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Synthesis and structure of a new aluminium citrate trimer from aqueous solution at very low pH †

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A novel trinuclear Al(III) citrate complex, $[Al(H_2O)_6][(Al_3(C_6H_4O_7)_2(OH)_2(H_2O)_4]_2(NO_3)\cdot6H_2O$, can be synthesised from solutions containing 1 : 1 and 10 : 1 aluminium to citrate ratios providing the pH is within the range 1.2–3.0.

In recent years there has been considerable interest shown in the chemistry of aluminium and the low molecular weight chelator citric acid, $(C_6H_8O_7)$.[1–3] However, due to the potential toxicity of aluminium much of this has focussed on speciation studies and solution state measurements.[4] All of these studies conclude that in the low pH region (1–3) monomeric citrate species dominate[4,5] whilst trimeric species dominate the higher pH regions (3–9).[6] Although there have been numerous solution-state studies the solid state chemistry of aluminium and citric acid has been much neglected. In fact, there have to date only been three crystal structure determinations of aluminium citrate complexes.[7–9] These comprise monomeric,[9] dimeric[7] and trimeric[8] clusters that form at pH 8, 3.5 and 9.0 respectively. In this paper we describe the synthesis and crystallographic characterisation of a trinuclear aluminium citrate complex **1** which forms in high yield at very low pH (1.66). This observation of higher nuclearity species existing in significant amounts at low pH is not predicted by existing speciation studies which show monomeric species dominating in this pH region.[5,6]

The trimeric complex **1** is formed *via* the reaction of an excess of aluminium nitrate nonahydrate with tri-sodium citrate and quinoline in water.‡ Crystals suitable for X-ray diffraction§ are formed after 48 h. The anion of **1**, $[Al_3(C_6H_4O_7)_2(OH)_2(H_2O)_4]^-$, contains two quadruply deprotonated citrate ligands. Each cit^{4-} is identical in its coordination, coordinating to two of the three aluminium centres. All three of the aluminium atoms are coordinated in distorted octahedral geometries (Fig. 1). Al(1) is bridged to Al(2) *via* two μ_2-hydroxide bridges (O(15) and O(16)) and these two aluminium centres are linked to Al(3) *via* the deprotonated α-hydroxy alcohol group of two different citrate ligands (O(3) and O(10) respectively). The octahedral coordination geometry of Al(1) and Al(2) is completed by two carboxylate oxygens (O(1), O(4), O(8) and O(13)) and a coordinated water molecule (O(17), O(18)). Al(3) completes its octahedral coordination sphere by coordination of a carboxylate oxygen from two different citrate ligands (O(6) and O(11)) and two coordinated waters (O(19) and O(20)). The aluminium–oxygen bond distances (Fig. 1) range from 1.823 (4)–1.959 (4) Å and are within the expected values for Al(III) complexes with the terminal Al-oxygen aquo bonds being much longer than the bridging Al–oxygen hydroxy bonds. The species crystallises as a double salt having a hexa-aquo aluminium(III) cation and a nitrate anion. In order to neutralize the charge the structure contains one $[Al(H_2O)_6]^{3+}$ cation and one $(NO_3)^-$ anion for every two $[Al_3(C_6H_4O_7)_2(OH)_2(H_2O)_4]^-$ anions. Presumably, since the monomeric $[Al(H_2O)_6]^{3+}$ species is predicted to be present in large amounts at low pH, it is preferred as a cation to a protonated quinoline molecule.

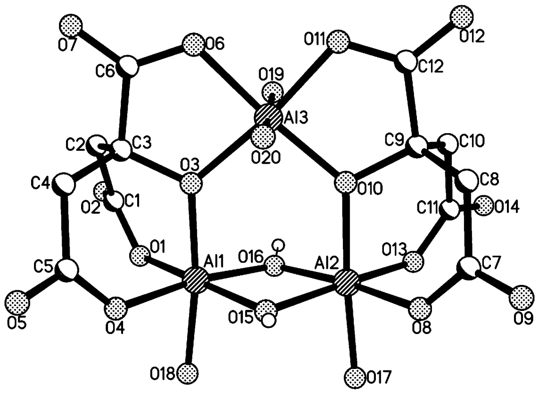
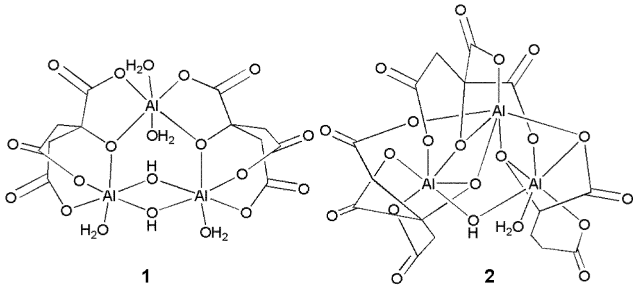


Fig. 1 Structure of the $[(Al_3(C_6H_4O_7)_2(OH)_2(H_2O)_4]^-$ anion showing the atom labelling scheme. Selected interatomic distances (Å) follow: Al(1) ··· O(1) 1.873 (4), Al(2) ··· O(15) 1.855 (4), Al(1) ··· O(3) 1.906 (4), Al(2) ··· O(16) 1.852 (4), Al(1) ··· O(4) 1.874 (4), Al(2) ··· O(17) 1.925 (4), Al(1) ··· O(15) 1.840 (4), Al(3) ··· O(3) 1.899 (4), Al(1) ··· O(16) 1.823 (4), Al(3) ··· O(6) 1.878 (4), Al(1) ··· O(18) 1.959 (4), Al(3) ··· O(10) 1.848 (4), Al(2) ··· O(8) 1.878 (5), Al(3) ··· O(11) 1.864 (4), Al(2) ··· O(10) 1.946 (4), Al(3) ··· O(19) 1.936, (4) Al(2) ··· O(13) 1.861 (4), Al(3) ··· O(20) 1.944 (4).

It is relevant to compare the structure of **1** with the trinuclear aluminium species synthesised by Feng *et al.*[8] In Feng's trimer the coordination geometries of the three aluminium atoms are almost completely satisfied by three cit^{4-} ligands and only one exogenous hydroxide ligand is present whereas in **1** there are only two cit^{4-} ligands, two hydroxide ligands and four coordinated waters (**1** in Scheme 1).



Scheme 1 Anionic structures of crystallographically characterised aluminium citrate clusters. $\mathbf{1}=[Al_3(C_6H_4O_7)_2(OH)_2(H_2O)_4]^-$, $\mathbf{2}=[Al_3(C_6H_4O_7)_3(OH)H_2O)]^{4-}$.[8]

Solid state ^{13}C (CPMAS) NMR studies of **1** show a broad signal at 177.8 ppm which is assigned to the three carboxylic acid groups of the bound citrate. Also present are two peaks at 72.9 and 75.7 ppm, assigned to the α-hydroxy carbons of the citrates and a further relatively broad peak at 42.9 ppm which is assigned to the carbons of the two ethyl groups. The insolubility of **1** prevents solution state NMR or other solution based spectroscopic studies.

The solid-state FT-Raman spectrum†¶ of **1** shows bands at 1462 and 1397 cm^{-1} which correspond to the carboxylate symmetric stretches and a broad band at 1598 cm^{-1} assigned to the

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† Electronic supplementary information (ESI) available: FT-IR, Raman and solid state NMR spectra. See http://www.rsc.org/suppdata/dt/b3/b312176c/

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corresponding antisymmetric stretches. The difference between the antisymmetric and symmetric stretch is of the order of 200 cm^{-1} which is characteristic of a coordinated, deprotonated carboxylic acid function.[1,10] The low frequency bands at 500 cm^{-1} and <350 cm^{-1} are assigned to the Al–OH–Al stretching and bending vibrations respectively whilst the intense band at 1052 cm^{-1} is assigned to the symmetric stretch of the nitrate anion.[11] The presence of this anion is further confirmed by the sharp band at 1384 cm^{-1} in the infrared spectrum and also by elemental analysis. ‡

Fig. 2 shows the packing diagram for **1** viewed down the *b* axis. An extensive hydrogen bonding network between **1** and the hexa-aquo aluminium cation and nitrate anion forms sheets which lie in the *ac* plane. The three waters of crystallisation lie between these sheets forming a three dimensional network. This hydrogen bonding is responsible for the sparing solubility of **1**.

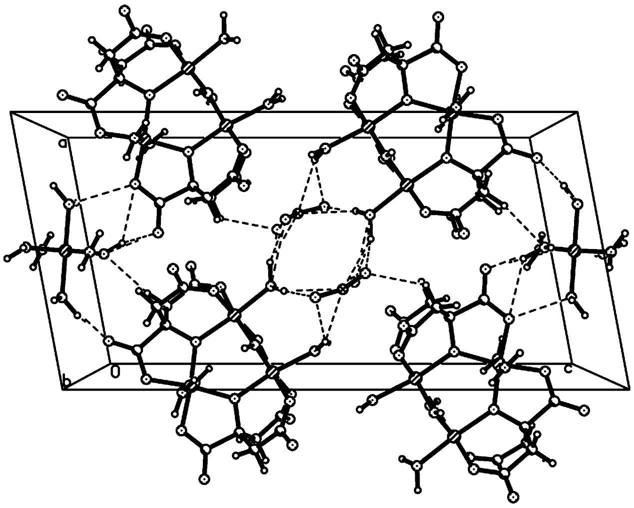

Fig. 2 Packing diagram of **1** showing the extended hydrogen bonding (dashed lines).

Our studies show that **1** will form in the pH range 1.2 to 3.0 but that the optimum pH for complex formation (based on yield) is 1.6. Attempts to synthesise **1** from a stoichiometrically correct reaction solution do not result in complex formation since the pH of this reaction solution is 3.1. However, stoichiometric preparation with pH adjustment to 1.6 produces **1** in 20% yield based on citrate. Furthermore, a 1 : 1 reaction between $Al(NO_3)_3{\cdot}9H_2O$, $Na_3C_6H_5O_7{\cdot}2H_2O$ and quinoline also produces **1** provided that the pH is within the defined range. However, the presence of quinoline is not a prerequisite in the formation of **1**, although the crystallisation time increases from two days to two weeks when it is not present. These studies allow us to conclude that a large excess of Al(III) is not required to form **1**, but that pH control within a relatively narrow range is key.

Whilst there is a wealth of literature available concerned with aluminium–citrate speciation, to the knowledge of the authors, none of these studies have been performed with an *excess* of aluminium present and furthermore only two studies extend below pH 2.1.[2,5] This is due in part to acknowledged difficulties in measurement at such low pH.[12] However, the results presented here demonstrate that in order to fully describe the speciation of aluminium, consideration must be given to situations where aluminium is present in excess:[13] Under these conditions, we have shown that new types of complex exist and that these complexes form in totally unexpected pH ranges.

The pH range over which **1** forms (1.2–3.0) encompasses the pH range of the gastric fluid within the stomach of many mammals. Whilst, under normal physiological conditions Al(III) would not be present at high concentrations, under certain disease conditions 0.1 mM Al(III) can be reached and exceeded, particularly in patients receiving dialysis or transfusion services.

Thus, in conditions where Al(III) is present in these molar ratios, **1** could be an important species and may represent a possible absorption pathway for Al(III) into the body.

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Notes and references

‡ 3.750 g (10 mM) of $Al(NO_3)_3{\cdot}9H_2O$ and 0.294 g (1 mM) of $Na_3C_6H_5O_7{\cdot}2H_2$ were dissolved in 15 mL of H_2O. 0.120 mL (1 mM) quinoline was added drop-wise to the resultant solution with constant stirring. The resultant light brown solution was stirred for a further 30 min (pH = 1.660). Crystals suitable for X-ray diffraction formed after 48 h. Similar reactions at 1 mM and 0.1 mM metal concentration also yield **1** providing the pH is within the required range. Yield = 22% based on citrate. (Found: C, 20.14; H, 4.40; N, 0.96; Al, 12.85. Calc. for $Al_7C_{24}H_{60}O_{55}N$: C, 20.14; H, 4.22; N, 0.98; Al, 13.19%).

§ Crystal data for **1**: $Al_7C_{24}H_{60}O_{55}N$, $M = 1431.59$, space group $P2(1)/n$, $a = 10.3785(12)$ Å, $b = 12.4967(15)$ Å, $c = 20.839(3)$, $\beta = 100.624(2)°$, $V = 2656.4(5)$ Å^3. $Z = 2$, $D_c = 1.790$ g cm^{-3}, μ(Mo Kα) = 0.280 mm^{-1}, $T = 100$ K, crystal size 0.20 × 0.20 × 0.02 mm. 478 parameters refined with 3830 unique reflections ($R_{int} = 0.0576$) to $R1 = 0.0630$, $wR2 = 0.1972$ (all data). The crystal was a thin plate which was very weakly diffracting. CCDC reference number 220850. See http://www.rsc.org/suppdata/dt/b3/b312176c/ for crystallographic data in CIF or other electronic format.

¶ FT-Raman spectra were obtained on a Bruker equinox 55 with FRA1062 FT-Raman attachment. $T = 298$ K, 450 mW incident power, 180° scattering, 1064 nm excitation wavelength. 512 scans at 4 cm^{-1} resolution.

1 A. Salifoglou, *Coord. Chem. Rev.*, 2002, **228**, 297.
2 M. Venturini and G. Berthon, *J. Inorg. Biochem.*, 1989, **37**, 69.
3 G. Berthon, *Coord. Chem. Rev.*, 1996, **149**, 241.
4 See for example; L. O. Öhman, *Inorg. Chem.*, 1988, **27**, 2565.
5 J. E. Gregor and H. K. Powell, *Aust. J. Chem.*, 1986, **39**, 1851.
6 L. O. Öhman and S. Sjöberg, *Acta Chem. Scand., Ser. A*, 1981, **A35**, 201.
7 M. Dakanali, C. P. Ratopoulou, A. Terzis, A. Lakatos, I. Banyai, T. Kiss and A. Salifoglou, *Inorg. Chem.*, 2003, **42**, 252.
8 T. L. Feng, P. L. Gurian, M. D. Healy and A. R. Barron, *Inorg. Chem.*, 1990, **29**, 408.
9 M. Matzapetakis, C. P. Raptopoulou, A. Terzis, A. Lakatos, T. Kiss and A. Salifoglou, *Inorg. Chem.*, 1999, **38**, 618.
10 K. Nakamoto, *Infrared and Raman Spectra of Inorganic and Coordination Compounds*, Wiley and Sons, New York, 5th edn., 1997.
11 A. Kestilä and M. E. E. Harju, *Thermochim. Acta*, 1993, **214**, 67.
12 A. E. Martell, R. J. Motekaitis and R. M. Smith, *Polyhedron*, 1990, **9**, 171.
13 A. E. Martell and R. J. Motekaitis, *Determination and Use of Stability Constants*, VCH, New York, 1989.