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The Speciation of Aluminum in Aqueous Solutions of Aluminum Carboxylates
Part I. X-ray Molecular Structure of $Al[OC(O)CH(OH)CH_3]_3$

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Abstract

The crystal structure of tris(2-hydroxypropanoate-(L))aluminum(III) was determined by X-ray crystallography and refined to $R = 0.044$. The molecular structure is uncomplicated and contains monomeric [Al(lact)$_3$] entities, in which the metal atom is surrounded by a distorted octahedral $\{O_6\}$ coordination sphere where the oxygen atoms of the carboxylate and of the hydroxyl group are the donating sites. The major source of the geometrical distortion is in the O–Al–O angles of the metallo-organic ring (*c.* 83°). The Al–O distances range from 1.86 to 1.91 Å. All hydroxyl hydrogen atoms are involved in very tight intermolecular hydrogen bonds (*c.* 2.50 Å) which involve the carbonyl groups of adjacent Al(lact)$_3$ unities.

The solid state IR spectrum of Al(lact)$_3$ is interpreted in terms of monohapto 'end on' coordination of the carboxylate donating site to Al^{III}.

Introduction

Bioscientists interested in various aspects of aluminum biology [1] have been using for many years aqueous solutions of aluminum lactate (Al(lact)$_3$) as a vehicle for administering Al^{III} to experimental animals or to cell cultures. The main reason for the popularity of aluminum lactate is probably the fact that it is 'freely soluble' in water [2] and that upon adjusting the pH of a relatively concentrated solution (0.01 M or more) from the initial value of *c.* 3 to the physiological one (*c.* 7.5), aluminum hydroxide precipitation does not occur, in contrast with the behaviour of solutions of simple inorganic salts of Al^{III}.

Calculations based on available thermodynamic data [3] lead to the expectation that Al^{III}/lactate complexes cannot exist in appreciable concentrations at pH 7.5. In fact, only solid aluminum hydroxide and a complicated array of polymeric and ill-defined aquo hydroxo metal complexes [4] (total solubility *c.* 10^{-7} M) are expected to be present at the physiological pH value. The absence of precipitation of the hydroxide from neutralized solutions of aluminum lactate must then be ascribed either to the presence of complexes different from those already known or to the occurrence of very slow processes.

In the frame of our ongoing research [5–7] on the role of the speciation in the biological effects of Al^{III} we report here on the molecular structure of Al(lact)$_3$ in the solid state. In Part II of this series, the aqueous solution state of this toxicologically relevant artificial toxin will be described. It may be anticipated that the unambiguous knowledge of the molecular structure of aluminum lactate in the solid state turns out to be a decisive tool for the elucidation of the intriguing nature of its aqueous solutions.

Experimental

Materials and Methods

Commercial aluminum lactate was from Fluka and its chirality was determined after conversion into lactic acid upon ionic exchange with Bio-Rex MSZ 50 resin (Bio-Rad) in the hydrogen form; the sample turned out to be in the essentially pure (> ≈90%) L form. Crystals were obtained from a slightly undersaturated aqueous solution by slow evaporation in a glass tube (3 mm i.d., 5 cm length) held inclined at about 30° from the horizontal and moderately heated at the bottom by means of a light bulb. After two weeks a white precipitate deposited on the lower wall of the tube, which was found to contain a few crystals mixed with a larger amount of amorphous material.

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TABLE 1. Experimental details of the X-ray crystallographic study of $Al[OCOCH(OH)CH_3]_3$

Crystal data	
Formula	$C_9H_{15}AlO_9$
M	294.91
Habit	monoclinic
Space group	$P2_1$
a (A)	14.277(2)
b (A)	9.265(1)
c (A)	10.828(1)
β (°)	100.7(1)
U (A^3)	1407.4
D_c (g cm^{-3})	1.388
μ (cm^{-1})	1.35
F(000)	616
Crystal dimensionn (mm)	0.4 X 0.3 X 0.3
Intensity measurements	
Scan rate (°min^{-1})	1.2
No. reflections measured	3773
No. independent reflections	3609
Structure refinement	
Refinement	blocked
Reflections included	2740
Parameters refined	343
R	0.044
Convergence largest shift	0.72
Highest peak in final Fourier difference map (A^{-3})	+0.39 −0.20
Z	4

Crystal Structure Determination

Data were collected on a Philips four circle diffractometer ($\theta-2\theta$ scan mode) with monochromatized Mo Kα radiation ($\lambda = 0.71069$ Å). Cell dimensions were determined by least-squares refinement of 25 medium angle settings ($15 \leqslant 2\theta \leqslant 30°$). Crystal data are summarized in Table 1.

Intensities measured up to $2\theta = 56°$ were significantly above the background [$I \geqslant 3\sigma(I)$]. The compound is stable under irradiation. After subtracting the background, the data were corrected for Lorentz and polarization factors. The structure was solved by a direct method (MULTAN 80) [8] and refined with cycles of blocked-matrix least-squares, with anisotropic thermal parameters for non-hydrogen atoms. The hydrogen atoms were found on a difference Fourier map but were not refined. The final conventional R value was 0.044. The full-matrix refinement was processed with unit weights. The scattering factor for Al was taken from ref. 9 and it was corrected for anomalous dispersion; other scattering factors were from the SHELX 76 program [10]. Final atomic coordinates are listed in Table 2.

Results and Discussion

The asymmetric unity in the crystal lattice of aluminum lactate contains two [Al(lact)$_3$] moieties (Fig. 1), one with a Λ, and the other with a Δ overall configuration.

Bond distances and selected bond angles are collected in Tables 3 and 4, respectively.

TABLE 2. Fractional coordinates of Al(lact)$_3$

Atom	x/a	y/b	z/c	Atom	x/a	y/b	z/c
Al(1)	0.7474(1)	0.0000(0)	0.7391(1)	Al(2)	0.7512(1)	0.4987(2)	0.2407(1)
O(1)	0.7550(2)	0.1388(4)	0.6175(3)	O(10)	0.7378(3)	0.3613(4)	0.1139(3)
O(2)	0.7332(2)	0.1658(4)	0.8370(3)	O(11)	0.7654(2)	0.3320(4)	0.3454(3)
O(3)	0.7384(3)	0.3689(5)	0.5657(3)	O(12)	0.7324(4)	0.1294(5)	0.0674(3)
O(4)	0.7539(2)	−0.1191(4)	0.8796(3)	O(13)	0.6217(2)	0.5115(4)	0.2473(2)
O(5)	0.8816(2)	−0.0059(5)	0.7857(3)	O(14)	0.7191(2)	0.6517(4)	0.1225(3)
O(6)	0.8494(2)	−0.2133(5)	1.0449(4)	O(15)	0.4883(2)	0.6360(5)	0.1871(4)
O(7)	0.7422(2)	−0.1469(4)	0.6205(3)	O(16)	0.7803(2)	0.6186(4)	0.3846(3)
O(8)	0.6125(2)	−0.0172(5)	0.6993(3)	O(17)	0.8807(2)	0.5227(4)	0.2404(3)
O(9)	0.6478(2)	−0.2735(5)	0.4763(4)	O(18)	1.0131(2)	0.6356(6)	0.3291(4)
C(1)	0.7404(4)	0.2698(7)	0.6405(4)	C(10)	0.7419(4)	0.2305(6)	0.1429(4)
C(2)	0.7253(4)	0.3030(6)	0.7738(4)	C(11)	0.7537(5)	0.1968(6)	0.2842(4)
C(3)	0.8019(7)	0.4064(8)	0.8356(5)	C(12)	0.6675(8)	0.1195(11)	0.3103(6)
C(4)	0.8352(3)	−0.1407(6)	0.9469(5)	C(13)	0.5720(3)	0.6114(6)	0.1854(4)
C(5)	0.9204(3)	−0.0720(6)	0.9036(5)	C(14)	0.6233(3)	0.7026(7)	0.1006(5)
C(6)	0.9679(4)	0.0421(9)	0.9979(5)	C(15)	0.5774(5)	0.6814(16)	−0.0376(6)
C(7)	0.6605(3)	−0.1870(6)	0.5639(4)	C(16)	0.9289(3)	0.6086(6)	0.3203(5)
C(8)	0.5747(3)	−0.1254(6)	0.6093(4)	C(17)	0.8743(3)	0.6741(7)	0.4170(5)
C(9)	0.5008(5)	−0.06819(9)	0.5054(6)	C(18)	0.9211(5)	0.6386(13)	0.5496(6)

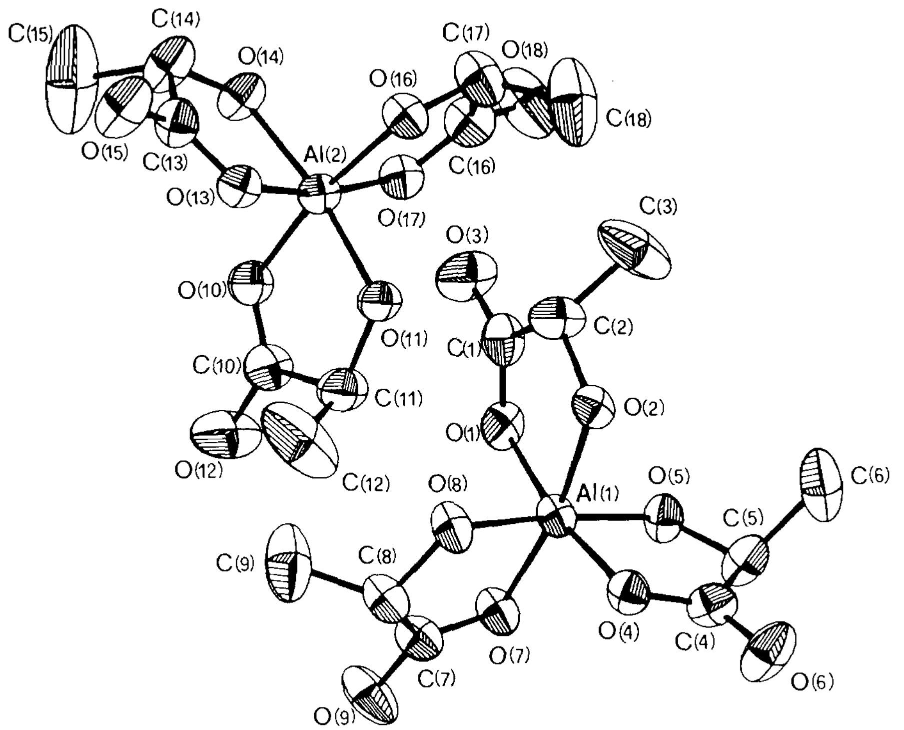

Fig. 1. Molecular structure of $\mathrm{Al(lact)_3}$.

TABLE 3. Interatomic distances within $\mathrm{Al(lac)_3}$ (A)

Al(1)–O(1)	1.858(4)	C(1)–O(1)	1.264(7)	C(1)–C(2)	1.530(7)
Al(1)–O(2)	1.899(3)	C(2)–O(2)	1.438(6)	C(4)–C(5)	1.521(7)
Al(1)–O(4)	1.869(4)	C(4)–O(4)	1.267(5)	C(7)–C(8)	1.513(7)
Al(1)–O(5)	1.889(3)	C(5)–O(5)	1.432(6)	C(2)–C(3)	1.514(10)
Al(1)–O(7)	1.863(4)	C(7)–O(7)	1.268(5)	C(5)–C(6)	1.537(8)
Al(1)–O(8)	1.901(3)	C(8)–O(8)	1.432(6)	C(8)–C(9)	1.490(8)
C(1)–O(3)	1.221(7)	C(4)–O(6)	1.241(6)	C(7)–O(9)	1.229(6)
Al(2)–O(10)	1.856(4)	C(10)–O(10)	1.250(6)	C(11)–C(10)	1.540(6)
Al(2)–O(11)	1.904(4)	C(11)–O(11)	1.413(6)	C(11)–C(12)	1.496(13)
Al(2)–O(13)	1.867(3)	C(13)–O(13)	1.278(6)	C(13)–C(14)	1.532(8)
Al(2)–O(14)	1.908(4)	C(14)–O(14)	1.424(6)	C(14)–C(15)	1.531(9)
Al(2)–O(16)	1.896(3)	C(17)–O(16)	1.419(6)	C(16)–C(17)	1.541(8)
Al(2)–O(17)	1.863(3)	C(16)–O(17)	1.278(6)	C(17)–C(18)	1.504(8)
C(10)–O(12)	1.234(6)	C(13)–O(15)	1.220(6)	C(16)–O(18)	1.214(6)

Inspection of the literature reveals that lactate behaves normally as a bidentate ligand, by utilizing the carboxylate and the hydroxyl ligating sites. This bonding mode occurs for $\mathrm{Cu^{II}}$ [11–13], $\mathrm{Mn^{II}}$ [14], $\mathrm{Zn^{II}}$ [15], $\mathrm{Ni^{II}}$ [16], while examples of monohapto bonding behaviour are given for $\mathrm{Cu^{II}}$ [17] and $\mathrm{Zn^{II}}$ [18]. Moreover, a mixed behaviour is also reported in the literature for $\mathrm{Cu^{II}}$ [12]. Finally, only heteroleptic lactate complexes appear to be known so far.

The molecular structure of aluminum lactate represents an example of both chelating behaviour of the ligand and homoleptic nature of the coordination compound. The geometry of the coordination sphere is a distorted octahedron, which is also observed in some of the above quoted heteroleptic complexes with divalent cations.

The major source of distortion is in the chelate O–Al–O angles (82.1–83.2°), which in fact produce a prominent deviation from 180° of the angles formed by mutually translocated oxygen atoms (e.g. O(5)–Al(1)–O(8) = 177.1°).

Bond distances between the central metal and the ligating oxygens deserve attention. The average figure for the three carboxylate–Al bonds is 1.866 Å and that for the hydroxy–Al ones is 1.899 Å. In neutral,

TABLE 4. Selected bond angles within Al(lact)$_3$

O(1)–Al(1)–O(2)	82.1(1)	Al(1)–O(1)–C(1)	119.4(3)	Al(1)–O(2)–C(2)	117.1(3)
O(4)–Al(1)–O(5)	82.6(1)	Al(1)–O(4)–C(4)	117.6(3)	Al(1)–O(5)–C(5)	117.1(3)
O(7)–Al(1)–O(8)	82.7(2)	Al(1)–O(7)–C(7)	117.6(3)	Al(1)–O(8)–C(8)	116.8(3)
C(1)–C(2)–O(2)	105.0(4)	C(4)–C(5)–O(5)	104.8(3)	C(7)–C(8)–O(8)	105.1(3)
C(2)–C(1)–O(1)	115.9(5)	C(5)–C(4)–O(4)	117.2(4)	C(8)–C(7)–O(7)	117.4(4)
O(1)–Al(1)–O(4)	170.3(2)	O(2)–Al(1)–O(7)	168.9(1)	O(5)–Al(1)–O(8)	173.1(2)
O(10)–Al(2)–O(11)	82.5(2)	Al(2)–O(10)–C(10)	119.0(3)	Al(2)–O(13)–C(13)	118.9(3)
O(14)–Al(2)–O(13)	82.1(1)	Al(2)–O(11)–C(11)	116.7(3)	Al(2)–O(14)–C(14)	117.4(3)
O(17)–Al(2)–O(16)	82.2(1)	Al(2)–O(17)–C(16)	118.9(3)	Al(2)–O(16)–C(17)	117.9(3)
C(11)–C(10)–O(10)	115.9(4)	C(14)–C(13)–O(13)	115.6(4)	C(17)–C(16)–O(17)	115.3(4)
C(10)–C(11)–O(11)	105.5(4)	C(13)–C(14)–O(14)	105.7(4)	C(16)–C(17)–O(16)	105.3(4)
O(14)–Al(2)–O(11)	171.0(2)	O(16)–Al(2)–O(10)	170.6(2)	O(13)–Al(2)–O(17)	169.3(2)

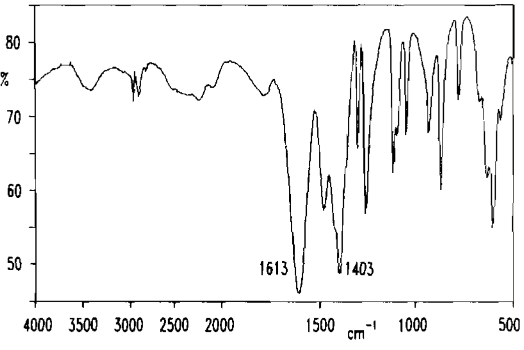

Fig. 2. Infrared spectrum of Al(lact)$_3$ in KBr.

hydrolytically very stable, complexes, such as Al(acac)$_3$ ($\log \beta_3 = 23.7$) [19] and Al(malt)$_3$ ($\log \beta_3 = 26.2$) [20] (acac = acetylacetonate, malt = maltolate), Al–O distances range from 1.892 Å [21] to 1.920 Å [20] respectively.

In spite of the expected stability of these Al–O bonds, aluminum lactate possesses a moderate hydrolytic stability ($\log \beta_3 = 5.79$) [3], which may be perhaps interpreted as the consequence of a particularly strong hydrogen bond stabilization of the free lactate ligand in the aqueous solutions. In fact, particularly tight hydrogen bonds are involved also in the stabilization of the lattice of aluminum lactate, i.e. bonds between the α-hydroxyl groups and the carbonyl groups in adjacent aluminum lactate moieties ($d_{av} = 2.5$ Å). This compact three-dimensional network can certainly be invoked for interpreting both the very scarce solubility of aluminum lactate in powerful polar solvents, such as dimethyl sulphoxide and dimethylformamide, and its high solubility in water (at least 0.5 M). Extensive three dimensional arrays of hydrogen bonds are also observed for all known X-ray structures of lactate metal complexes.

The solid state IR spectrum of aluminum lactate is depicted in Fig. 2.

The most interesting bands exhibited by Al(lact)$_3$ are those at 1613 and 1403 cm^{-1}, which we attribute to ν_{as} and ν_s of metal-coordinated lactate ligand. The joined availability of X-ray molecular structures of many metal carboxylates and of their IR spectra has made possible an effective correlation [22] of the various bonding modes with the difference between the above mentioned ν(CO)s: ionic ($\Delta \approx 170$ cm^{-1}), covalent monodentate ($\Delta > 170$ cm^{-1}), and covalent chelate ($\Delta < 170$ cm^{-1}). Our datum ($\Delta = 210$ cm^{-1}) is of interest in that it fits with the expectation based on the above mentioned correlation and it indicates that such criterion can be applied also in the case of monohapto behaviour of a carboxylate site, which participates in fact in the formation of a chelate ring.

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