

From $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$ to $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$. A quantity of 0.20 g (0.25 mmol) of $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$ was placed in a 25 mL flask and dissolved in 2 mL of water, affording a yellowish solution with pH ~5. The resulting flask was heated to 70 °C, in a water bath, overnight. On the following day, the solution was blue. The heat was turned off and the reaction mixture was allowed to stir further until the temperature of the solution returned to room temperature. Subsequently, the pH of the solution was adjusted to pH ~8 with aqueous KOH, and the reaction was allowed to stir for 30 min. Then, the reaction flask was placed in the refrigerator and addition of 2-propanol resulted in a blue crystalline material after a few days. The crystalline product was isolated by filtration and was dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$. Yield: 0.080 g (83%).

From $K_2[V_2O_4(C_6H_6O_7)_2] \cdot 4H_2O$ to $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$.

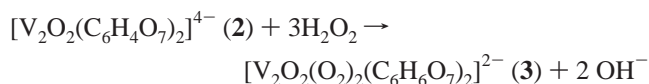
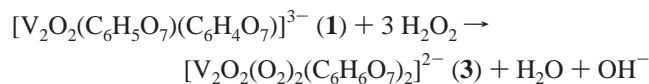
A quantity of 0.25 g (0.36 mmol) of $K_2[V_2O_4(C_6H_6O_7)_2] \cdot 4H_2O$ was placed in a 25 mL flask and dissolved in 5 mL of water, affording a light yellow solution with pH ~ 3.5 . The resulting flask was heated to 70 °C, in a water bath, overnight. On the following day, the solution was blue and the pH was ~ 4 . The heat was turned off and the reaction mixture was allowed to stir further until the temperature of the solution returned to room temperature. Subsequently, the pH of the solution was adjusted to pH ~ 7.5 with aqueous KOH and the reaction was allowed to stir for 30 min. Then, the reaction flask was placed in the refrigerator and addition of 2-propanol resulted in a blue crystalline material after a few days. The crystalline product was isolated by filtration and was dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$. Yield: 0.090 g (65%).

From $K_2[V_2O_4(C_6H_6O_7)_2] \cdot 4H_2O$ to $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$. A quantity of 0.16 g (0.23 mmol) of $K_2[V_2O_4(C_6H_6O_7)_2] \cdot 4H_2O$ was placed in a 25 mL flask and dissolved in 5 mL of water, affording a light yellow solution with pH ~ 3.5 . The resulting flask was heated to 50 °C, in a water bath, for 1 day. On the following day, the heat was turned off and the blue reaction mixture was allowed to stir further until the temperature of the solution returned to room temperature. Then, the reaction mixture was filtered and the flask was placed in the refrigerator. Addition of 2-propanol resulted in a blue hair-like crystalline material after a few days. The crystalline product was isolated by filtration and was dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $K_3[V_2O_2(C_6H_4O_7)(C_6H_5O_7)] \cdot 7H_2O$. Yield: 0.020 g (23%).

From $(NH_4)_6[V_2O_4(C_6H_4O_7)_2] \cdot 6H_2O$ to $(NH_4)_4[V_2O_2(C_6H_4O_7)_2] \cdot 2H_2O$. A quantity of 0.51 g (0.67 mmol) of $(NH_4)_6[V_2O_4(C_6H_4O_7)_2] \cdot 6H_2O$ was placed in a 25 mL flask and dissolved in 3 mL of water, affording a greenish solution with pH ~ 7 . The resulting solution was heated to 80 °C, in a water bath, overnight. On the following day, the solution was blue. The heat was turned off and the reaction mixture was allowed to stir further until the temperature of the solution returned to room temperature. The solution was then reduced to dryness by means of a rotary evaporator. Warm 2-propanol mixed with warm water was subsequently added to the residue, ultimately affording a blue oil. The reaction mix was placed in the refrigerator. A few days later blue crystals appeared at the bottom of the flask. The crystalline product was isolated by filtration and dried in vacuo. The FT-IR spectrum of the product was identical to that of an authentic sample of $(NH_4)_4[V_2O_2(C_6H_4O_7)_2] \cdot 2H_2O$. Yield: 0.10 g (48%).

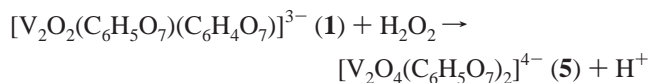
Results

Chemical Transformations. In a fashion reminiscent of their expedient syntheses, a number of key dinuclear vanadium–citrate complexes were transformed by simple chemical reactions. Specifically, the complexes $K_3[V_2O_2(C_6H_5O_7)(C_6H_4O_7)] \cdot 7H_2O$ ^{14a} (**1**) and $K_4[V_2O_2(C_6H_4O_7)_2] \cdot 6H_2O$ ^{14a} (**2**) reacted easily with hydrogen peroxide, on ice, affording orange-red solutions from which, upon addition of ethanol, complex $K_2[V_2O_2(O_2)_2(C_6H_6O_7)_2] \cdot 2H_2O$ ^{15a,16d} (**3**) was isolated. The stoichiometric reactions describing these transformations are shown below:



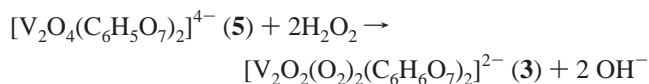
Both starting materials are dinuclear complexes containing vanadium(IV) ions. Therefore, hydrogen peroxide acts both as a one-electron oxidant per vanadium(IV) as well as a reagent providing peroxo ligands capable of binding vanadium(V). The common product of both reactions, complex **3**, is a dinuclear complex containing the $[V_2O_2(O_2)_2(C_6H_6O_7)_2]^{2-}$ core, bearing two peroxo moieties attached to two corresponding vanadium(V) ions, with an additional two coordinated citrates that are doubly deprotonated. Complex **3** has been reported before and was well characterized spectroscopically and crystallographically.^{15a,16d} The presence of excess hydrogen peroxide in both reactions neutralizes the produced hydroxide ions and provides a fairly acidic solution from which complex **3** was isolated.

The reactivity of complex **1** was also investigated in the presence of lower than excess quantities of hydrogen peroxide. In this case, a little more than 3 equiv of hydrogen peroxide per vanadium resulted in the formation and isolation of complex $K_4[V_2O_4(C_6H_5O_7)_2] \cdot 5.6H_2O$ ¹⁷ (**5**). The stoichiometric description of the reaction and the isolated product are given below:



Here too, the starting material contained vanadium(IV), which was oxidized by hydrogen peroxide to vanadium(V). The product was a dinuclear vanadium(V)–citrate complex containing triply deprotonated citrate ligands attached to the two metal ions. Complex **5** has been shown to be a dinuclear species with the two coordinated citrate ligands exhibiting protonated terminal carboxylates (not bound to vanadium ions), one for each ligand.¹⁷

The reactivity of complex **5** was further investigated in the presence of hydrogen peroxide. Specifically, hydrogen peroxide reacted in a facile manner with complex **5**, affording the isolation of a crystalline product, which was identified as complex **3**. The stoichiometric reaction between the two complexes is given below:

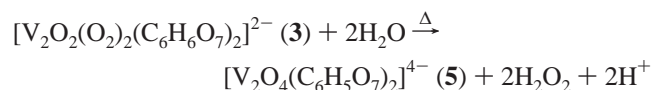


The presence of hydrogen peroxide in more than the predicted stoichiometric equivalents renders the solution acidic enough for the product to be isolated. In this case, both the starting material and the derived product were dinuclear complexes containing vanadium(V) in their respective cores. Therefore, in the absence of any vanadium(IV) in need of being oxidized to vanadium(V), hydrogen peroxide acted merely as the source of peroxo moieties capable of binding vanadium(V). Finally, in the presence of the acidic hydrogen peroxide the coordinated citrates to vanadium(V) ions are doubly deprotonated, in contrast to the corresponding

Aqueous Vanadium–Citrate Interconversions

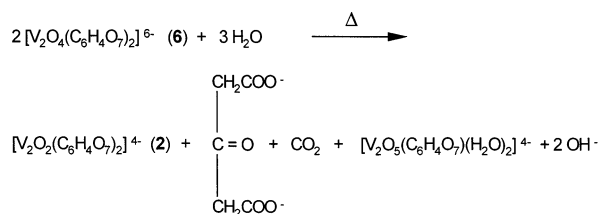
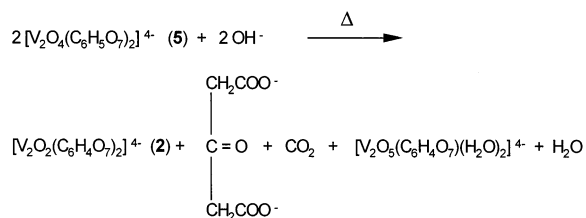
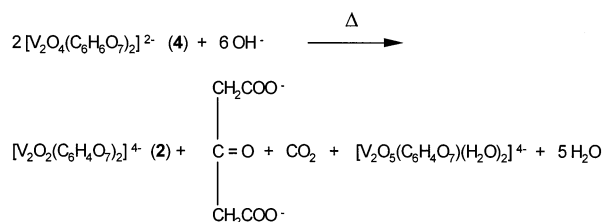
citrate in complex **5**, in which these ligands are triply deprotonated. Here too, protonation of the coordinated citrate ligands is directed toward the uncoordinated terminal carboxylate groups, which do not participate in binding to the metal ion.

In a reverse reactivity investigation, complex **3** was heated to 50 °C for 2 h and resulted in decolorization of the reddish color of the peroxo starting material. Addition of ethanol afforded a yellow crystalline material, which was identified as complex **5**. Schematically, this thermal transformation is shown below:



In this thermally induced transformation, the peroxo moiety departs from the anionic assembly, affording most likely hydrogen peroxide, which under the experimental conditions degrades further. The isolation of complex **5** from this reaction, in connection with the previously described forward reaction, does establish a two-way conversion between the two species. Under the optimally employed experimental conditions of this transformation, no other species could be isolated.

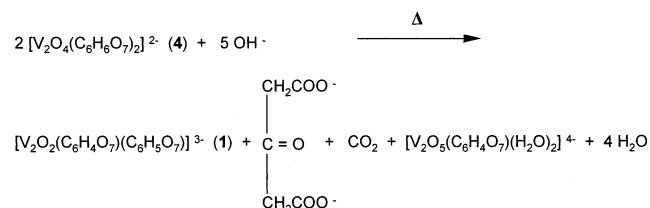
In the case of dinuclear nonperoxo containing vanadium(V)–citrate complexes bearing citrate ligands of differing protonation states, there was an interesting reactivity based on thermally induced transformations. Specifically, complexes **4**,^{15a,16a} **5**, and **6**¹⁸ afforded a blue solution upon heating. Adjustment of that solution to pH ~8 followed by addition of 2-propanol at 4 °C yielded a blue crystalline product.



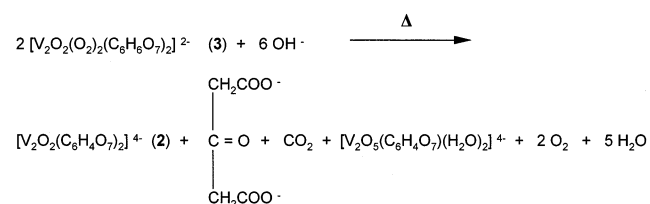
In the case of complex **6**, the ammonium salt of the hexaanionic assembly was employed for the transformation.

In the case of complexes **4** and **5**, the K^+ salts of the respective dianionic and tetraanionic assemblies were used. In all three cases, the isolated crystalline material was identified as complex **2**.

It should be noted that the starting materials are all complexes containing vanadium(V), whereas the derived product, complex **2**, contains vanadium(IV). Therefore, what in essence takes place here is a reaction leading to the reduction of the vanadium(V) dimer (vide supra). A suggested plausible reaction (in each case of complexes **4**, **5**, and **6**) consistent with the observations made here is shown above. In a similar fashion, complex **4** transformed to complex **1**. A plausible rendition of the process is shown below:



Along the same lines, having established a stepwise connection between complex **3** and complex **2**, the possibility was explored to directly connect the two species through a single conversion. Thus, complex **3** was heated in water, resulting in a color change of the solution to blue. The color stayed as such and did not change any further, even when the solution was allowed to return to room temperature after some time. Adjustment of the solution pH to ~8 afforded a blue crystalline product at 4 °C, following addition of 2-propanol. The overall chemical transformation can tentatively be depicted as shown below:



On the basis of the herein observations and literature reports, the results are consistent with a reactivity pattern similar to those seen with complexes **4–6**, where oxidative decarboxylation (vide supra) was the source of reducing equivalents for the vanadium(V) ions in complex **3**. The peroxo moiety very likely departs early on from the assembly upon heating, and eventually the evolved hydrogen peroxide degrades to give off oxygen upon pH adjustment.

In all of the transformations attempted in this work, the derived products were single crystalline in nature. Precipitation of these crystalline products was achieved by addition of alcohols (ethanol and 2-propanol) to the reaction mixtures of the investigated reactions. The identity of the products was confirmed by FT-IR spectroscopy, in light of the fact that these materials had been previously synthesized and their distinct FT-IR spectroscopic signatures were known. Specifically, (a) the antisymmetric and asymmetric vibrations for

the carboxylate groups of the citrate ligands coordinated to vanadium(IV) and vanadium(V); (b) the difference between the symmetric and antisymmetric stretches, $\Delta(\nu_{\text{as}}(\text{COO}^-) - \nu_{\text{s}}(\text{COO}^-))$, which was greater than 200 cm^{-1} ; and (c) the O—O stretch, where applicable, in the case of peroxo-containing species were all useful in the identification of the product.¹⁹ The FT-IR signatures for the individual complexes were in line with previous assignments in dinuclear $\text{V}^{\text{IV,V}}$ complexes,^{15,19–21} and consistent with past infrared frequencies attributed to carboxylate-containing ligands bound to different metal ions.²² Furthermore, on a number of occasions, X-ray crystallography was used, in addition to FT-IR spectroscopy, for the identification of the product(s). Unit cell determination of a single-crystal derived from the investigated reaction(s) confirmed the identity of the material(s), thus certifying the results of FT-IR spectroscopy.

Discussion

The synthetic challenge of vanadium(IV,V)—citrate complexes in aqueous solutions has led to the successful isolation and characterization of a series of new species with characteristic structural and chemical attributes.^{14–17,23,24} Their position, in aqueous vanadium(IV,V)—citrate speciation, however, demanded that interspecies correlations be established for them to be considered viable participants in the respective distribution schemes. To this end, efforts to unravel such relations were made in the recent past, revealing limited connections between structurally characterized species in aqueous solutions.^{17,18,25} In the present work, a systematic effort was made to link the existing dinuclear species through transformations consistent with their chemical and structural properties.

Complexes **1–6** are all dinuclear vanadium—citrate species containing vanadium in two different oxidation states. Therefore, they could be grouped into two categories of species, namely those containing vanadium(IV) (**1**, **2**) and those containing vanadium(V) (**3–6**) (Figure 1).

In the case of complexes **1** and **2**, interaction with excess hydrogen peroxide resulted in the oxidation of vanadium(IV) to vanadium(V) and the concurrent binding of the

peroxo moiety to vanadium(V). While these changes occurred, the nuclearity of the product structure was retained. The derived peroxo vanadium(V)—citrate dinuclear complex **3** contained bound citrate ligands in the doubly deprotonated form. Complex **3** is a well-known species that has been independently synthesized, isolated, and structurally characterized in the form of its K^+ and ammonium salts.^{15a,16d}

Addition of a little more than 3 equiv of hydrogen peroxide to **1** also resulted in the oxidation of vanadium(IV) to vanadium(V), while the initial nuclearity of the derived product was maintained. In this case, complex **5** was isolated and identified by FT-IR spectroscopy. This reactivity toward hydrogen peroxide differs from the one mentioned above in that the lack of excess equivalents of hydrogen peroxide did not afford peroxo binding to vanadium(V) in addition to the initial oxidation from vanadium(IV). This observation, in fact, prompted further assessment of the reactivity of complex **5** toward hydrogen peroxide. Indeed, when a separate reaction was run on complex **5** with hydrogen peroxide, the reddish peroxo vanadium(V)—citrate complex **3** was obtained. This series of two stepwise reactions was quite useful in establishing the sequence of events unfolding in the course of the oxidation of vanadium(IV) to vanadium(V) and concomitant peroxo binding to that metal ion. It showed that the direct reaction between **1** and hydrogen peroxide was indeed a more complex reaction. The data here suggest that the events follow the order (a) oxidation of vanadium(IV) to vanadium(V) and (b) binding of peroxo O_2^{2-} group to vanadium(V).

In view of the fact that **5** affords **3** in the presence of hydrogen peroxide, the reactivity of **2** toward the same reagent appears now to follow the same route. It was previously shown that **2** yields **5** in the presence of hydrogen peroxide.¹⁷ Given the immediately ensuing reaction of **5** affording **3**, the data suggest that a similar route can be envisaged for **2** as well.

Overall, it was shown that vanadium(IV)—citrate complexes can interconnect with their vanadium(V) congeners with or without peroxo groups bound to the metal ion, through pathways involving either stepwise or direct reactions of the respective complexes with varying amounts of hydrogen peroxide.

The fact that **5** appears to be a key species of the chemical reactivity investigated herein was also shown by the reverse reactivity toward that complex starting from **3**. Heating the latter resulted in the isolation of **5**, thus providing a two-way conversion between **3** and **5**. This linkage also provided a new opportunity for further exploration of the reactivity of **3** toward **2**.

Thus far, the explored reactivity pathways led from vanadium(IV)-containing dimers to vanadium(V)-containing dimers. In view of the reverse reactivity relationship between **3** and **5** through a thermal transformation, potential pathways were sought leading from the vanadium(V)-containing dimers to the vanadium(IV)-containing ones. This reverse reactivity perusal started with the conversion of **3** to **5**. The next logical step included the transformation of **5** to **2**. A thermally induced transformation was attempted that led to **2** upon pH

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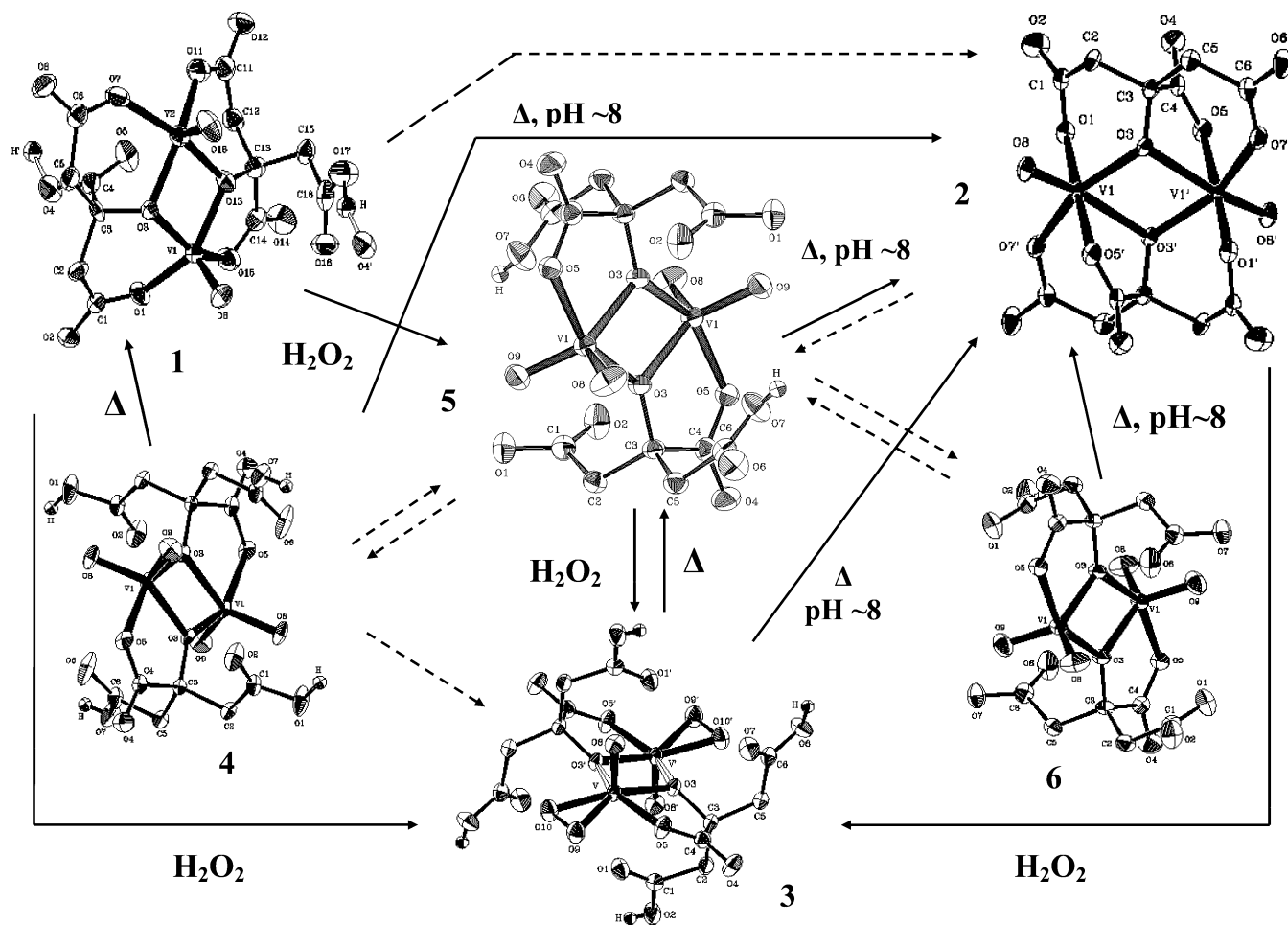


Figure 1. Reactivity scheme of transformations among different vanadium(IV,V)-citrate anionic complexes. Dashed arrows reflect previously established interconversions between vanadium-citrate species.^{14a,18}

adjustment of the final solution. Bearing in mind that the starting material was a vanadium(V) species and the finally isolated product was a vanadium(IV) species, it was apparent that reduction had taken place. It is worth noting that the reverse reaction leading from 2 to 5 was previously shown to take place.¹⁷ Thus, a two-way connection was in place here as well.

Furthermore, 3 was employed in a thermal transformation reaction directly linking it with 2. The reaction proceeded uneventfully and pH adjustment and addition of 2-propanol afforded once again complex 2. In this case too, the interconnection of 3 and 2 was largely established and was supported by the stepwise conversion of 3 to 5 and then on to 2. The experimental conditions employed to achieve both stepwise and direct transformation between 3 and 2 revealed the complex nature of events unfolding in the process: (a) departure of the peroxo group O_2^{2-} and (b) subsequent reduction of vanadium(V) to vanadium(IV), which at pH 8 led to 2.

As a continuation of the above approach, the second group of complexes, namely 4–6, all containing vanadium(V) were examined as to their potential linkage to vanadium(IV) species. In all three cases, the thermally induced transformations upon subsequent pH adjustment to ~8 led to the well-known complex 2. Here too, the predominant feature of the

observed reactivity pattern was the reduction of vanadium(V) to vanadium(IV) and the retention of the dinuclear nature of the derived complex. It should be mentioned that complexes 4, 5, and 6 were previously shown to interconvert, in a pH dependent manner, in aqueous solutions.¹⁸ Linkage with complex 1 was also established in a similar fashion. A representative example of that was the transformation of 4 to 1 by heating aqueous solutions of the former.

Overall, the chemical transformations examined in this work established firmly the stability of the V_2O_2 unit in all of the employed and product dinuclear complexes, at both oxidation states IV and V for the vanadium ions. This conclusion is one of the fundamental aspects of the aqueous chemistry of vanadium and its aqueous speciation in the presence of citrate. Concurrently, the data (a) are entirely consistent with the literature reports suggesting the presence of the V_2O_2 core unit (similar to the one found in the synthetic complexes isolated and structurally characterized) in aqueous media^{13a,26} and (b) confirm the results of the vanadium(IV,V)-citrate chemistry investigated thus far.

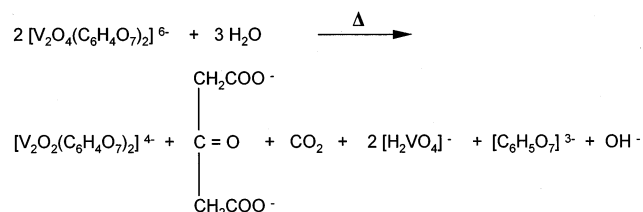
Vanadium(V)-Assisted Oxidative Decarboxylation of Citrate. In a number of the investigated transformations a

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prevailing feature was the reduction of vanadium(V) to vanadium(IV). In all of these cases, no external reducing agents were employed. Therefore, the hypothesis was examined that internal redox reactions could take place, leading to the reduction of vanadium(V) to vanadium(IV).

Having all starting materials containing vanadium(V), the thought was that vanadium(V) could act as an oxidizing agent with the target being the coordinated citrate ligand(s) inside the anionic complex in **3–6**. To this end, previous reports of such reactivity in the literature cited decarboxylation as the prevailing process in which redox-active metal ions were involved.^{22d,27} In this case, with the vanadium being in the +5 oxidation state, the possibility of the coordinated citrate being decarboxylated was very likely. Reports in the literature had previously shown that citrate can be decarboxylated to give the ketonic species acetone dicarboxylate and carbon dioxide in a two-electron process.²⁷ Various reports, in fact, had cited the likely oxidative decarboxylation of hydroxycarboxylic acids in the presence of vanadium(V) in both aqueous and nonaqueous solvents.²⁸ On these facts, attention was directed toward the identification of the product of such a likely process during the thermal transformations mentioned above, all of which had taken place in aqueous solutions. Indeed, in all cases examined, the presence of the ketonic species was confirmed,^{27,29} thus lending credence to the previous literature reports on vanadium(V)-assisted oxidative decarboxylation. On the basis of this finding, a reasonably logical proposal was put forward to account for the transformations occurring in solution for all complexes **3–6** (Figure 1). The proposal invokes the participation of two dinuclear complexes in the unfolding reaction. During this thermal transformation, vanadium(V)-assisted oxidative decarboxylation of citrate provides the necessary electrons for the reduction of one complex with the concurrent decomposition of the other. The reaction affords the reduced product $[\text{V}_2\text{O}_2(\text{C}_6\text{H}_4\text{O}_7)_2]^{4-}$, acetone dicarboxylate, carbon dioxide, and a transformed vanadium(V) species, such as $[\text{V}_2\text{O}_5(\text{C}_6\text{H}_4\text{O}_7)(\text{H}_2\text{O})_2]^{4-}$. The presence of the latter vanadium(V) species was based on (a) reports on aqueous spe-

ciation of the vanadium(V)–citrate system proposing similar species in the same pH range^{13a} and (b) previous findings from our work supporting the existence of fully deprotonated citrate ligand(s) coordinated to vanadium(V).¹⁸ Overall, this tentative scheme was adopted for a number of such transformations presented in the Experimental Section of this work. Alternatively, the components H_2VO_4^- , $\text{C}_6\text{H}_5\text{O}_7^{3-}$, and OH^- could also reflect products of the “decomposed” species $[\text{V}_2\text{O}_5(\text{C}_6\text{H}_4\text{O}_7)(\text{H}_2\text{O})_2]^{4-}$ in an overall reaction scheme shown below for compound **6**:



The aforementioned proposal, albeit logical, needs further perusal and unequivocal identification of the pathway(s) for all the species derived.

The establishment of the vanadium(V)-assisted oxidative decarboxylation, operating in the examined transformations, offers a good insight into the interconversion relations between pairs of dinuclear vanadium–citrate complexes bearing vanadium at different oxidation states, with the individual participant complexes purported to exist as viable components in the aqueous distribution schemes of vanadium(IV)– and vanadium(V)–citrate systems.

Conclusions

A variety of transformations linking dinuclear vanadium(V) complexes with their vanadium(IV) counterparts, and vice versa, were explored and established in a pairwise fashion. The observed chemical reactivity revealed the presence of intermediate dinuclear complexes as part of the route(s) followed in the investigated transformations. It also unraveled potential chemical pathways involving key dinuclear species the conversion of which to other forms, with the same or different vanadium oxidation state, could contribute to the understanding of the discrete speciation equilibria in which the individual species participate. Oxidative reactions were observed involving hydrogen peroxide, whereas vanadium(V)-assisted oxidative decarboxylations led to the reduced vanadium(IV)-containing dinuclear species. Collectively, the data derived from this work shed considerable light into the chemical reactivity of species, previously reported and structurally characterized, as components in vanadium(IV)– and vanadium(V)–citrate speciation. Having been aware of the importance of the properties of such well-characterized species in the assessment of the solubility and bioavailability of vanadium–citrate species in biologically relevant processes, further inquiry into reactivity patterns and pathways involving these and similar species is in order. Research directed toward the identification and characterization of new species, thus far elusive, as well as their properties and their relation to already known vanadium complexes is currently under investigation in our lab.

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- (29) Briefly, the investigated reaction mixture was acidified with HNO_3 to pH ~ 1 . Subsequently, an ethyl acetate extraction took place followed by removal of the organic solvent in vacuo. The residue was redissolved in water. The reaction leading to the identification of the ketonic species included treatment of the resulting aqueous extract with a phenylhydrazine solution in HCl, followed by additional treatment with a 2.5 N NaOH solution. The measured absorbance ratio of A_{520}/A_{420} was significantly greater than 1.30 (relative to the appropriate control) and consistent with the presence of the ketonic species in the reaction medium.²⁷ Gas chromatography–mass spectroscopy (electron impact) further confirmed the chemical findings. Specifically, the mass spectrum of the dimethyl ester derivative (formed by addition of diazomethane to the reaction solution) of the putative acetone dicarboxylic acid product of the oxidative decarboxylation of citrate showed peaks: m/e 174 [M^+], 143 [$\text{M}^+ - \text{OCH}_3$], 101 [$\text{M}^+ - \text{CH}_2\text{COOCH}_3$], 59 [$\text{M}^+ - \text{CH}_2\text{COCH}_2\text{COOCH}_3$].

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