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A New Dinuclear Vanadium(V)–Citrate Complex from Aqueous Solutions. Synthetic, Structural, Spectroscopic, and pH-Dependent Studies in Relevance to Aqueous Vanadium(V)–Citrate Speciation

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Vanadium interactions with low molecular mass binders in biological fluids entail the existence of vanadium species with variable chemical and biological properties. In the course of efforts to elucidate the chemistry related to such interactions, we have explored the oxidative chemistry of vanadium(III) with the physiologically relevant tricarboxylic citric acid. Aqueous reactions involving VCl_3 and anhydrous citric acid, at pH ∼ 7, resulted in blue solutions. Investigation into the nature of the species arising in those solutions revealed, through UV/visible and EPR spectroscopies, oxidation of vanadium(III) to vanadium(IV). Further addition of H_2O_2 resulted in the oxidation of vanadium(IV) to vanadium(V), and the isolation of a new vanadium(V)–citrate complex in the form of its potassium salt. Analogous reactions with $K_4[V_2O_2(C_6H_4O_7)_2]\cdot 6H_2O$ and H_2O_2 or V_2O_5 and citrate at pH ∼ 5.5 afforded the same material. Elemental analysis pointed to the molecular formulation $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (**1**). Complex **1** was further characterized by FT-IR and X-ray crystallography. **1** crystallizes in the triclinic space group $P\bar{1}$, with $a = 11.093(4)$ Å, $b = 9.186(3)$ Å, $c = 15.503(5)$ Å, $\alpha = 78.60(1)^\circ$, $\beta = 86.16(1)^\circ$, $\gamma = 69.87(1)^\circ$, $V = 1454.0(8)$ Å^3, and $Z = 2$. The X-ray structure of **1** reveals the presence of a dinuclear vanadium(V)–citrate complex containing a $V^V_2O_2$ core. The citrate ligands are triply deprotonated, and as such they bind to vanadium(V) ions, thus generating a distorted trigonal bipyramidal geometry. Binding occurs through the central alkoxide and carboxylate groups, with the remaining two terminal carboxylates being uncoordinated. One of those carboxylates is protonated and contributes to hydrogen bond formation with the deprotonated terminal carboxylate of an adjacent molecule. Therefore, an extended network of hydrogen-bonded $V^V_2O_2$-core-containing dimers is created in the lattice of **1**. pH-dependent transformations of **1** in aqueous media suggest its involvement in a web of vanadium(V)–citrate dinuclear species, consistent with past solution speciation studies investigating biologically relevant forms of vanadium.

Introduction

The importance of vanadium in biological fluids has attracted a lot of interest in recent years.[1] To this end, vanadium in a number of biological loci has been earmarked as essential for the physiological function of lower and higher organisms. Vanadium has been found in metalloenzymic systems, including the metal cofactors of the nitrogen fixing alternative nitrogenases,[2] the haloperoxidases catalyzing the first step of the insertion of halogens into organic substrates,[3] and nonenzymatic systems such as those encountered in ascidians and Amanitae (e.g., amavadin).[4] It was also found to exhibit a variety of biological activities as an external

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cofactor, effecting antitumorigenic,[5] mitogenic,[6] and enzyme inhibitory functions.[7] Lately, it has been shown to act as an activator of insulin-linked processes in diabetes mellitus, thus establishing its potential as an effective insulin mimetic agent.[8]

In the form of two predominant oxidation states, V(IV) and V(V), vanadium is thought to exert its influence by interacting with a plethora of molecules in biological fluids. Such molecules include both high molecular mass (e.g., proteins) as well as low molecular mass (e.g., organic acids, amino acids, etc.) ligands. Among the potential low molecular mass binders found in biological fluids such as human plasma, the tricarboxylic acid, citric acid, is prevalent.[9] Its abundance in plasma, at concentrations reaching 0.1 mM, enables it to promote aqueous chemistries with different metal ions, including vanadium, thereby increasing their solubility and potential bioavailability. Furthermore, depending on the redox conditions prevailing at various intracellular and extracellular sites in human fluids, citric acid has the potential to develop its interactive chemistry with vanadium at either oxidation state (IV or V). Therefore, a rich vanadium−citric acid chemistry is expected to arise in biologically relevant media, numerous aspects of which remain unexplored. Efforts to delineate such chemistries in aqueous media have been carried out in the past[10] and have resulted in a number of biodistribution schemes and potential structural features for participating vanadium species purported to exist in them. The importance of the derived information is reflected into the systematic investigations aimed at comprehending the nature and the chemical and biological properties of low molecular mass vanadium species of reasonable aqueous solubility and bioavailability, all arisen through the interactive complexation chemistry with organic substrates, like citrate. Synthetic efforts along these lines have resulted in a number of vanadium−carboxylate complexes with variable coordination geometries and vanadium oxidation numbers.[11−13] Despite these efforts, numerous aspects of the chemistry of vanadium with tricarboxylic acids have yet to be elucidated. To that end, we have launched systematic synthetic studies targeting vanadium(IV) and vanadium(V) complexes bearing the physiologically relevant citric acid. Herein, we report on the pH-specific synthesis of a new dinuclear vanadium(V)−citrate complex by three different methods, its isolation from aqueous solutions, and its spectroscopic and structural properties. Furthermore, pH-dependent transformations on this new dimer have been carried out and reveal its involvement in a web of interconnecting equilibria encompassing other known vanadium(V)−citrate species.

Experimental Section

Materials and Methods. All experiments were carried out in the open air. Nanopure quality water was used for all reactions. VCl_3, V_2O_5, anhydrous citric acid, and 30% H_2O_2 were purchased from Aldrich. $K_4[V_2O_2(C_6H_4O_7)_2]\cdot 6H_2O$ was prepared as previously described.[12] An authentic sample of $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ was prepared according to the literature.[11a,13] KOH was supplied by Fluka.

Physical Measurements. FT-infrared measurements were taken on a Perkin-Elmer 1760X FT-infrared spectrometer. UV/visible spectra were recorded on a Hitachi U-2001 spectrophotometer in the range 200−900 nm. The EPR spectra of the intermediate blue solutions derived from reactions leading to **1** were recorded on a Bruker ER 200D-SRC X-band spectrometer, equipped with an Oxford ESR 9 cryostat at 9.174 GHz, 10 dB, and at 4 K. Elemental analyses were performed by Quantitative Technologies, Inc.

Preparation of Complexes. (a) $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (1). Method 1. VCl_3 (0.09 g, 0.57 mmol) and anhydrous citric acid (0.11 g, 0.57 mmol) were placed in a flask and dissolved in 5 mL of H_2O. To the resulting reaction mixture was added 0.10 M KOH dropwise with stirring, until the color of the solution became dark green and the pH was ~9. Subsequently, the reaction mixture was stirred overnight. On the following day, the solution was blue and the pH was ~7. The reaction mixture was taken to dryness by means of a rotary evaporator, and the residue was redissolved in ~3 mL of water. The flask was placed in an ice bath, and to it was added

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H_2O_2 30% (~0.19 mL, 1.84 mmol) dropwise with continuous stirring. The color of the reaction mixture became orange, and stirring was continued for an additional 35 min. Subsequently, ethanol was added and the flask was placed in the refrigerator. A week later, yellow crystalline material precipitated, which was isolated by filtration and dried in vacuo. Yield: 0.16 g (69.9%). Anal. Calcd for **1**, $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ ($C_{12}H_{21.20}O_{23.60}K_4V_2$, MW = 801.37): C, 17.97; H, 2.64; K, 19.47. Found: C, 17.43; H, 2.61; K, 18.99.

(b) Method 2: From $K_4[V_2O_2(C_6H_4O_7)_2]\cdot 6H_2O$. $K_4[V_2O_2(C_6H_4O_7)_2]\cdot 6H_2O$ (0.074 g, 0.10 mmol) was dissolved in 3 mL of water. The solution was blue, and the pH was ~7. The reaction flask was then placed in an ice bath, and 30% H_2O_2 (0.043 mL, 0.42 mmol) was added dropwise with continuous stirring. The color of the solution turned orange, and stirring was continued for an additional 35 min. Subsequently, ethanol was added and the reaction flask was placed at 4 °C. A few days later, yellow crystals formed, which were isolated by filtration and dried in vacuo. Yield: 0.02 g (26%). Positive identification of the crystalline material as complex **1** came from the FT-infrared spectrum and the X-ray unit cell determination carried out on a single crystal.

(c) Method 3. V_2O_5 (0.20 g, 1.10 mmol) was placed in 6 mL of water. To that was added KOH (0.25 g, 4.46 mmol) with continuous stirring. The slurry was stirred overnight with heating at 50 °C. The next day, the solution was colorless. To that solution was added anhydrous citric acid (0.80 g, 4.16 mmol) with stirring. Following dissolution of the tricarboxylic acid, the pH was adjusted, with 0.1 M KOH, to ~5.5, and the color of the solution turned yellow-green. Stirring was continued for an additional 1 h, and the color of the reaction mixture stayed the same. Subsequently, ethanol was added and the reaction flask was placed at 4 °C. A couple of days later, yellow crystals appeared at the bottom of the flask. The crystalline material was isolated by filtration and dried in vacuo. Yield: 0.40 g (45.5%). The crystals were positively identified as complex **1** by the FT-infrared spectrum and the determination of the unit cell dimensions for a single crystal by X-ray crystallography.

pH-Dependent Interconversions. From $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ to $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$. A quantity of complex **1** (0.95 g, 1.19 mmol) was placed in a 25 mL round-bottom flask and dissolved in 4 mL of water. The pH of the solution was adjusted with dilute hydrochloric acid to pH ~ 3.5, and the resulting solution was stirred for approximately 30 min. The color of the solution turned light green and stayed as such. Subsequently, the reaction mixture was placed in the refrigerator. A few days later, light greenish crystals appeared at the bottom of the flask. The crystals were isolated by filtration and dried in vacuo. The yield was 0.74 g (89.6%). The FT-IR spectrum of the crystalline material was identical to that of an authentic sample of $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$.[11a,13]

From $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ to $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$. A quantity of $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ (0.25 g, 0.36 mmol) was dissolved in 4.0 mL of water, in a 25 mL round-bottom flask, with brief and mild heating. Addition of KOH helped adjust the pH of the solution to approximately pH ~ 5.5. The resulting reaction solution was stirred for 30 min at room temperature. The color of the solution turned oily yellow and stayed as such. Subsequently, ethanol was added and the reaction mixture was placed at 4 °C. A couple of days later, yellowish crystals appeared at the bottom of the flask. They were isolated by filtration and dried in vacuo. The yield of the transformation was 0.13 g (45.2%). The FT-infrared spectrum of the crystalline material revealed that the product of the transformation was $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$.

Table 1. Summary of Crystal, Intensity Collection, and Refinement Data for $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (**1**)

formula	$C_{12}H_{21.20}O_{23.60}K_4V_2$
fw	801.37
temp, K	298
wavelength	Mo Kα 0.71073
space group	$P\bar{1}$
a (Å)	11.093(4)
b (Å)	9.186(3)
c (Å)	15.503(5)
α (deg)	78.60(1)
β (deg)	86.16(1)
γ (deg)	69.87(1)
V (Å^3)	1454.0(8)
Z	2
D_{calcd}/D_{measd} (Mg m^{-3})	1.830/1.81
abs coeff (μ) (mm^{-1})	1.309
range of h, k, l	$-13 \rightarrow 13$, $-10 \rightarrow 10$, $0 \rightarrow 18$
GOF on F^2	1.063
R^a	0.0510^b
$R_w{}^a$	0.1392^b

[a] R values are based on F's; R_w values are based on F^2. $R = \sum||F_o| - |F_c||/\sum(|F_o|)$; $R_w = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{1/2}$. [b] For 4619 reflections with $I > 2\sigma(I)$.

X-ray Crystallography. Crystal Structure Determination. X-ray quality crystals of compound **1** were grown from water−ethanol mixtures. A single crystal, with dimensions 0.30 × 0.40 × 0.50 mm (**1**), was mounted on a Crystal Logic dual-goniometer diffractometer, using graphite-monochromated Mo Kα radiation. Unit cell dimensions for **1** were determined and refined by using the angular settings of 25 automatically centered reflections in the range $11° < 2\theta < 23°$. Relevant crystallographic details are given in Table 1. Intensity data were measured by using $\theta - 2\theta$ scans. Three standard reflections were monitored every 97 reflections, over the course of data collection, and showed less than 3% variation and no decay. For **1**, Lorentz and polarization corrections were applied by using Crystal Logic software. Further experimental crystallographic details: for **1**, $2\theta_{max} = 50°$; scan speed 4.2°/min; scan range $2.2 + \alpha_1\alpha_2$ separation; reflections collected/unique/used, 5292/5088 ($R_{int} = 0.0101$)/5088; 448 parameters refined; $(\Delta/\sigma)_{max} = 0.701$; $(\Delta\rho)_{max}/(\Delta\rho)_{min} = 1.310/-1.055$ e/Å^3; R/R_w (for all data), 0.0553/0.1442.

The structure of complex **1** was solved by direct methods using SHELXS-86[14] and refined by full-matrix least-squares techniques on F^2 with SHELXL-93.[15] All non-H atoms in the structure of **1** were refined anisotropically. Four water solvate molecules were refined each with occupancy factor 1. The remainder three solvate water molecules were refined with occupancy factors less than 1, totalling 1.6 molecules. Most of the H atoms of the water molecules were not included in the refinement. All the H atoms of the anion in **1** were located by difference maps and were refined isotropically.

Results

Syntheses. The primary synthesis of complex **1** was based on simple starting reagents, including VCl_3 and citric acid. Reaction of these reagents in water, in the presence of a base, led, upon overnight stirring, to a blue solution. KOH was used as a base in the reaction mixture. It helped establish the pH of the solution (pH ~ 7), to which hydrogen peroxide

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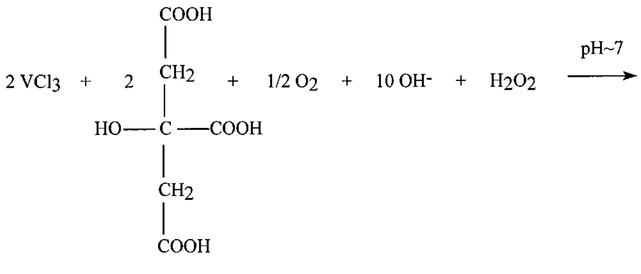
(14) Sheldrick, G. M *SHELXS-86: Structure Solving Program*; University of Göttingen: Göttingen, Germany, 1986.

(15) Sheldrick, G. M *SHELXL-93: Structure Refinement Program*; University of Göttingen: Göttingen, Germany, 1993.

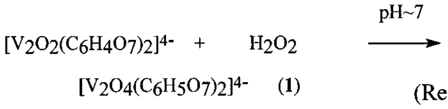
would subsequently be added, and concurrently provided the necessary counterions needed to balance the charge generated on the final complex anion of **1**. In order to gain insight into the nature of species forming in the blue solutions, the UV/visible spectra of these solutions were investigated. The spectra, in the visible range, were consistent with the presence of vanadyl-containing moieties in the initial reaction mixture.[12] This contention was further confirmed by the EPR spectra of the same solutions taken at 4 K.[12] It appears, then, that under the employed experimental conditions, vanadium(III) was oxidized to vanadium(IV). Collectively, the spectral data on the blue solutions suggested that the intermediate species forming in the initial reaction mixture was the $[V_2O_2(C_6H_4O_7)_2]^{4-}$. This complex contains vanadium(IV) in the form of two vanadyl $(V^{IV}{=}O)^{2+}$ moieties linked together in a dinuclear $V^{IV}{}_2O_2$ unit.[12] The $[V_2O_2(C_6H_4O_7)_2]^{4-}$ species very likely serves as the intermediate complex upon which hydrogen peroxide is added. Concomitant oxidation of vanadium(IV) to vanadium(V) afforded the anionic complex **1** (reaction 1). Complex **1** was then crystallized out of solution in the form of its potassium salt.

The overall stoichiometric reaction leading to complex **1** is shown schematically below:



(Reaction 1)

On the basis of the derived nature of the species forming in the intermediate blue solutions of reaction **1**, it was decided to use such a species as a starting material for the synthesis of complex **1** (reaction 2).



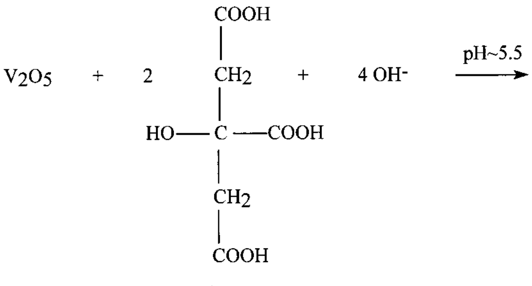
$$[V_2O_2(C_6H_4O_7)_2]^{4-} + H_2O_2 \xrightarrow{pH\sim7} [V_2O_4(C_6H_5O_7)_2]^{4-}\ (1)$$

(Reaction 2)

Thus, reaction of $K_4[V_2O_2(C_6H_4O_7)_2]\cdot 6H_2O$, in water (pH ~ 7), with hydrogen peroxide led to the oxidation of vanadium(IV) to vanadium(V), finally affording yellow crystals of complex **1**. The isolated crystalline material was identical to that obtained by the direct method of synthesis (method 1), as that was confirmed by FT-IR spectroscopy and X-ray unit cell determination for a single crystal of **1**.

In both routes employed for the synthesis of complex **1**, oxidation of vanadium(III)/vanadium(IV) to vanadium(V) took place. Precipitation of the products from the reaction mixture, in crystalline form, was achieved by addition of ethanol at 4 °C.

In a third approach, employing vanadium(V) as a starting material, V_2O_5 and citric acid reacted in water at optimal pH ~ 5.5 and afforded a yellow crystalline material upon addition of ethanol at 4 °C. The reaction was equally facile to the ones mentioned previously. In this case, both the starting material and the isolated product contained vanadium(V) (reaction 3). The crystalline product was positively identified by FT-IR spectroscopy, and the crystal cell unit constants were determined by X-ray crystallography for one of the isolated single crystals.



(Reaction 3)

Elemental analysis on the K^+ salt of the isolated crystalline material suggested the formulation $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (**1**). Complex **1** in the crystalline form appears to be stable in air indefinitely. It is insoluble in alcohols (CH_3OH, *i*-PrOH, etc.), acetonitrile, and dimethyl sulfoxide (DMSO), but it dissolves readily in water.

Interconversions. A pH-dependent transformation of $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (**1**) in an aqueous solution resulted in the isolation of $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ (**2**). A simple dissolution of complex **1** in water and adjustment of the reaction solution pH with acid to ~3.5 was sufficient to lead to the facile isolation of the well-known dinuclear complex $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$. Structural evidence for complex **2** was amply provided in the literature.[11a,16] The reverse transformation, starting from $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$, proceeded equally well, affording complex **1**, $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$. Specifically, adjustment of the solution pH of $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ in water, with a base, to ~5.5 led to the isolation of complex **1** by addition of the precipitating solvent ethanol at 4 °C. The overall reversible transformation between $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ and $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ suggested that the two complexes interconvert in a pH-dependent manner, and are consequently linked as participating species in a speciation scheme for the vanadium(V)–citrate system in aqueous medium.

It is worth pointing out that, from the synthetic point of view, the aforementioned transformation could very well be considered as a fourth method of synthesis and isolation of complex **1** from the well-known dinuclear species $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$.

X-ray Crystallographic Structure. $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (1). The X-ray crystal structure of **1** consists of discrete anions and cations. Complex **1** crystallizes in the triclinic system $P\bar{1}$ with two molecules (heretofore referred to as A and B) per unit cell. The ORTEP diagram of the anion in **1** is shown in Figure 1. Selected interatomic

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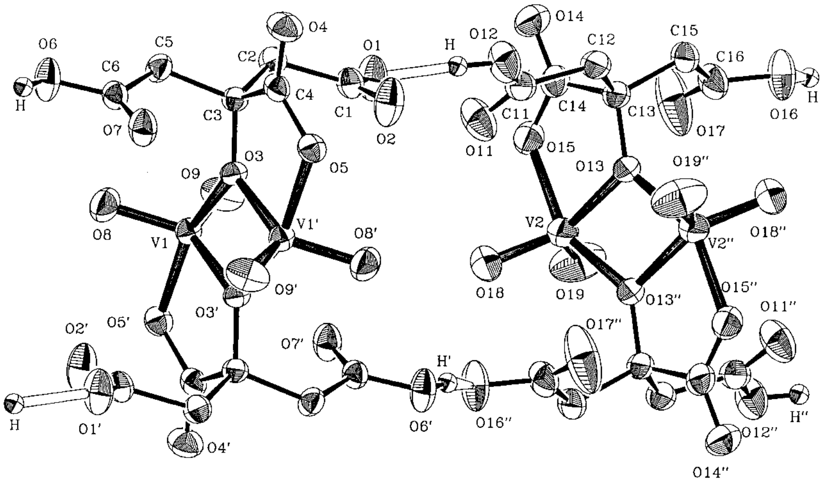

Figure 1. ORTEP structure of the $[V_2O_4(C_6H_5O_7)_2]^{4-}$ anion with the atom-labeling scheme in **1**. Thermal ellipsoids are drawn by ORTEP and represent 50% probability surfaces.

distances and bond angles for **1** are listed in Table 2. The anion in **1** is a dimer of two vanadium(V) ions with two citrate ligands. The central core consists of a rhombic $V^V{}_2O_2$ unit, with the two vanadium ions, in the oxidation state +5, bridged by the alkoxide oxygens of the coordinated citrates. The $V^V{}_2O_2$ core is planar, and the coordinated citrate ligands around it are triply deprotonated. As such, the citrates create a distorted trigonal bipyramidal coordination environment around the vanadium ions of the $V^V{}_2O_2$ core. In this environment, the equatorial donor atoms include the two VO_2^+ doubly bonded oxygens O(8) and O(9), and O(18) and O(19) for A and B, respectively. The third donor atom is the citrate alkoxide oxygen O(3)′ for A, and O(13)″ for B, which also serves as the bridge between the two vanadium ions in the $V^V{}_2O_2$ core. The axial ligand donor atoms include the central carboxylate oxygen of the coordinated citrate ligand and the second alkoxide oxygen of the $V^V{}_2O_2$ core. The calculated trigonality index, τ, for both crystallographically independent molecules is 0.41 ($\tau = \varphi_1 - \varphi_2/60$, where φ_1 and φ_2 are the two largest angles in the coordination sphere; $\tau = 0$ for a perfect square pyramid, and $\tau = 1$ for a perfect trigonal bipyramid).[17] Beyond the two binding sites of the citrate ligand attached to vanadium, there remain two more terminal carboxylate groups. These groups are not coordinated to the central core and thus move away from it. One of the carboxylate groups is deprotonated, while the second one is protonated. This is a novel feature in the structural chemistry of vanadium(V)−citrate dimers, whereby the two terminal carboxylate groups are either both protonated[11a,13,16] or both deprotonated.[18] In all cases, however, the terminal carboxylates do not appear to exhibit a preference for binding to the $V^V{}_2O_2$ core. As a result, they stay away from it.

Moreover, the protonated terminal carboxylate group of each citrate in **1** offers an additional novelty to the structure of **1**. Through its proton, it serves as a scaffold for hydrogen bond formation with the deprotonated terminal carboxylate group of an adjacent dimer. This way, a 1:1 interaction occurs

Table 2. Selected Bond Distances (Å) and Angles (deg) for $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O^a$

V(1)−O(8)	1.634(3)	V(2)−O(18)	1.624(3)
V(1)−O(9)	1.618(3)	V(2)−O(19)	1.622(3)
V(1)−O(3)	1.970(2)	V(2)−O(13)	1.974(3)
V(1)−O(3)′	2.017(2)	V(2)−O(13)″	2.005(3)
V(1)−O(5)′	1.966(2)	V(2)−O(15)″	1.977(3)
C(1)−O(1)	1.282(4)	C(11)−O(11)	1.221(5)
C(1)−O(2)	1.225(5)	C(11)−O(12)	1.298(5)
C(3)−O(3)	1.425(4)	C(13)−O(13)	1.420(4)
C(4)−O(4)	1.224(4)	C(14)−O(14)	1.223(5)
C(4)−O(5)	1.290(4)	C(14)−O(15)	1.303(5)
C(6)−O(6)	1.288(4)	C(16)−O(16)	1.286(5)
C(6)−O(7)	1.228(4)	C(16)−O(17)	1.203(6)
C(1)−C(2)	1.518(5)	C(11)−C(12)	1.510(5)
C(2)−C(3)	1.533(4)	C(12)−C(13)	1.537(5)
C(3)−C(4)	1.537(5)	C(13)−C(14)	1.533(6)
C(3)−C(5)	1.527(4)	C(13)−C(15)	1.534(5)
C(5)−C(6)	1.508(5)	C(15)−C(16)	1.513(5)
O(9)−V(1)−O(8)	106.9(2)	O(19)−V(2)−O(18)	108.5(2)
O(9)−V(1)−O(3)′	129.1(1)	O(19)−V(2)−O(13)″	127.0(2)
O(8)−V(1)−O(3)′	124.0(1)	O(18)−V(2)−O(13)″	124.5(2)
O(8)−V(1)−O(5)′	97.6(1)	O(19)−V(2)−O(15)″	96.4(2)
O(9)−V(1)−O(5)′	98.1(1)	O(18)−V(2)−O(15)″	98.4(1)
O(5)′−V(1)−O(3)′	77.8(1)	O(15)″−V(2)−O(13)″	78.2(1)
O(8)−V(1)−O(3)	101.2(1)	O(18)−V(2)−O(13)	100.8(1)
O(9)−V(1)−O(3)	100.3(1)	O(19)−V(2)−O(13)	99.9(2)
O(3)−V(1)−O(3)′	70.9(1)	O(13)−V(2)−O(13)″	71.2(1)
O(5)′−V(1)−O(3)	148.6(1)	O(13)−V(2)−O(15)″	149.3(1)
O(2)−C(1)−O(1)	123.4(3)	O(11)−C(11)−O(12)	122.9(3)
O(2)−C(1)−C(2)	121.2(3)	O(11)−C(11)−C(12)	123.3(3)
O(1)−C(1)−C(2)	115.3(3)	O(12)−C(11)−C(12)	113.7(3)
C(1)−C(2)−C(3)	115.0(3)	C(11)−C(12)−C(13)	114.3(3)
O(3)−C(3)−C(2)	110.9(3)	O(13)−C(13)−C(12)	110.8(3)
O(3)−C(3)−C(5)	111.7(3)	O(13)−C(13)−C(15)	110.7(3)
C(2)−C(3)−C(5)	108.4(3)	C(12)−C(13)−C(15)	108.3(3)
O(3)−C(3)−C(4)	106.1(2)	O(13)−C(13)−C(14)	106.5(3)
C(2)−C(3)−C(4)	110.6(3)	C(12)−C(13)−C(14)	110.1(3)
C(5)−C(3)−C(4)	109.1(3)	C(14)−C(13)−C(15)	110.4(3)
O(4)−C(4)−O(5)	123.8(3)	O(14)−C(14)−O(15)	123.3(4)
O(4)−C(4)−C(3)	120.5(3)	O(14)−C(14)−C(13)	120.9(4)
O(5)−C(4)−C(3)	115.7(3)	O(15)−C(14)−C(13)	115.8(3)
C(6)−C(5)−C(3)	116.5(3)	C(16)−C(15)−C(13)	114.7(3)
O(7)−C(6)−O(6)	124.0(3)	O(17)−C(16)−O(16)	123.4(4)
O(7)−C(6)−C(5)	121.7(3)	O(17)−C(16)−C(15)	122.4(4)
O(6)−C(6)−C(5)	114.3(3)	O(16)−C(16)−C(15)	114.1(4)

[a] Symmetry transformations used to generate equivalent atoms: (′) $-x + 1, -y + 1, -z + 1$; (″) $-x + 2, -y, -z$.

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Table 3. Bond Distances (Å) and Angles (deg) in Dinuclear Vanadium(V)−Carboxylate Compounds

compound	distances (Å)			angles (deg)	
	V═O	V−O	V···V	(O−V−O)$_{eq}$[j]	(O−V−O)$_{ap}$[k]
$K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ **(1)**[a,b]	1.618(3)−1.634(3)	1.966(2)−2.017(2)	3.236(1)−3.247(1)	106.9(2)−129.1(1)	70.9(1)−101.2(1)
$K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ **(2)** [c,11a,16]	1.611(2)−1.623(2)	1.957(2)−2.013(2)	3.211(2)	106.4(1)−130.5(1)	72.0(1)−101.6(1)
$Na_2[V_2O_4(C_6H_6O_7)_2]\cdot 2H_2O$[c,13]	1.605(4)−1.642(3)	1.957(3)−2.000(3)	3.225(1)	106.8(2)−137.3(2)	71.3(1)−101.5(2)
$(NH_4)_2[V_2O_4(C_6H_6O_7)_2]\cdot 2H_2O$[c,16]	1.607(3)−1.636(2)	1.964(2)−2.012(2)	3.223(1)	107.3(1)−133.9(1)	71.7(1)−101.1(1)
$(Me_4N)_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$[c,13]	1.600(2)−1.624(2)	1.972(2)−2.026(2)	3.265(1)	107.2(1)−137.7(1)	70.5(1)−102.4(1)
$K_2(NH_4)_4[V_2O_4(C_6H_4O_7)_2]\cdot 6H_2O$ **(3)**[d,18]	1.620(2)−1.625(2)	1.961(2)−2.005(2)	3.219(1)	106.6(1)−128.3(1)	71.5(1)−101.4(2)
$(NH_4)_2[V(O)_2(OC(CH_2CH_3)_2COO)]_2$[e,21]	1.605(2)−1.617(2)	1.973(1)−1.984(2)	3.204(2)	108.5(1)−126.7(1)	71.9(1)−100.6(1)
$Na_2[V_2O_4(C_4H_6O_3)_2]\cdot 7H_2O$[f,22]	1.619(2)−1.624(1)	1.990(1)−2.004(1)	3.210	108.0(1)−131.8(1)	71.8(1)−104.4(1)
$Rb_2[V_2O_4(OCH_2COO)_2]$[g,23]	1.614(2)	1.944(2)−1.998(2)	3.206(2)	107.9(1)−128.6(1)	71.1(1)−100.4(1)
$Cs_2[V_2O_4(C_4H_4O_5)_2]\cdot 2H_2O$[h,23]	1.610(4)−1.619(5)	1.963(4)−2.016(4)	3.241(2)	107.8(3)−131.2(2)	70.9(2)−102.2(2)
$Cs_2[V_2O_4(C_3H_4O_3)_2]\cdot 2H_2O$[i,23]	1.599(5)−1.635(5)	1.949(3)−2.004(4)	3.214(2)	107.9(2)−130.9(2)	71.2(1)−102.2(2)

[a] This work. [b] $C_6H_5O_7^{3-}$ = citrate. [c] $C_6H_6O_7^{2-}$ = citrate. [d] $C_6H_4O_7^{4-}$ = citrate. [e] ($^-OC(CH_2CH_3)_2COO^-$) = 2-ethyl-2-hydroxybutyrate. [f] $C_4H_6O_3^{2-}$ = 2-hydroxy-2-methylpropanoate. [g] $^-OCH_2COO^-$ = glycolate. [h] $C_4H_4O_5^{2-}$ = malate. [i] $C_3H_4O_3^{2-}$ = lactate. [j] O−V−O angle range in the equatorial plane. [k] O−V−O angles between the axial and equatorial ligands.

between adjacent dimers that results in the formation of chains of hydrogen-bonded $V^V{}_2O_2$ dimers. This additional feature may provide further stabilization of the crystal lattice in complex **1**.

It is also noteworthy that the mode of coordination of the citrate ligands around the vanadium(V) ions in **1** is relevant to the coordination mode of the R-homocitrate ligand attached to the Fe−Mo−S cofactor of the conventional nitrogenase enzymes, and to the coordination of the citrate ligand in the corresponding active site heterometallic cofactor in the NifV$^-$ nitrogenase enzymes.[19] A model species displaying the coordination mode of homocitrate to a vanadium(V) ion is the dinuclear complex $[K_2(H_2O)_5][(VO_2)_2(R,S\text{-homocitrate})_2]\cdot H_2O$, previously reported in the literature.[20]

Comparisons of the bond distances and angles in **1** with corresponding distances and angles in other vanadium(V)-containing dimers[13,16,18,21−23] are given in Table 3. It appears that similar distances and angles are observed in a number of $V^V{}_2O_2$-core-containing dimers, exhibiting distorted trigonal bipyramidal geometry of the bound citrates around the vanadium(V) ions.

The citrate ligands in the anion of **1** adopt an extended conformation upon binding to the vanadium ion. The carbon atoms C(1), C(2), C(3), C(5), and C(6) in A, and C(11), C(12), C(13), C(15), and C(16) in B of the citrate backbone are coplanar, with the largest standard deviation being 0.061 for C(3) in A and 0.098 for C(13) in B. The central carboxylate planes O(4)−C(4)−O(5) in A and O(14)−C(14)−O(15) in B are rotated ~1.9° out of the O(3)−C(3)−C(4) plane and 2.9° out of the O(13)−C(13)−C(14) plane, respectively. These values are congruent with those seen in other vanadium(V)−citrate complexes, suggesting a similar approach of the citrate to the metal ion in all cases of complex assemblies.

Table 4. Hydrogen-Bonding Interactions in $K_4[V_2O_4(C_6H_5O_7)_2]\cdot 5.6H_2O$ (**1**)

interaction	D···A (Å)	H···A (Å)	D−H···A (deg)	symmetry operation
O6−HO16···O16	2.468	1.658	161.2	−1 + *x*, 1 + *y*, *z*
O12−HO12···O1	2.502	1.602	174.3	*x*, *y*, −1 + *z*
OW1−HW1A···O2	2.846	1.954	169.9	*x*, *y*, *z*
OW2−HW2A···O6	2.792	2.030	150.0	*x*, *y*, *z*
OW2−HW2B···O15	2.943	2.171	169.3	2 − *x*, −*y*, −*z*

The V···V distance in the anion of **1** is 3.247(1) and 3.236(1) Å for A and B, respectively, similar to those observed in previously reported vanadium(V)−citrate dinuclear compounds.

Four potassium counterions are also present in **1**, and they counterbalance the 4− charge generated on the complex anion. The potassium cations in **1** are in contact with the carboxylate oxygens of the citrate anion as well as the VO_2^+ and lattice water oxygens at distances in the range 2.741(3)−3.141(3) Å (eight contacts for K1 and K2), and 2.659(7)−3.294(4) Å (seven contacts for K3 and K4). The presence of water molecules of crystallization in **1** is responsible for the establishment of an extensive hydrogen-bonding network (Table 4).

FT-IR Spectroscopy. The FT-infrared spectrum of **1** in KBr revealed the presence of vibrationally active carboxylate groups. Specifically, both antisymmetric and symmetric vibrations for the carboxylate groups of the coordinated citrate ligands dominated the spectrum. Thus, antisymmetric stretching vibrations $\nu_{as}(COO^-)$ were present for the carboxylate carbonyls in the range 1719−1649 cm^{-1}. Symmetric vibrations $\nu_s(COO^-)$ for the same groups were present in the range 1408−1371 cm^{-1}. The frequencies of the observed carbonyl vibrations appeared to be shifted to lower values in comparison to the corresponding vibrations in the free citric acid, indicating changes in the vibrational status of the citrate ligand upon coordination to the vanadium.[24] The difference between the symmetric and antisymmetric stretches,

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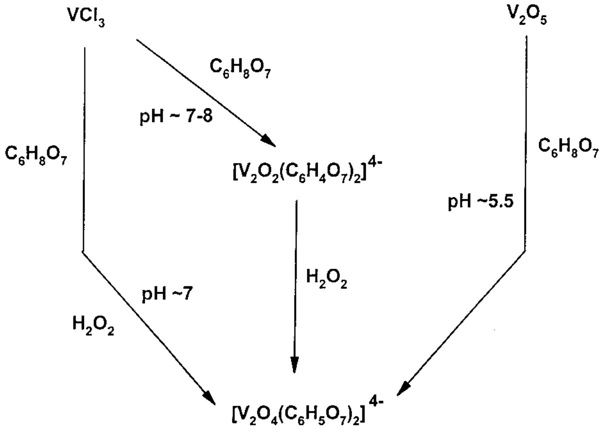

Figure 2. Variable synthetic routes leading to the $[V_2O_4(C_6H_5O_7)_2]^{4-}$ anionic complex.

$\Delta(\nu_{as}(COO^-) - \nu_s(COO^-))$, was greater than 200 cm^{-1}, indicating that the carboxylate groups of the citrate ligand were either free or coordinated to the metal ion in a monodentate fashion.[24] This was further confirmed by the X-ray crystal structure of **1**. The $\nu(VO_2^+)$ vibrations for the VO_2^+ groups in **1** were present in the range 936−868 cm^{-1}. All of the aforementioned assignments were in agreement with previous assignments in dinuclear V(V) complexes,[13,21,23,25,26] and in line with prior reports on carboxylate-containing ligands bound to different metal ions.[27]

Discussion

The Aqueous Chemistry. The synthesis of a new dinuclear $V^V{}_2O_2$ variant of the vanadium−citrate family of species, complex **1**, was achieved through a variety of synthetic approaches (Figure 2). Specifically, redox reactions involving vanadium(III) and vanadium(IV) as well as nonredox reactions involving vanadium(V) led to the formation and ultimate isolation of complex **1** in the form of its potassium salt. Regardless, therefore, of the vanadium oxidation state in the starting reagents used, the ultimate vanadium oxidation state achieved and consistently exhibited by the isolated crystalline product of reactions 1−3 was that of vanadium(V).

The basic structural features of the anionic complex in **1** involve a planar $V^V{}_2O_2$ core supported by the central alkoxide oxygens of the citrate ligands bound to vanadium(V) ions. Moreover, the geometrical data on this central core unit are similar to those encountered in other vanadium(V)−citrate dimers,[11,13,16,18] thus attesting to the stability of the $V^V{}_2O_2$ core. The latter notion is further supported by the fact that, under diverse experimental conditions involving different vanadium starting materials, the same $[(V^VO_2)_2O_2]^0$ scaffolding unit was assembled and eventually isolated in the presence of citrate. Hence, the $V^V{}_2O_2$ core emerges as a unit integrally connected with the overall stability of the anionic complex surrounded by the organic citrate ligands. This is in line with previous observations on the core structure of dinuclear vanadium species.[11,13,16,18]

Direct comparison of **1** with $K_2[V_2O_4(C_6H_6O_7)_2]\cdot 4H_2O$ (**2**)[11,13] and $K_2(NH_4)_4[V_2O_4(C_6H_4O_7)_2]\cdot 6H_2O$ (**3**)[18] leads to significant observations regarding differences and similarities in the respective species. Specifically, the structural features that remain constant in all three classes of complexes are (a) the planar $[V^V{}_2O_2]$ core unit, (b) the $[V^VO_2]^+$ basic scaffolding unit of the dinuclear core, (c) the +5 oxidation state of vanadium in the $[V^V{}_2O_2]$ core, (d) the trigonal bipyramidal (TBP) coordination sphere around each vanadium(V), (e) the mode of coordination of the citrate ligand around each vanadium (citrate utilizes its central alkoxide and carboxylate groups to bind vanadium), (f) the 1:1 vanadium(V) to citrate stoichiometry in the anionic assembly, and (g) the anionic charge on the vanadium(V)−citrate complex(es).

The structural features in which the complexes differ from one another are (a) the protonation state of the citrate ligands bound to the $[V^V{}_2O_2]$ core and (b) the overall charge on the complex anionic assembly. Hence, $[V_2O_4(C_6H_6O_7)_2]^{2-}$ in **2** bears a 2− charge, whereas $[V_2O_4(C_6H_5O_7)_2]^{4-}$ in **1** bears a 4− charge, and $[V_2O_4(C_6H_4O_7)_2]^{6-}$ in **3** bears a 6− charge.

Enhancement of the stability of the entire lattice in **1** is likely achieved through hydrogen bonds generated (a) between the protonated termini of the uncoordinated carboxylates in the citrate ligands bound to vanadium and the analogous deprotonated carboxylates of adjacent vanadium citrate anionic complexes and (b) between the water molecules in the crystal lattice and the VO_2^+ and carboxylate oxygens in the bound and unbound citrates. Similar hydrogen-bonding networks were observed in numerous other vanadium−citrate and vanadium−carboxylate complexes reported in the past.[11,12,13,28]

In a pH-dependent fashion, **1** was reversibly converted to **2**, a well-known dinuclear species with a structure similar to that in **1**,[11,13] yet a complex with both of its terminal carboxylate citrate groups protonated. This reversible interconversion denoted the linkage between the two species via protonation−deprotonation processes. Practically, adjusting the pH of the solution containing one species or the other induced protonation or deprotonation of only one of the terminal carboxylates on both citrates attached to the $V^V{}_2O_2$ core. Evidently, the (de)protonation process occurred at a specific site; that of an uncoordinated carboxylate group. It is worth noting that an analogous pH-dependent chemistry

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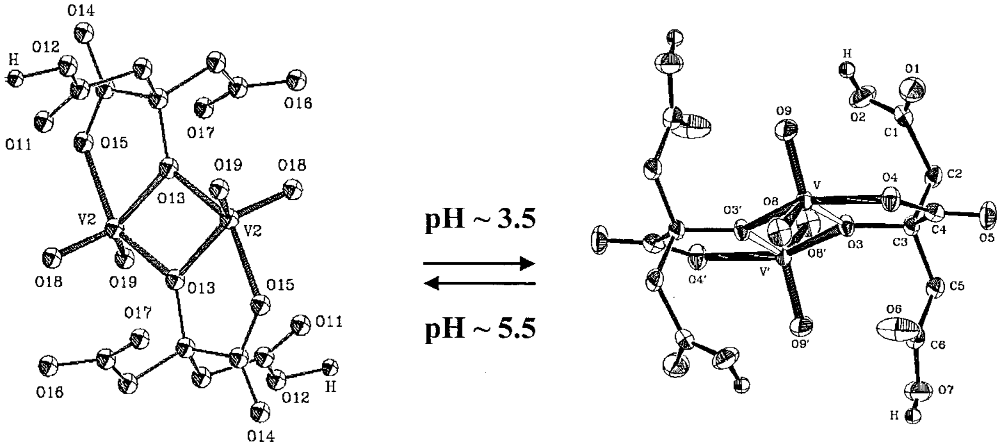

Figure 3. pH-dependent interconversion of complexes **1** and **2** in aqueous solution.

was also observed in the case of vanadium(IV)−citrate complexes in aqueous solutions.[12] There, however, the impact of pH acid−base chemistry was felt not only on the conformational state of the $V^{IV}_2O_2$ core but also on the protonation state of the vanadium-bound citrate ligands.

Interspecies Structural Correlations. Taking into consideration the known structures of vanadium(V)−citrate dinuclear complexes, there seems to be a correlation between the (de)protonation state of citrates in **1**, $[V_2O_4(C_6H_4O_7)_2]^{6-}$, and $[V_2O_4(C_6H_6O_7)_2]^{2-}$ on one hand and the overall charge on the respective complexes on the other. Full deprotonation of bound citrates is linked with an overall charge of 6− in **3**. Double deprotonation of bound citrates is linked with an overall charge of 2− in **2**. Thus, the anion in **1** resides in the middle, with triply deprotonated citrate ligands affording a total charge of 4−. It appears, therefore, that **1** may be an intermediate species in a series of vanadium(V) structural forms, which interconvert in a pH-dependent fashion. For at least one of those species lying at low pH values, complex **2**, chemical interconnection with **1** was finally established (Figure 3). This interconversion signifies the importance of pH in the aqueous chemistry of vanadium with citric acid. Apparently, pH is a pivotal factor dictating structural changes upon the species forming in aqueous solutions between vanadium and citrate at variable pH values (vide supra). It can be envisaged that pH, acting like a molecular switch, could conceivably "allow" protons to be attached on or taken off the basic $V^V_2O_2$-core-containing citrate dimers in aqueous media. Such an activity, though, would require a very stable vanadium−citrate assembly in a wide pH range (e.g., 3−7). The stability of an assembly of this kind has already been shown and has been established crystallographically.[11,13,16,18] *Hence, under the employed experimental conditions, a pH-dependent acid−base chemistry, in a stable* $V^V_2O_2$*-core-containing vanadium(V)−citrate structure, develops around the core and is centered on the periphery of the attached organic ligand in the anionic complex. The specific site of action involves consistently uncoordinated terminal carboxylic groups.* The potential implications of such a contention may be reflected on the chemistry of metallosites bearing organic acid moieties in biological systems. A relevant example of such chemistry is that unfolding at the nitrogenase enzyme active site, in which a proton shuttle purportedly associates the R-homocitrate ligand (congener to citrate), attached to the iron−molybdenum(vanadium) cofactor assembly (FeMoco or FeVco), with the catalytic reduction of hydrazine to ammonia.[29]

Potential Links to Biologically Related Vanadium(V) Chemistry. A number of solution speciation studies were carried out in the past on vanadium(V)−carboxylate systems, including vanadium(V)−citrate.[30] The studies had proposed the existence of dinuclear vanadium(V)−citrate species bearing a $V^V_2O_2$ core. Even though scant data on such structures were available at that time, the synthetic chemistry in the area offered a significant insight, with a number of such dinuclear $V^V_2O_2$ species, including the one presented in this work, isolated from aqueous media and spectroscopically and structurally characterized. In view of the collective progress made over the years, it appears that the aqueous chemistry of simple vanadium(V)−citrate complexes may be linked to species in (bio)distribution schemes of vanadium(V) in the presence of citrate. To this end, the pH-dependent transformations reported here between **1** and **2** (albeit reflecting changes removed from the physiological pH value and covering a fairly wide pH range) point to such a potential linkage between related vanadium species, interconverting within the prevailing pH range(s) provided for in biological fluids.

Furthermore, given that citric acid is a physiological ligand capable of binding and solubilizing vanadium, it would be helpful to know if species emerging from such chemistry represent vanadium forms capable of eliciting interactions from molecular targets at the cellular level. Thus, the

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potential bioavailability of these vanadium(V)−citrate species arises as a prominent property, in need of further perusal, and an issue of great importance in view of the reported interconversions of vanadium(V)−citrate species as a function of pH. In light of the importance of relevant chemistries in vanadium ion speciation schemes linked to (bio)processes, efforts are currently under way to synthesize and characterize new forms of vanadium with citrate or citrate-like organic carboxylates, and elucidate their (bio)chemical properties.

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Supporting Information Available: X-ray crystal crystallographic files, in CIF format, and listings of positional and thermal parameters and H-bond distances and angles for **1**. This material is available free of charge via the Internet at http://pubs.acs.org.

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