PART 1. INVESTIGATION OF ALUMINUM AMINO ACID COMPLEXES

PART 2. STRUCTURAL STUDIES OF ALUMINUM CHALCOGEN BONDS

DISSERTATION

Presented to the Graduate Council of the

University of North Texas in Partial

Fulfillment of the Requirements

For the Degree of

DOCTOR OF PHILOSOPHY

BY

Philip W. Gravelle, B.Sc.

Denton, Texas

May, 1996

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Five different complexes of aluminum and amino acids have been synthesized and characterized. Reaction between aluminum halides and amino acids that do not contain either a carboxylate or a hydroxy group in the side chain produce complexes of the general formula, $[Al(\text{amino acid})_n(\text{halide})_{3-n}]_m$. The most prevalent form of this form of complex is where n = 2, and an example of this in which the halide is replaced by hydroxide ligand has been structurally characterized. The complex for which n = 3 may be obtained by employing a large excess of acid, and that for which n = 1 may be obtained by employing either equimolar conditions or an excess of aluminum halide.

Reactions of aluminum halides with amino acids that contain either a carboxylate or hydroxy-containing side chain may result in complexes in which the side-chain is also bound. These proved impossible to characterize fully in the case of aspartic acid. For serine, however, a complex in which the amino acid binds in a chelating fashion through both the carboxylate and hydroxy groups was isolated.

It was possible to form complexes when utilizing aluminum alkyls as the metal source. However, these complexes could only be isolated when the reactivity of the species was controlled by the presence of bulky groups. In these cases, the monomeric $R_2Al(\text{amino acid})$ complexes were obtained.

Four complexes that contain aluminum-chalcogen bonds were structurally characterized. These included the bulky alkoxide complexes $(BHT)_2AlH(OEt_2)$, $(BHT)_3Al$(cyclohexanone), and the cubane $[(t\text{-amyl})AlS]_4$.

ACKNOWLEDGEMENTS

I am particularly indebted to my advisor, Dr. Simon Bott, for his contribution to my studies. It was a privilege to learn from a mentor with such an illustrious record in X-ray crystallography, even at this early stage of his career. He guided through this most unaccommodating of projects and also provided funding for the duration of my studies for which I am very grateful.

In addition, he made possible for me to learn from one of friends and peers, Professor Andrew Barron, formerly of Harvard University and now at Rice University. Professor Barron is clearly the best *aluminium* chemist in the world at present and it was another privilege to visit his Chemistry laboratories. I was also very grateful for the contributions by his students, in particular, Drs. John Leman and Jeff Harlan. I am also very grateful to him for providing crystals for the X-ray crystallographic studies.

This work would not have been possible without the help of some outstanding undergraduate workers including Julie Pirro, Jason Bradley and Jason MacDonald.

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A special note of thanks of extended to Ms Marilyn Christansen at the ISB library. She never hesitated to assist me in any possible means during my literature searches which

occasionally involved coming in to work at some unsociable hours.

Finally, I have to thank my parents for their support and ensuring that my studies at UNT were completed

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ABBREVIATIONS

MeOH . . . . . methanol

DMSO . . . . . dimethylsulfoxide

DMF . . . . . dimethylformamide

NMR . . . . . nuclear magnetic resonance

py . . . . . pyridine

salen . . . . . salicylideneamine

solv . . . . . solvent

THF . . . . . tetrahydrofuran

TMA . . . . . trimethylaluminum

CVD . . . . . chemical vapor deposition

CHAPTER 1

INTRODUCTION

1-1. Aluminum[1,2]

Aluminum was named by Sir Humphry Davy after alum, $KAl(SO_4)_2 \cdot 12\ H_2O$, a compound known and used since the ancient Greeks for numerous purposes. It is the thirteenth element in the periodic table, and is the second member of group 13 (or the p-block group III).

The chemistry of this element is dominated by the 3+ oxidation state, and, with very few exceptions, it is considered to be a metal.[3] The isolation of pure aluminum was not trivial, and the several methods that were developed in the nineteenth century based on chemical or electrical reduction of aluminum chloride species were sufficiently expensive that aluminum was almost regarded as almost a precious metal. In 1886, however, C. M. Hall and independently P. L. T. Héroult, discovered the Hall-Héroult-Hall process, by which aluminum may be obtained relatively cheaply by the electrolysis of alumina (Al_2O_3) in cryolite (Na_3AlF_6). Since that time, the industrial applications of aluminum and its compounds have increased to the extent that it is now the second most important elemental metal after iron.

The extensive use of aluminum is encouraged by the fact that it is the most abundant metal in the earth's crust (8.1% by mass).[4] It is generally found in the form

of its silicates, oxides and hydroxides, and to a lesser extent as its fluorides. Examples of natural silicates include micas, feldspars and aluminosilicate clays. Hydroxide and oxide ores include Al_2O_3, the main constituent of bauxite, gibbsite, $Al(OH)_3$, and bohemite, which consists mainly of the oxyhydroxide, $AlO(OH)_2$. The most common fluoride containing ore is cryolite, $NaAlF_6$. It should be noted that the bonding to aluminum in these minerals is by very hard bases . By comparison, gallium, the next heaviest member of group 13, is found in both the oxide and sulfide forms, whereas the heaviest members of this group, indium and thallium, are found in nature strictly as their sulfides.[4,5]

1-2. Aluminum in Biological Systems

The environmental chemistry of aluminum should be negligible, as the natural sources of the element are distributed almost exclusively in soils and clays and very little is found in river or sea waters.[6] Natural erosion of aluminum does occur to a small extent in the form of solubilized silicates and phoshphates. Unfortunately, however, in tandem with the utility of aluminum in modern industry, the increased prevalence of acid rain has led to the leaching of aluminum into the ecosystem through acidification of soils and ground waters.[7]

These increased levels of aluminum have led to a heightened awareness of the potential toxicity of its compounds. Within the environmental context, these compounds may be divided into three categories:[8]

1. Non-labile monomeric organic complexes, in particular complexes with the decay products of plants, humic and fulvic acids;[9]
2. labile monomeric inorganic complexes which include soluble sulfates, fluorides and hydroxides;
3. acid soluble aluminum consisting of polymeric aluminum complexes and strongly bound organic complexes.

It is this latter group that causes the most damage to the environment. Symptoms of aluminum injuries in flora include root damage and cell elongation,[5] although some plants which have been exposed to aluminum for a long period on the evolutionary scale have evolved defense mechanisms against aluminum toxicity. Tea for example, which is grown in acidic soils, stores aluminum in its old leaves and these may contain up to 3% (by weight) of aluminum, whereas the young leaves contain as little as 0.01%.[5] Aluminum rich soils have been shown to be detrimental to crop growth and ingestion of aluminum rich grasses coupled with low Mg^{2+} intake has led to a condition known as grass tetany in ruminant animals.[4]

A combination of low pH and elevated aluminum levels leads to the incorporation of the metal into mayfly nymphs and consequently into the food chain. In addition, the presence of aluminum in acidified water has been shown to cause gill damage in larger fish, as well as to effect drastically levels of electrolytes.[5]

Human exposure to aluminum is usually *via* routes other than those mentioned above. Aluminum sulfate is added as an anti-flocculant to drinking water supplies for

cosmetic purposes; aluminum hydroxide is used as an antacid.[10] Other pharmaceutical preparations such as anti-perspirants, which contain aluminum hydroxychlorides, are other means for the uptake of aluminum.[6] These are just a few examples of the numerous means that humans may be exposed to aluminum.

During normal functioning, almost all (greater than 99%) aluminum is removed from the body in the feces, and the small fraction that does cross the intestinal barriers is excreted within 3 hours in urine.[6] However, in some cases the barriers to aluminum absorption are breached. The group of people most commonly affected by exposure to aluminum is long term kidney dialysis patients who are treated with aluminum salts[5, 10] to nullify hyperphosphatemia.

Conditions which arise from aluminum toxicity include dialysis encephalopathy, dialysis osteodystrophy,[5] certain forms of dementia and accumulations of alumino-silicate plaques in brain tissue[11] which has been associated with some forms of Alzheimer's disease.

The chemistry of aluminum in biological systems is dictated by its size rather than its size to charge ratio.[4] It therefore competes with Mg^{2+} and Fe^{3+} rather than larger cations such as Na^{+} or Ca^{2+} for oxygen bearing ligands in biosystems.[6] This is illustrated by the table of ionic radii in Table 1-1.[12] Of particular interest within the context of this work is the competition with Fe^{3+}, as the aqueous chemistry of these two ions is somewhat similar.[13] Neither exists in a soluble form at physiological pH (*vide infra*), but nature has designed methods to overcome this problem in the case of ferric iron that also work to stabilize aluminum. The remaining part of this introduction, therefore, will focus

on this aspect of aluminum biochemistry.

The main transporter of iron *in vivo* is transferrin, a protein of molecular weight of *ca.* 80,000 atomic mass units, amu's, (Daltons), which transports iron in the ferric form before reduction to the ferrous ion for release.[14] Although the binding strength of Fe^{3+} to transferrin is 10^9 times greater than that of Al^{3+},[6] the similarity in their size to charge ratio, (0.54Å for Al^{3+} compared to 0.65Å for Fe^{3+}) enables aluminum to utilize the 30% sites, or 50 μM of unoccupied binding sites on the protein by mimicking the ferric iron and binding to the protein.[7] Transferrin has been crystallographically characterized and the binding site consists of two tyrosine residues, a histidine and an aspartic acid residue.[15] The remaining coordination sites on the metal ion are occupied either by a carbonate or bicarbonate anion, the binding of which to the metal center stabilizes the entire complex.[14] Other siderophiles, such as lactoferrin which transports iron in milk, possess similar binding sites.[16]

It has been established that transferrin is the main large molecular weight carrier of aluminum and carries approximately 90% of aluminum found *in vivo*.[17] The other 10% is transported by citrate and it is as the complex of this ligand that aluminum may penetrate the intestinal membranes and enter into the blood stream.[18] It appears that the success of this ligand in surviving in physiological conditions lies in its ability to chelate to the metal.[9] Plants may use this factor to detoxify aluminum and hence remove the metal from their systems.

Ferric iron is stored physiologically as ferritin. This protein consists of a "coat" of 24 polypeptide subunits which may encapsulate up to 4500 iron atoms in an iron oxide

Table 1-1. Table of Ionic Radii[12]

Ion	Coordination Number				
	4	5	6	8	12
Al^{3+}	0.39	0.48	0.54		
Fe^{3+}	0.49	0.58	0.69 LS	0.78	
			0.79 HS		
Fe^{2+}	0.77 LS		0.75 LS		
			0.92 HS		
Mn^{3+}			0.72 LS		
			0.79 HS		
Mn^{2+}	0.80 HS		0.81 LS		
			0.97 HS		
Cr^{3+}			0.76		
Co^{3+}			0.69 LS		
			0.75 HS		
Co^{2+}	0.72 HS		0.79 LS		
			0.89 HS		
Ga^{3+}	0.47	0.55	0.62		
In^{3+}	0.62		0.80	0.92	
Tl^{3+}	0.75		0.89	0.98	
Mg^{2+}	0.57	0.66	0.72	0.89	
Ca^{2+}			1.00	1.12	1.34

LS = low spin
HS = high spin

hydroxide core, the outside of which is bound *via* phosphate and carboxylate groups to the peptide.[19] There is evidence that aluminum is present in brain ferritin,[20] and the structure of the silicon-containing aluminum plaques associated with Alzheimer's may bear some resemblance to the core found in ferritin.

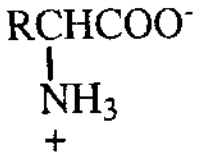
In order to overcome the dangers of aluminum in biological systems, it is essential to understand the full nature of the interactions between the metal and its binding sites. While the ideal approach would involve detailed *in vivo* studies, the complexity of these systems precludes the possibility of obtaining detailed data.

In common with the studies of many other complex bioinorganic systems, therefore, the initial investigations should be of model complexes.[21,22] These may be employed both to determine thermodynamic and kinetic data for binding, as well as to provide benchmark spectroscopic and structural data that may be used in the analysis of the actual biological systems. The disadvantages of this approach are that some information, such as steric interactions, hydrogen bonding and the effect of the gross structure of the macro-systems, may be excluded through over-simplification.

The first part of this dissertation concerns some preliminary studies on the complexes formed between aluminum and simple "biologically-relevant" species - in particular, amino acids. While such studies lose relevance in that true biological systems do not consist of isolated amino acids, we hoped to obtain information about both the nature and strength of any complexation as well as the relative preference for binding.

1-3. Amino Acids

Amino acids are ubiquitous in nature and are the building blocks of proteins. α-Amino acids have the general formula shown in (**1**), consisting of a carbon atom bound to a hydrogen, a carboxylate, an amine group, and a side chain. In the cases where this side-chain is not hydrogen, these are chiral species (occuring naturally as the *L*-enantiomer). The structures of the naturally occuring amino acids are shown in Figure 1-1.[23]



1

Their chemical properties generally follow those of both amines and of carboxylic acids.[23] In addition, the presence of both functional groups gives rise to the possibility of oligomerization *via* condensation reactions (Scheme 1-1).

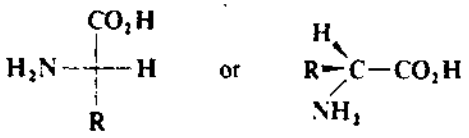
Scheme 1-1

As one would expect, the 'speciation' of amino acids in aqueous media is dependant on the pH and, given the presence of both acidic and basic functional groups, is rather complex. At low pH, the carboxylate group is protonated and the amino acid has an overall positive charge. Deprotonation of the carboxylate group occurs at different pH for various amino acids but generally occurs at around 2.5 - 4. At neutral pH, most amino acids exist as zwitterions (the form shown in (**1**)), and at higher pH values, the ammonium group is deprotonated giving a negatively charged species.

The zwitterionic form also exists in the solid state; thus, ionic interactions between the ammonium group and the carboxylate group result in a polymeric structure and also enable very strong hydrogen bonding to water molecules in the crystal lattice. The two most obvious results of this are that amino acids have high melting points and are practically insoluble in all organic solvents.[24] Several amino acids are also found to be insoluble in water at neutral pH. These properties for the amino acids of interest in the work are listed in Table 1-2.

For the purposes of this work, we will divide amino acids into two types:

1. **Non-coordinating** which contain a hydrocarbon side chain (for example, glycine, alanine, phenylalanine, leucine and valine).
2. **coordinating**, in which the side chain may bind to an aluminum center (for example, serine, aspartic acid, glutamic acid, tyrosine, cysteine and histidine.)



STRUCTURE OF R	NAME[a]
Neutral Amino Acids	
$-H$	Glycine
$-CH_3$	Alanine
$-CH(CH_3)_2$	Valine[c]
$-CH_2CH(CH_3)_2$	Leucine[c]
$-CHCH_2CH_3$ (with CH_3 branch)	Isoleucine
$-CH_2-C_6H_5$	Phenylalanine
$-CH_2CONH_2$	Asparagine
$-CH_2CH_2CONH_2$	Glutamine
$-CH_2$ (indole)	Tryptophan
Proline (complete structure)	Proline
$-CH_2OH$	Serine
Hydroxyproline (complete structure)	Hydroxyproline
$-CH_2SH$	Cysteine
$-CH_2-S-S-CH_2-$	Cystine
$-CH_2CH_2SCH_3$	Methionine
R Contains an Acidic (Carboxyl) Group	
$-CH_2CO_2H$	Aspartic acid
$-CH_2CH_2CO_2H$	Glutamic acid
R Contains a Basic Group	
$-CH_2CH_2CH_2CH_2NH_2$	Lysine
$-CH_2CH_2CH_2NH-C(=NH)-NH_2$	Arginine
$-CH_2$ (imidazole)	Histidine

Figure 1-1. The structure of naturally-occuring amino acids.

Table 1-2. Physical Properties of Selected Amino Acids

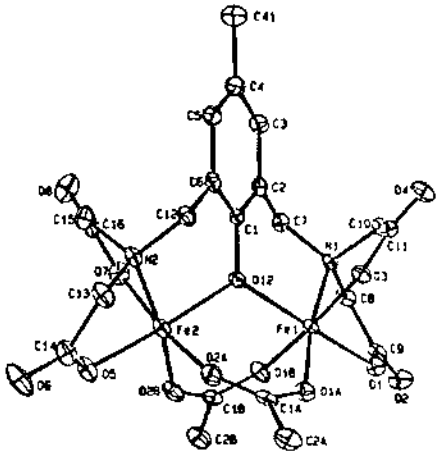
Amino Acid	mp (°C)	pKa	Solubility in water (g/L) 25°C	solubility in ethanol (g/L) 25°C
Alanine	297 dec	2.34 9.69	127.3	6.7×10^{-2}
Phenylalanine	283 dec	1.83 9.13	29.6	0.33
Leucine	293-295 dec	2.36 9.60	24.26	0.72
Valine	315	2.29 9.72	88.5	1.58
Proline	220-222	1.99 10.60	1620	667
Aspartic Acid	270-271	1.88 3.65 9.60	4.50	1.54×10^{-3}
Serine	228 dec	2.21 9.15	0.90	3.93×10^{-4}
Tryptophan	289 dec	2.38 9.39	13.68	
Cysteine	175-178 dec	1.71 8.33 1078	0.112	

1-4. Metal Complexes of Amino and Other Acids[25,26]

Amino Acid Complexes

Despite the fact that the coordination chemistry of amino acids has only indirect bearing on studies of biological systems, there is a reasonable amount of data on the subject. While a general review of the area is not appropriate, some general trends that are of relevance should be noted - namely, the nature of the binding, and the nuclearity of the complexes.

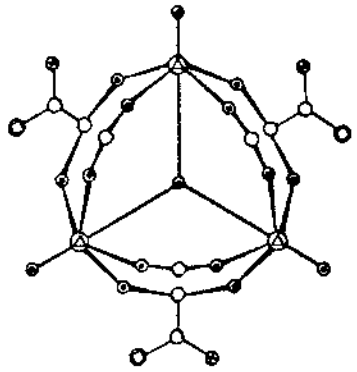
No mononuclear homoleptic complexes have been documented, and the simplest binuclear complexes typically contain bulky ligands and bridging oxo- or hydroxy-groups in addition to the amino acid ligands (for example, the $Fe_2L(OAc)_2$ anion, where L=*N,N'*-(2-hydroxy-5-methyl-1,3-xylylene)bis(*N*-carboxymethylglycine) (**2**).[27]



2

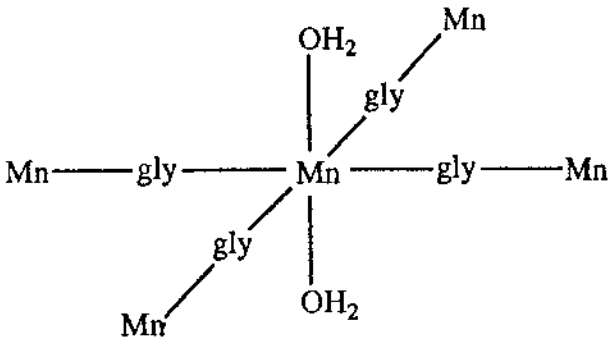
For simpler complexes in which bulky ligands are not present, there is a strong predilection of the metal to possess a μ^3-oxo bridge at the center of a trinuclear complex. This is common for several metals and has been reported for the α-alaninato (**3**)[28] and

glycinato[29] complexes of iron, and for complexes of vanadium,[30] chromium[31] and manganese.[32]

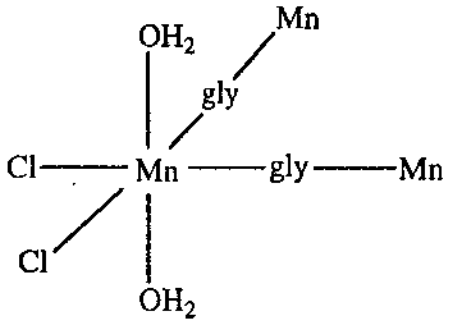


3

The manganese complexes of glycine and alanine are rather different, forming polymeric arrays in which the repeating unit contains one manganese. Two different structural types were observed, (**4a**) and (**4b**), depending upon the nature of the halide counterion.In $[Mn(gly)_2(OH_2)_2]Br_2$,[33] the complex crystallized as shown in (**4a**), but when chloride was the anion,[34,35] structure (**4b**) predominated. A similar mode of co-ordination was observed for the analogous cobalt complex.[35]



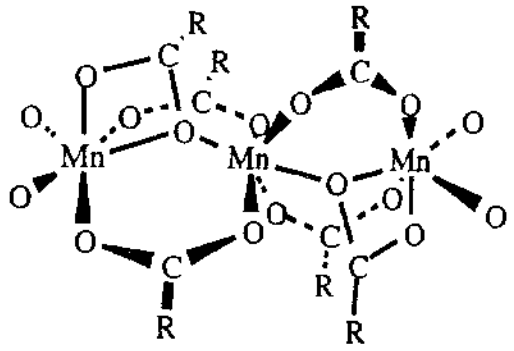
(a)



(b)

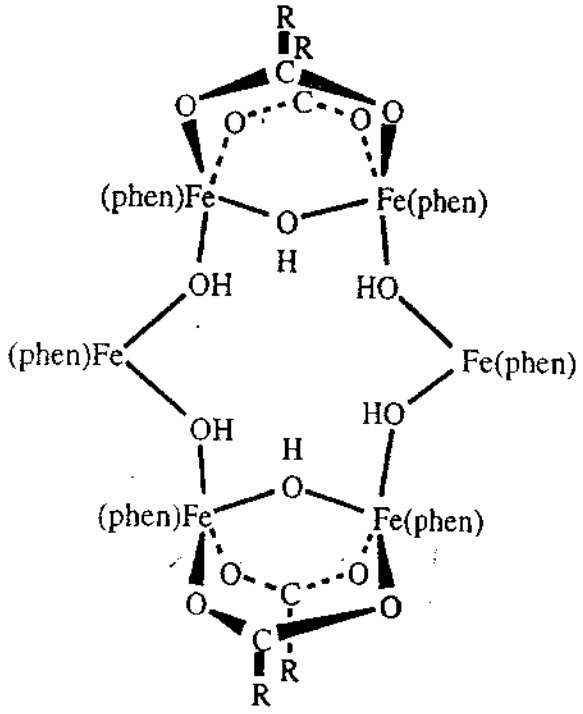
4

Complexes containing the non-biologically relevant β-alanine, in which the ammonium group is displaced by an extra carbon atom from the carboxylate group, led to different structures. The manganese complex (**5**) was again polymeric, although the repeating unit was trinuclear and contained both bridging and chelating carboxylate groups.[36] The β-alaninato complex of iron (III) (6) consisted of a hexanuclear species, in which two pairs of iron atoms were bridged by two carboxylate groups each.[37]



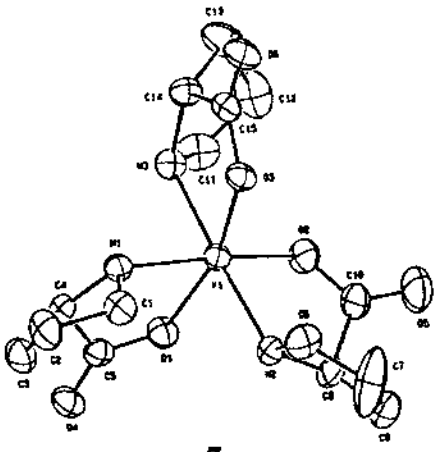
$R = CH_2CH_2NH_2$

5



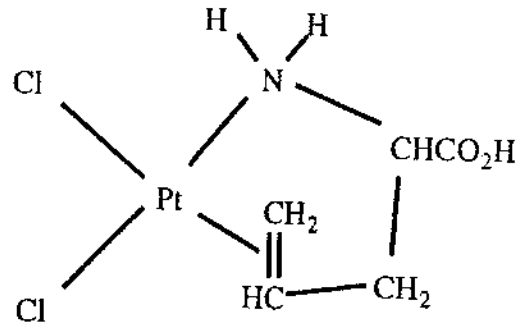
6

The species discussed above all involve fairly hard metal ions, which bind preferrentially to the carboxylate group (usually in a bridging fashion). Complexes of amino acids with metal ions of intermediate hardness form complexes in which the metal is chelated to the amino acids *via* both the carboxylate oxygen and the amino group forming the thermodynamically stable five membered ring.[25] Included in this group of complexes are those of iron (II),[38] tungsten,[39] and vanadium (7).[40]



7

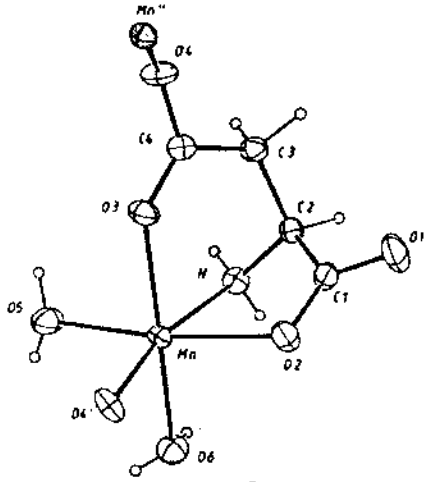
Finally, soft metal centers tend to coordinate to the amine group that becomes deprotonated upon complexation. One example of this somewhat rare form of interaction[25,26,41,42] includes the complex of Pt(II) with allylglycine (8).[43]



8

The complexes discussed thus far have all involved non-coordinating amino acids. Studies of coordinating amino acids are very rare, and only the aspartato complex of manganese (II) has been structurally characterized (9). The mode of binding was typical of multidentate carboxylic acids and involved both the carboxylate and the amino sites at one end of the amino acid, and the carboxylate group on the side chain.[44] The preferences for the mode of bonding of the two carboxylates was somewhat surprising in

that the side chain carboxylate was found to bridge two manganese centers, with the remainder of the co-ordination sphere completed by the bidentate amino acid group and three solvent ligands.

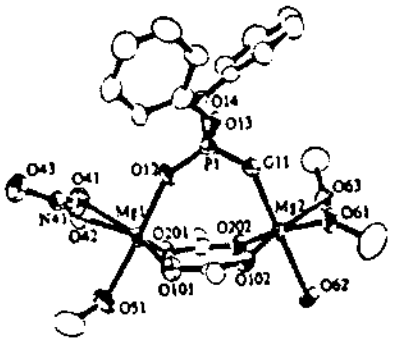


9

Other Acids[45]

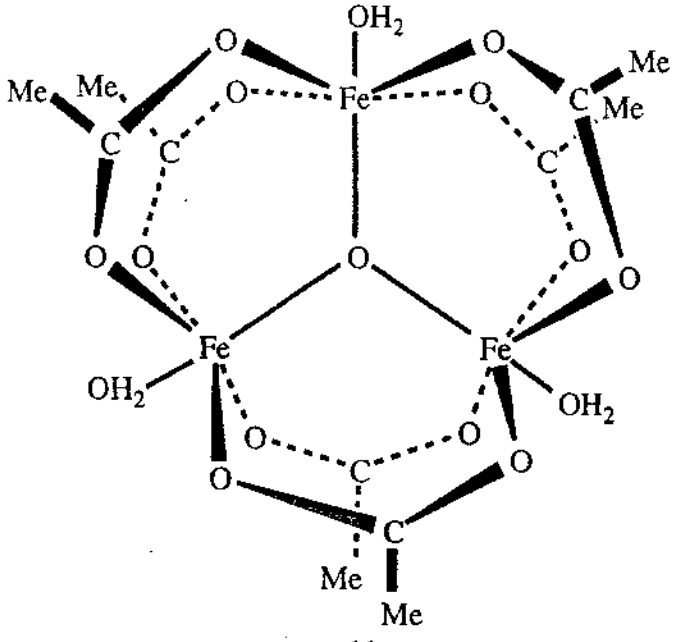
The amino acid carboxylate complexes discussed above form a small subset of a large field - that of metal carboxylate complexes in general. While again, a comprehensive review of the area would be inappropriate, it would be remiss to neglect a discussion of some of the more salient aspects of this field. The chemistry of iron carboxylates is particularly relevant, due to the similarity between this ion and Al^{3+} discussed previously, as well as parallels that have been drawn between Fe(III) carboxylate chemistry and that of ferritin.[46]

Carboxylates of metals from all parts of the periodic table have been studied, although particular focus has been directed towards the transition metals. The only main group complex of note is the dinuclear magnesium complex (**10**),[47] due to the observed competition between Mg^{2+} and Al^{3+}.



10

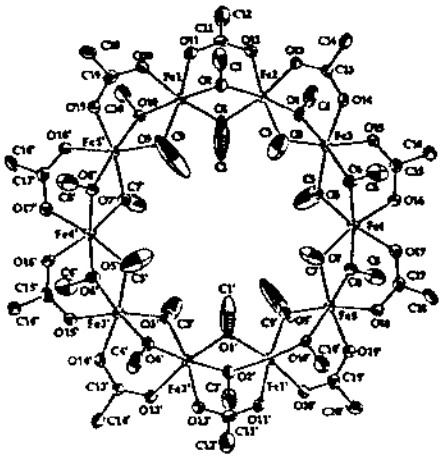
Transition metal carboxylate complexes include examples of species very similar to the amino acid complexes discussed above. Thus, for example, the basic acetato-iron(III) complex (11)[48] is isostructural with the alaninato-iron(III) complex (**3**).



11

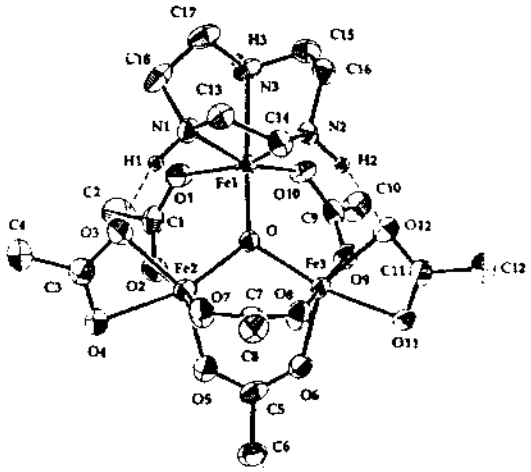
There are, however, many metal carboxylate complexes that feature bonding modes and nuclearities that have not been observed, as yet, for amino acid complexes.

One may point to the series of Fe(III) acetates and benzoates that contain four,[19] six,[49] eight,[50] ten (**12**),[51] eleven,[52] twelve,[53,54] seventeen[55] and nineteen[56] metal atoms.



12

The dominant structural features of the complexes discussed thus far is the overwhelming tendency of the carboxylate group to bridge two different metal atoms. However, despite the smaller size of Fe^{3+}, chelation has been observed in two cases, (**13**)[57] and (**14**),[58] as well as examples of bridging through one oxygen, (**14**) and (**15**).[58]



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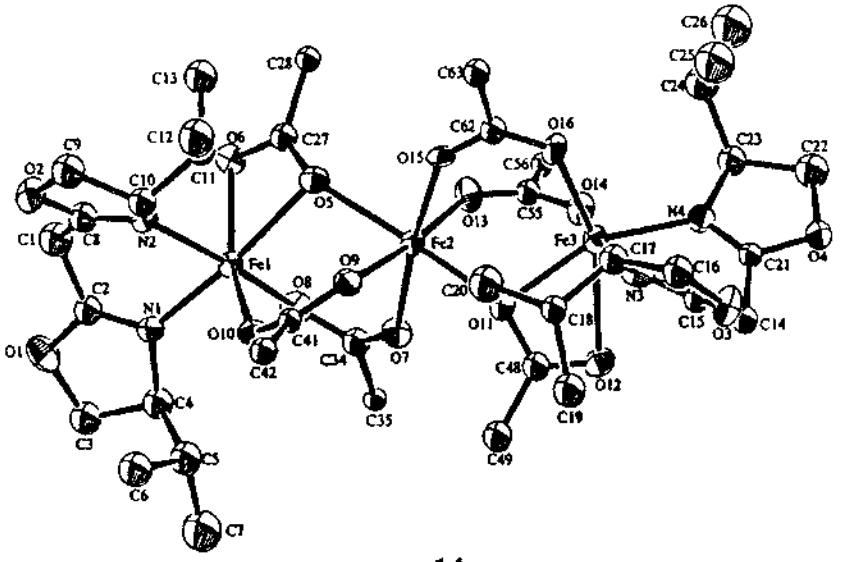

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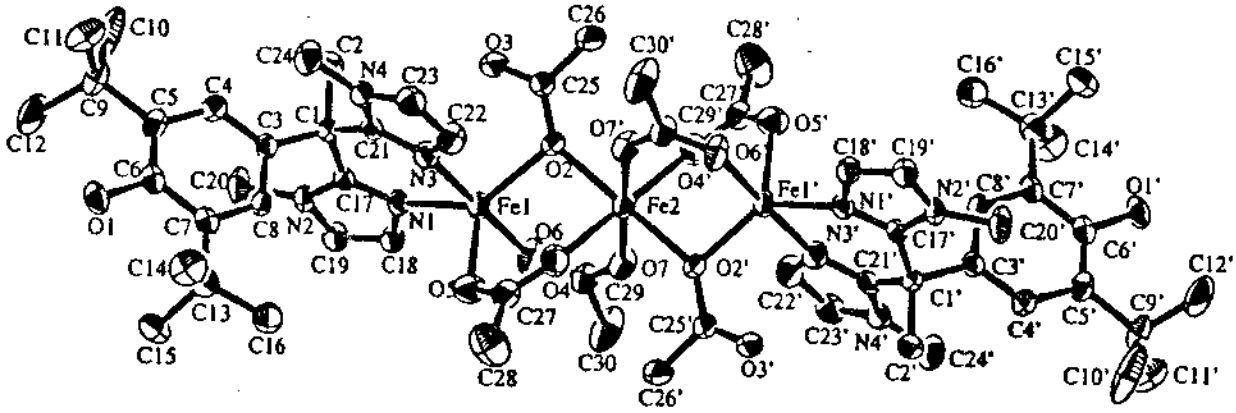

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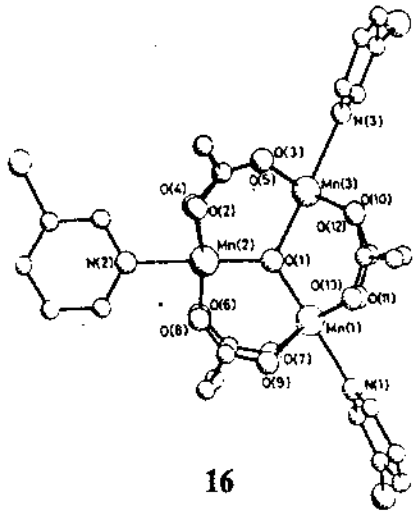
The trends observed for the chemistry of Fe^{3+} are general throughout the first transition series; namely, multiple nuclearity, bridging carboxylates and some form of oxygen bridge. However, even simple changes in reaction conditions may drastically affect the structure of the product. One striking example of this occurs in the manganese acetate system. When crystallized from non-aqueous solvent, the structure is the typical trinuclear μ^3-oxo bridged species (**16**).[59]



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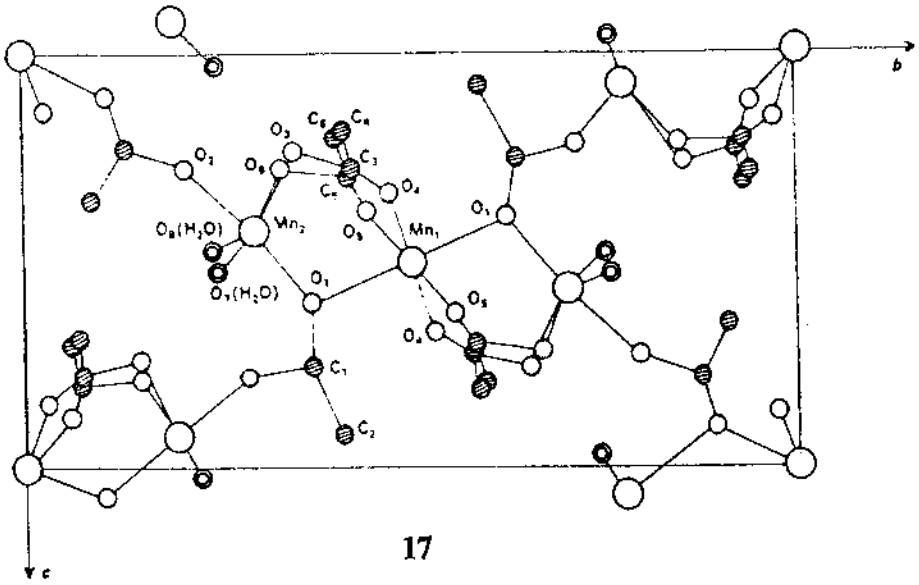
Crystallization from water, however, results in a polymeric structure without the oxo-bridge. The repeating unit is bimetallic, in which each metal center is bridged by two "normal" acetates and a third mono-oxygen bridge that comes either from a third acetate (17)[60] or water molecule.[61]



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It may be seen from the discussion in this section that the field of metal-carboxylate chemistry is both extensive and varied. While certain trends may be observed, the general theme of the reported work is the difficulty encountered in

predicting and directing the formation of desired products. Given the predominance of binding through the carboxylate group observed for the amino acid complexes of harder species that was discussed in the first section, and the wide spectrum of different structural types that was illustrated in the second, we may conclude that our study of aluminum complexes with amino acids will essentially be an investigation of aluminum carboxylates.

1-5. The Chemistry of Aluminum and Relevant Group 13 Members

Aqueous Speciation

Given the conclusion above, before embarking on an investigation of aluminum amino acid chemistry, one must become familiar with the general chemistry of this metal ion, particularly with regard to carboxylates and possibly reactions with amino acid side chain substituents. Because of both the nature of the project (to draw analogies with physiological conditions) and the fact that amino acids are predominantly water-soluble, it is appropriate to begin with aluminum's behavior in water.

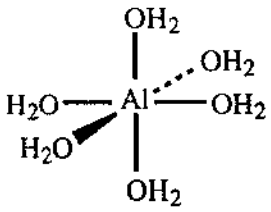
Aluminum exists in aqueous solutions in two predominant forms. At pH below *ca* 5.5, the dominant form is the octahedral hexaaquaaluminum cation, $[Al(H_2O)_6]^{3+}$, while the tetrahedral $Al(OH)_4^-$ anion exists at pH above 6.2. At high pH, the dimeric $[Al_2O(OH)_6]^{2-}$ anion may also form.[62] At the mid-range pH values around 6, most of the metal precipitates as the highly insoluble hydroxide, $Al(OH)_3$, which has a solubility product of 1.9×10^{-33}.[63]

At pH between 4 and 6.5, hydrolysis of the heaxaquaaluminum cation takes place and the removal of successive protons leads to the formation of the $[Al(H_2O)_5(OH)]^{2+}$ cation, otherwise abbreviated as $[Al(OH)]^{2+}$, and $[Al(H_2O)_4(OH)_2]^{+}$, commonly refered to as $[Al(OH)_2]^{+}$.[4] Subsequent hydrolyses lead to other aluminum species of higher nuclearity, examples of which include $[Al_2(H_2O)_8(OH)_2]^{2+}$ (characterized by X-ray)[64] and $[Al_3(OH)_4(H_2O)_{10}]^{5+}$.[62]

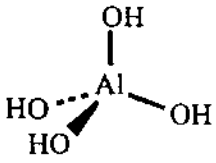
These species are not particularly stable and disproportionate into more stable, higher oligomers. These include the hexamer $Al_6(OH)_{12}{}^{6+}$ (from which can form the double and triple ring species $Al_{10}(OH)_{22}{}^{8+}$ and $Al_{13}(OH)_{30}{}^{9+})^{8}$ and the tridecameric $[AlO_4Al_{12}(OH)_{24}(H_2O)_{12}]^{7+}$ cation,[65] commonly known as "Al_{13}", which is thought to be particularly toxic.[66] These species are illustrated in Figure 1-2.

Full characterization of the speciation in aqueous solutions is complicated by many factors. As might be expected, there are mulitple equilibria present in solution, and the nature of these depends both on the route by which various species are formed and, adding even more complexity, with time![67]

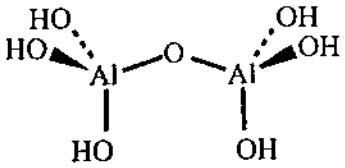
The reaction chemistry of aluminum in aqueous solution is dominated by two effects. As aluminum is a rather hard acid in most of its aqueous species, it prefers ligands that contain hard donor groups. However, this leads to competition with protons, which are also hard acids.[68] It follows then that ligands with a high pK_a will have a higher affinity for aluminum and so we would expect the aluminum to bind to alkoxides (whose conjugate acids have pK_a values of *ca.* 14) more strongly than to carboxylate groups (whose conjugate acids possess pK_a values of *ca.* 4).



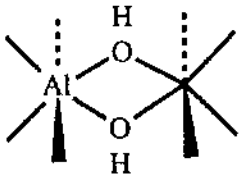
$Al(H_2O)_6^{3+}$



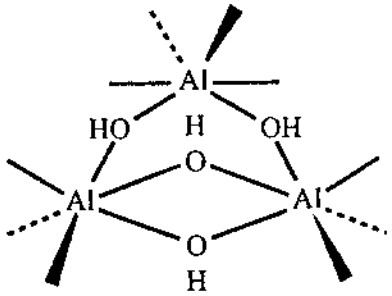
$Al(OH)_4^-$



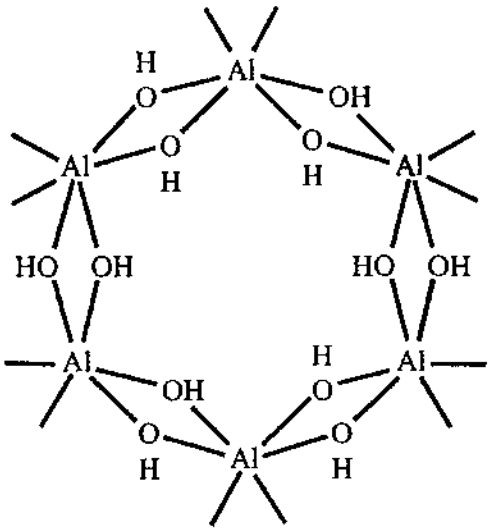
$Al_2O(OH)_6^{2-}$



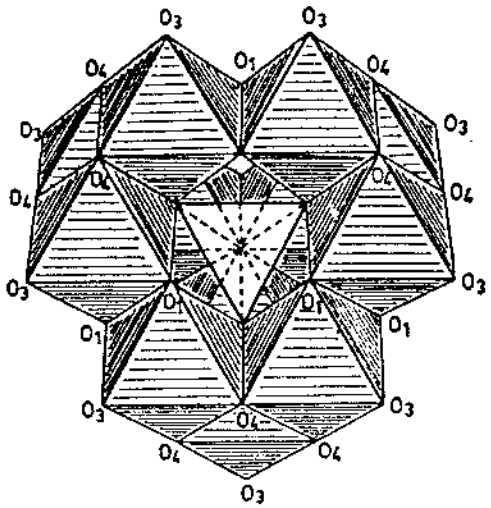
$Al_2(H_2O)_8(OH)_2^{4+}$



$Al_3(OH)_4(H_2O)_{10}^{8+}$



$Al_6(OH)_{12}(H_2O)_{12}^{6+}$



$Al_{13}O_4(OH)_{24}(H_2O)_{12}^{7+}$

Figure 1-2. Some common aqueous aluminum species.

In addition to the competition between H^+ and Al^{3+} for these hard donor sites, there is also competition between the ligands and water and OH^-, hard donor molecules themselves, for binding to aluminum. At very high or very low pH, therefore, where there are excesses of H^+ and OH^-, respectively, no complexation usually occurs between aluminum and non-water derived species. The optimum pH for ligation is typically in the range 3 to 6.[68]

Reaction with Acids in Aqueous Solution

Some work has been reported on the reactions of aluminum with water in aqueous medium, and, in some cases the results have been confirmed by X-ray crystallography.

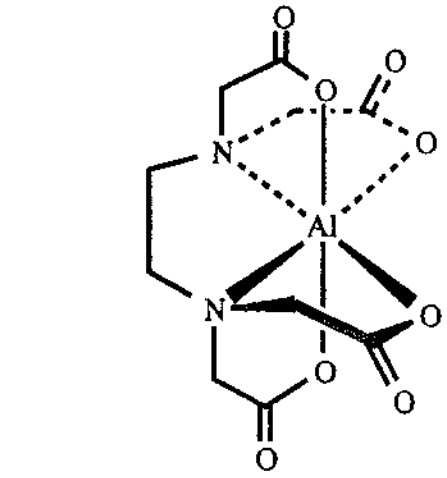
An early report, primarily aimed at demonstrating the utility of ^{27}Al NMR, investigated complexation of aluminum by a number of polycarboxylic acids.[69] The primary finding was that the stablilities for the EDTA, citrate and lactate complexes were in the same order as the number of donor sites on the respective ligands. For lactate and citrate, complexes formed with relative ease at lower pH, but the ligands were gradually displaced by water and by hydroxide as the basicity of the solution was increased, with complete removal of the ligands at the high pH's. The citrate complex, with three carboxylate and one hydroxyl site, was found to resist hydrolysis to a far greater extent than lactate, which possesses one carboxylate and a hydroxyl site. The complex of aluminum with EDTA, however, was found not to be hydrated for a wide range of pH, showing high resistance to hydrolysis. Crystal structures of complexes with all three acids were reported by various workers (Figure 1-33). EDTA (Fig. 1-3a) completely

surrounds one aluminum center, rendering the metal inert to hydrolysis.[70] The citrate complex (Figure 1-3b), in agreement with an in-depth potentiometric study,[71] consisted of three citrate ions bound in three different ways to three aluminum atoms, as well as a bridging hydroxide and terminal water ligands.[72] In the lactate complex (Figure 1-3c),[73] both the carobxylate and hydroxide end of three lactate residues bind to the aluminum, forming five-membered chelate rings.

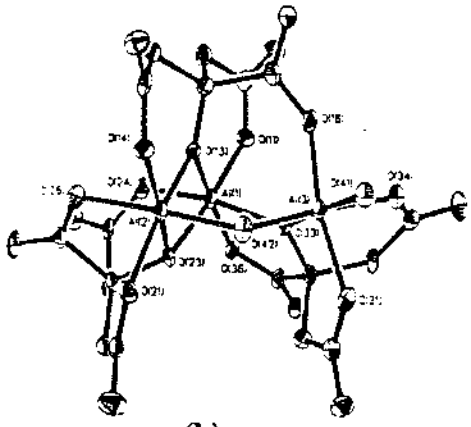
Several potentiometric studies have compared the binding strength of different types of acids.[74,75,62] In general, the order of complex stability goes in the order dicarboxylic acids » hydroxycarboxylic acids » carboxylic acids.

There is very little work available on amino acid complexes of aluminum in aqueous solution, and what there is is rather controversial. Öhman claimed that only weak, if not negligible interactions between alanine,[75] glycine, aspartic acid, glutamic acid, serine, proline, hydroxyproline, histidine and threonine[76] and aluminum exist in aqueous media. Other workers,[77] however, claimed to have evidence showing that both alanine and glycine do form ternary complexes with aluminum of the type $[Al_2(OH)_2(ala)_2]^{2+}$ at acidic pH above 3.5 and $[Al(OH)_3(ala)]^-$ at neutral and slightly higher pH. The general consensus is, however, that amino acids are weak binders to aluminum at best, being even weaker than simple monocarboxylic acids.[78]

The reasons for the overall series of reactivity are rather straightforward. Polycarboxylic and hydroxycarboxylic acids may serve as multidentate ligands, thus stabilization *via* the chelate effect occurs. The reason for the low stability of amino acid complexes compared to monocarboxylic complexes is undoubtedly the repulsion due to



(a)



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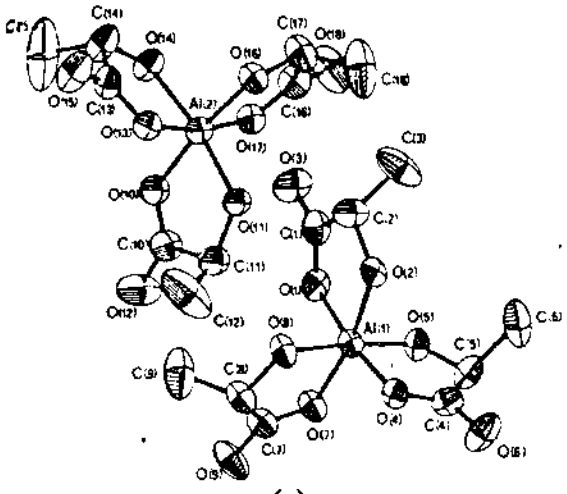


(c)

Figure 1-3. Structures of some aluminum complexes with multidentate acids.

the protonated amine group.

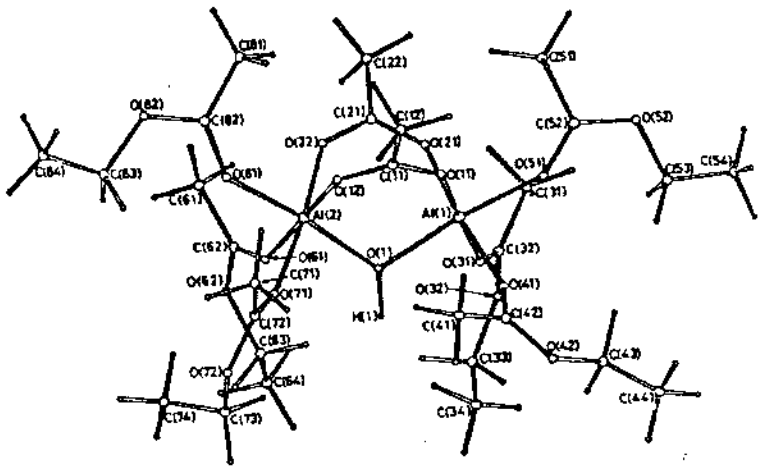
This latter hypothesis may be partially confirmed by consideration of two reports. Complexes of pyridoxal derivatives of amino acids (in which the amino group is no longer protonated) have been investigated and identified by heteronuclear NMR and infrared spectroscopies.[79] Binding was shown to occur readily at the carboxylate site. In studies of aminohydroxamic acid (analogues of amino acids) complexation of aluminum, it was found that the NH_3^+ moiety gives rise to two contrasting effects. The group itself enhances complexation due to its electron-withdrawing nature, yet repels the metal ion if in close proximity. Thus, complexes of β-substituted acids formed much stronger complexes than the α-isomer.[80]

Reaction with Acids in Non-Aqueous Solution

The above discussion implies that the study of aluminum amino acids in aqueous medium is a somewhat fruitless endeavor, due both to the competition with aqueous species and unfavorable electronic effects. Changing the solvent, however, does not necessarily prove beneficial as aluminum may still form compexes with the solvent. For example, several species have been identified in solutions of $AlCl_3$ in methanol, including $AlCl_3$.MeOH, $AlCl_3(MeOH)_3$, $AlCl_2(MeOH)_4]^{2+}$ (which has been shown to be the dominant species) and $Al(MeOH)_6]^{3+}$, among other, as yet unidentified moieties. Similarly, the speciation of $AlCl_3$ in a mixture of DMSO and ether has been shown to contain seven different species.[81]

The speciation of $AlCl_3$ in THF,[82,83] ether, pyridine and CH_3CN differs somewhat from that found in methanol.[81] In these solvents, the primary species are $AlCl_3$.(Solv), $AlCl_3(Solv)_3$, $[AlCl_2.(Solv)_4]^{2+}$, $[Al(Solv)_6]^{3+}$ (Solv= solvent) and the anionic species, $[AlCl_4]^-$ (75% of the aluminum in solution is generally in this latter form). Use of organoaluminum complexes in organic solvents does not neccessarily simplify the situation either. For example, pyridine solutions of trimethylaluminum have been observed to contain the ion-pair $[py_2AlMe_2]^+[AlMe_4]^-$.[84]

Although not as extensively studied, some alumium carboxylates have been reported in non-aqueous media despite the potential drawbacks. Atwood has reported three complexes arising from the reaction of carboxylic acids with trimethylaluminum (Figure 1-4).[85,86,87] One aluminum choride complex of a carboxylate has been reported and characterized by X-ray crystallography (**18**). The synthetic route into this species, however, is rather indirect, resulting from ester cleavage in the reaction between $AlCl_3$ and ethyl actetate.[88] Finally, several aluminum salen[89] and alumoxane[90] complexes of carboxylates have been reported, although not structurally characterized.



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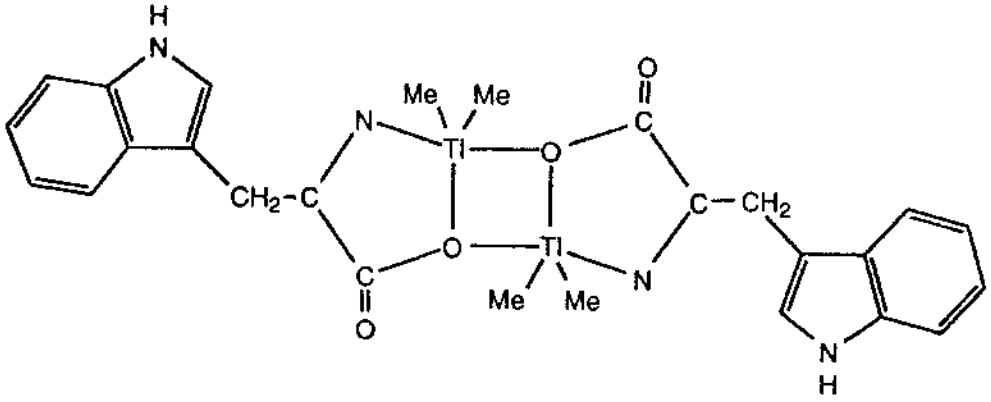
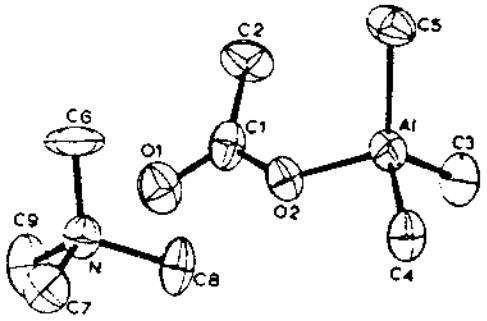
Carboxylates of Other Group 13 Elements

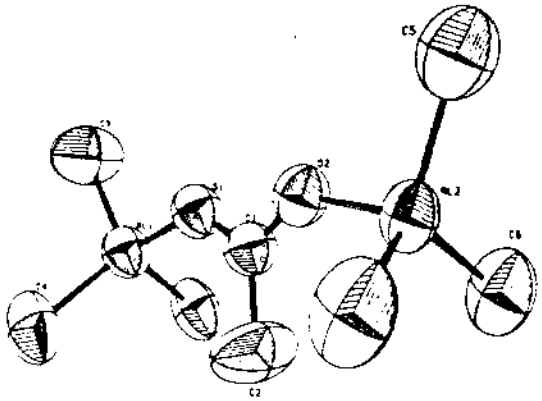
Aluminum differs from the other group 13 elements in that it has the hardest ion. The chemistry of boron is typically covalent, while gallium, indium and thallium are all much softer than aluminum. One would expect, therefore, that amino acid complexes of these elements would involve interaction of some form with the nitrogen. Thus, the tryptophanato (**19**)[91] and the phenylalaninato[92] complexes of thallium, the prolinato and glycinato (**20**) gallium complexes,[93,94] and the prolinato (**21**)[95] complex of boron all form complexes in which the amino acid binds in a chelating *N,O*- fashion.

Given the softer character of the heavier members of group 13, one would not expect a very extensive chemistry with carboxylate ligands. Five examples of such complexes have been well characterized,[96-100] examples of which are shown in Figure 1-5. Thus, gallium acetate is isostructural with the basic transition metal acetates (Figure 1-5a), while indium and thallium show a predilection for chelating carboxylate groups, due to their large size (Figure 1-5b and 1-5c).

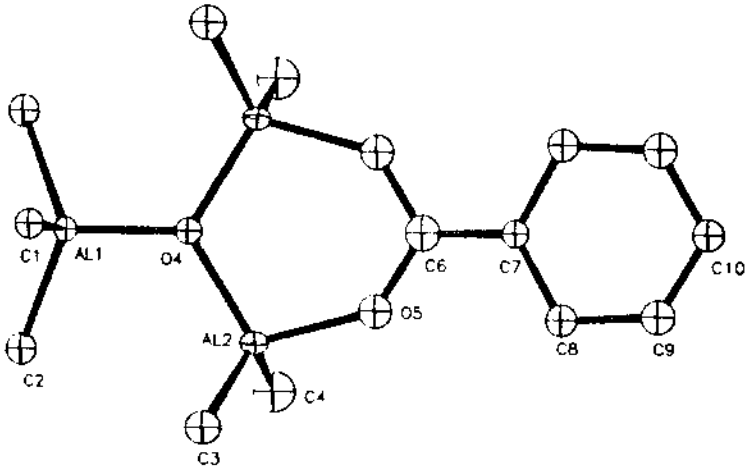




$AlMe_3 \cdot CH_3COO^-$

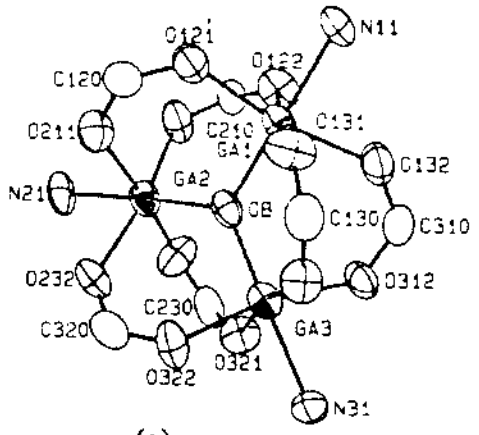


$(AlMe_3)_2 \cdot CH_3COO^-$



The benzoic acid complex of $AlMe_2(\mu\text{-}OAlMe_3)$

Figure 1-4. Crystal structures of Atwood's aluminum carboxylate complexes.



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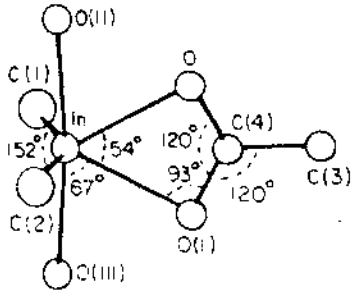

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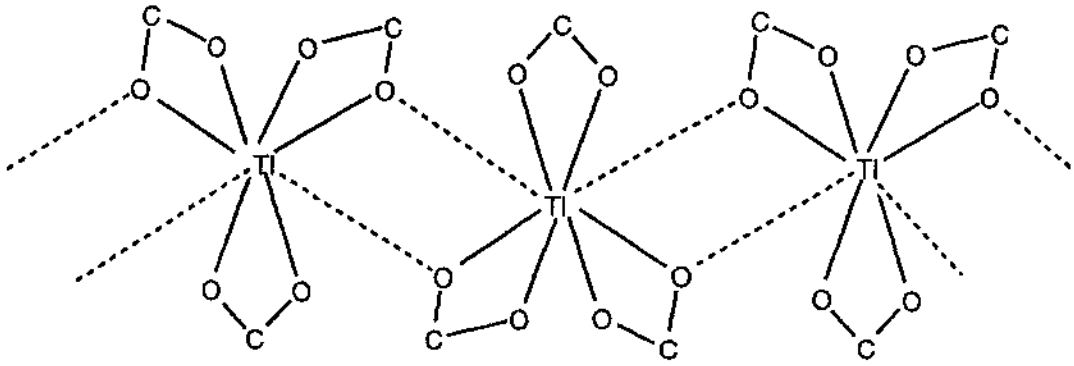
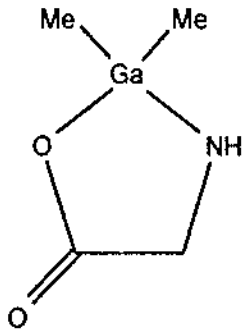


(c)

Figure 1-5. Sample group 13 carboxylate complexes.



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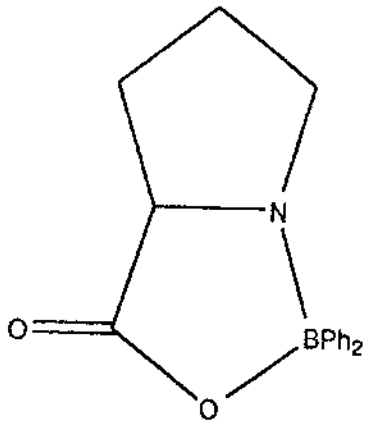

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CHAPTER 2

GENERAL EXPERIMENTAL DISCUSSION

In order to avoid repetition throughout the text, this chapter contains general details of experimental methods employed, as well as introductory comments on the salient features of techniques important in this work.

2-1. Synthesis

All manipulations were undertaken under purified nitrogen using Schlenk apparatus and/or a Vacuum Apparatus DXL Dri-Box with standard air and moisture sesnsitive techniques. All solvents were pre-dried and distilled under nitrogen. Methanol, ethanol and isopropyl alchohol were dried by heating over magnesium filings and iodine until the brown coloration disappeared and then refluxed for a minimum of four hours.[101] Toluene, pentane, benzene, hexanes, ether and pyridine were dried with sodium. Methylene chloride and acetonitrile were dried with calcium hydride. THF was dried by reflux with potassium and benzophenone until a purple color appeared and subsequently distilled. Acetone was purified by addition of potassium permanganate until the purple coloration lasted for five minutes and then charging with magnesium sulfate.[101] DMSO, DMF and heptane, pre-dried and stored under nitrogen by the manufacurer, were used as received from Aldrich Chemical Co. Deuterated solvents were used as received from

Aldrich Chemical Co. and Janssen Chimica Co.

2-2. Spectroscopy

General

Infrared spectra were recorded on a Nicolet 20 SXB FT-IR spectrometer. Samples were prepared either as KBr pellets or, where this was not possible (in cases where the samples were viscous liquids), as concentrated samples smeared on a NaCl plate.

^{27}Al and ^{11}B NMR spectra were recorded on a Varian 300-VXR NMR spectrometer. $^{13}C\{^{1}H\}$ and $\{^{1}H\}$ NMR spectra were recorded on a Varian Gemini 200 MHz NMR spectrometer. Low temperature ^{1}H NMR spectra were recorded on both 300 MHz and 200 MHz instruments. Chemical shifts are reported relative to external TMS for $^{13}C\{^{1}H\}$ and ^{1}H NMR spectra, or aqueous $[Al(H_2O)_6]^{3+}$ for ^{27}Al NMR spectra. CD_3OD was used as the lock solvent unless otherwise stated. Where the solvent is quoted in the protonated form, $CDCl_3$ was used as an external lock and the spectrum referenced to the chemical shifts of the protonated solvents.

^{27}Al NMR

As aluminum has an NMR active nucleus which exists in 100% abundance, ^{27}Al NMR can be a very powerful probe for determining the speciation of aluminum in solution.[81] However, because aluminum has a quadrupolar nucleus (spin of 5/2), this dominates its relaxation and some information is lost by Fourier Transform, leading to broad lines. While this is a somewhat negative effect, because symmetrical species relax

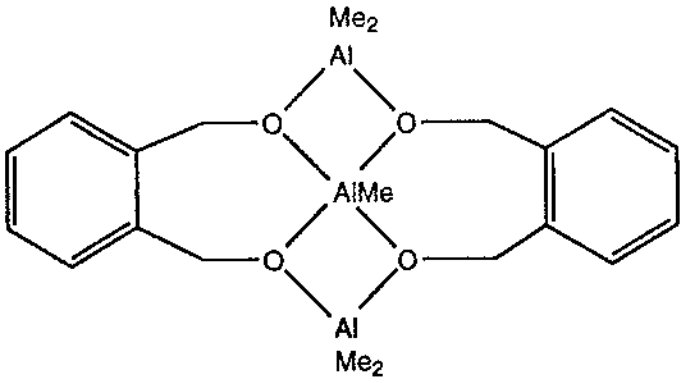
more slowly than asymmetric ones, the line width of a ^{27}Al NMR peak is fairly diagnostic of the symmetry of the aluminum coordination sphere. Care must be taken when applying this concept, however, as any exchange processes present may also lead to broadening of signals.[102] The two effects may be distinquished by variable temperature studies, however. In cases where exchange is the dominant factor, signals should sharpen at low temperatures; conversely, because the rate of quadrupolar relaxation decreases at high temperatures, peaks that are broadened due to this effect will become sharper at high temperatures.[103]

The range of chemical shifts in the ^{27}Al spectrum is approximately 300 ppm.[104] $[Al(H_2O)_6]^{3+}$, which has the narrowest resonance of all aluminum species,[105] has been accepted as the standard and its resonance has been assigned at 0 ppm. Based on this convention, octahedral species are typically observed with chemical shifts in the range of 40 to -46 ppm; tetrahedral species have a wide range of chemical shifts and have been observed in the range 140 to 40 ppm; trigonal aluminum alkyls are seen above 150 ppm; [81] and penta-coordinate aluminum atoms have chemical shifts intermediate between those of octahedral and tetrahedral resonances. These trends are illustrated in Table 2-1, which lists the chemical shifts in the ^{27}Al NMR of the aluminum reagents (in different solvents) used in this investigation. It should be noted that these shifts are by no means hard and fast rules for determining geometry as there are some notable exceptions. For example, tetrahedral AlI_4^- has a chemical shift of -26.7 ppm (compared to 104.2 ppm for $AlCl_4^-$).[81]

Despite these drawbacks, ^{27}Al NMR has been employed frequently to elucidate or confirm the structure of aluminum complexes. For example, $AlCl_3$ in methanol was

shown to contain several species including $AlCl_3(MeOH)_3$, $[AlCl_2(MeOH)_4]^{2+}$ and $[Al(MeOH)_6]^{3+}$.[106] Similarly, aluminum chloride in THF was also monitored by ^{27}Al NMR and various species identified.[107] The shifts found are listed in Table 2-1.

A typical application of the technique may be seen by a comparison of two studies of alumium alkoxides. The ^{27}Al NMR of complex (**1**), for which an X-ray structure was also reported, contains peaks at 160 and 73.9 ppm assigned to the four- and five-co-ordinate aluminum atoms respectively.[108] Based on this, the product of the reaction of 2-propanol with aluminum chloride was shown to include four- and five-coordinate aluminum centers by assignment of signals at 98 and 87 ppm to the four-coordinate and 63 ppm to the five-coordinate aluminums.[109]



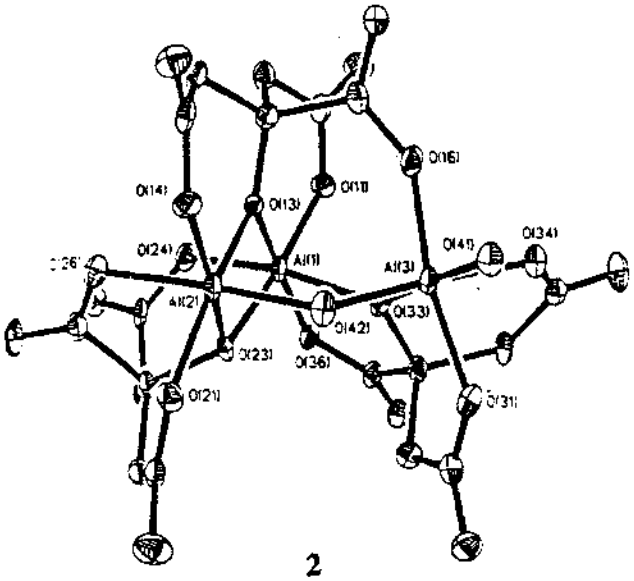
1

Where both O and N donor ligands are bound to an aluminum center, such as in a series of salicylideneimine complexes,[89] the spectra generally shift downfield. Thus, the five-coordinate examples (in which the fifth site is filled by an oxygen) have shifts at approximately 25 - 30 ppm, while the octahedral species display shifts of slightly greater than zero.

Table 2-1 ^{27}Al NMR Shifts of Aluminum Reagents in Different Solvents[81]

reagent	solvent	δ (ppm)	$W_{1/2}$ (Hz)
$Al(NO_3)_3.9H_2O$	D_2O	0.0	2.0
$Al(NO_3)_3$	CD_3OD	0.4	10.94
$AlCl_3$	CD_3OD	15.8	
		14.3	
		8.7	
		7.6	
$AlCl_3$	CD_3CN	103.8	4.13
		98.0	7.63
		-12.3	351.0
		-14.2	1190
		-21.5	178.5
		-32.5	13.23
$AlCl_3$	THF	102.8	16.70
		63.5	375.4
		17.0	310
AlI_3	CD_3OD	10.8	271.6
		3.3	332.7
AlI_3	THF	40.4	1785
		25.1	2432
		8.0	225.8
AlI_3	CH_3CN	57	$> 10^5$
		-22.2	183
		-31.6	179
		-32.3	20.21
		-47.7	15.65
TMA	ether	183.0	1758
TMA	THF	176.2	1690
TMA	CH_2Cl_2	156.9	260
TMA	pyridine	164	2470
BHT_2AlMe	THF	55	> 5000

^{27}Al NMR has also been found to be applicable for determining speciation in aqueous systems, to the extent that much of the information on aluminum carboxylates is derived from this source. The speciation of aluminum in its reactions with lactic and citric acids at varying pH were identified by consideration of both linewidth and chemical shift.[110] The crystal structure of the latter complex (**2**), which contains three metal



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centers in slightly distorted octahedral environments, confirmed the structural assignment by ^{27}Al NMR in which octahedral peaks were observed at 12.6, 10.7 and 0.2 ppm.[72] In the studies of these two acid complexes, a combination of binary acid complexes and ternary acid/aluminum/water or hydroxy complexes were observed. In general, the more solvated the aluminum center, the more downfield the shifts. Thus, for example, the homoleptic trislactato aluminum (III) complex was observed at 24 ppm, whereas the ternary aquo/lactato complexes were seen between 9 and 15 ppm.

In the work described herein, ^{27}Al NMR was employed both to provide evidence of reaction, and to assign the gross structure of the aluminum-containing products.

^{13}C NMR

Decoupled ^{13}C NMR ($^{13}C\{^{1}H\}$) contains, in theory, a signal for each type of carbon present in the sample under investigation. Within the context of this work the region of the spectrum between 160 and 190 ppm, which contains signals due to carboxylate carbons, was considered to be the most important. The shift of the carboxylate carbon is rather sensitive to its environment, as exemplified by the data in Table 2-2. Ideally, this method should provide an excellent way to identify the speciation of the amino acids present in solution.

Table 2-2. Carboxylate Shifts of the Three Different Forms of Alanine[111]

pH	Species	^{13}C COO Shift
0.43	$NH_3^+CH(Me)COOH$	172.9
4.96	$NH_3^+CH(Me)COO^-$	177.0
12.52	$NH_2CH(Me)COO^-$	185.7

In practice, however, three major drawbacks became apparent. Given the extreme sensitivity of the shift, it is difficult to distinguish between changes due to simple solvation rather than actual reaction. Even when reaction does occur, as may be determined from a consideration of other factors such as physical appearance, peaks of different shifts may actually correspond to essentially equivalent carbons. For example, the ^{13}C NMR of the aluminum-citrate complex (**2**) contained nine carboxylate signals! Finally, the strength of the carboxylate signal is not only reduced by the usual drawback

of ^{13}C NMR (namely the low abundance and sensitivity of the nucleus), but will be weaker than the signals due to the remaining carbons due to the lack of an enhancing nuclear overhauser effect (NOE).[112] The unfortunate result is that the carboxylate peak is difficult to identify, and even if found, any fine structure is almost impossible to determine; comparison with other reported results, therefore, becomes questionable.

In order to overcome this problem, certain experiments were performed with amino acids that were enriched at the carboxylate carbon with ^{13}C. This not only led to the intense enhancement of signals due to this carbon, but also enabled the determination of the relative abundance of the species present. Unlike ^{1}H NMR spectroscopy, where integration of peaks allows the abundance of protons in each peak to be calculated, this is not possible with normal ^{13}C NMR as carbon has a much longer relaxation time. In order to eliminate such magnetic effects, gated decoupling may be employed with enriched samples. This technique has previously been employed in biochemical studies where ^{13}C probes have been introduced at the carboxylate sites of amino acids in proteins to determine metabolic pathways.[113] The T_1 relaxation for the carboxylate carbon was considered to be 1.6 s for large polypepetides, and although no work in the literature was available for free amino acids, a delay of 10 s was used in this work to err on the side of safety.

Although study of the carboxylate carbon was the most important consideration within the context of this work, other information could be obtained by a consideration of other parts of the spectrum. In cases where the amino acid has a reactive side-chain, coordination of this side-chain may be inferred. Finally, the number of alkyl groups left

on an aluminum center in reactions of, for example, trimethylaluminum, may be determined.

^{1}H NMR

Although ^{1}H is the usual nucleus investigated by NMR, various factors contributed to this not being the case in these studies.

Given that the primary mode of coordination is *via* the carboxylate group, it is unlikely that reaction of aluminum with a zwitterionic amino acid would have much effect on the ^{1}H NMR spectrum.

When beginning the project, we thought that NMR study of this nucleus would provide information about the behavior of the amino group. This functionality could do one of four things during the course of the reaction: remain protonated (which would give rise to signals between 6 and 9 ppm); be deprotonated (moving the signal upfield to between 0 and 5 ppm); bind to the metal after deprotonation; or react in some other fashion *via* condensation or cyclization routes. Unfortunately, in reality, several factors combined to reduce the importance of the method.

Amine protons have a propensity to exchange with one another and with those of the solvent.[114] Not only, therefore, was this an inherent problem with the investigation, but a considerable number of the products were soluble in protic solvents only. In most cases, low temperature ^{1}H NMR can reduce the rate of exchange,and enable observation of these signals. Unfortunately, as the temperature is decreased, the likelihood of obtaining a suitably good shim also decreases and, to add insult to injury, the solubility

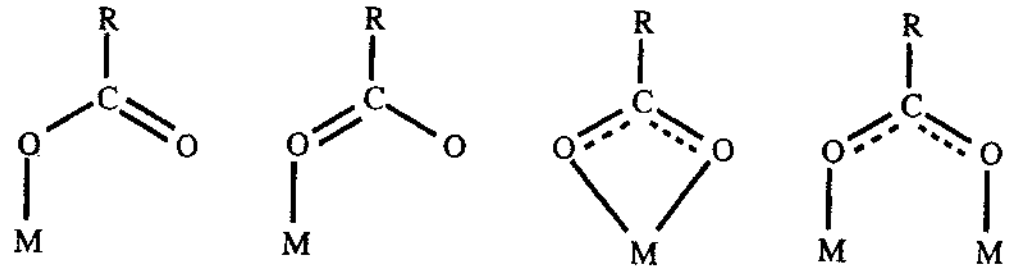
of the products was such that temperature reduction resulted in partial precipitation (which also increases the problems with shimming). In some cases, particularly with the products from the TMA reactions and when using deuterated pyridine as the lock solvent, the solutions would frequently be viscous, which results in broader peaks.

In a substantial portion of this work, some of the reaction mixtures were exposed to pyridine during the work up. This solvent was found to be particularly persistent and difficult to remove without corrupting the integrity of the products. As pyridine gives rise to signals in the same region as those of protonated amine groups, a certain amount of information was lost in such spectra.

The overall result of these problems was that the resolution of ^{1}H spectra was poor and that the multiplicities of signals were sometimes lost. The only positive note was that the drawbacks discussed would not affect the utility of ^{1}H NMR spectra to diagnose chelation. [102]

Infrared Spectroscopy

Once again, the primary use of this technique was to examine the nature of the carboxylate groups. The differences between the asymmetric and symmetric modes of vibration of the carboxyl oxygens, ν_a(C=O) and ν_s(C=O) respectively, commonly refered to as $\Delta\nu$(C=O), may identify the mode of co-ordination to the metal center.[115] One may break down the possible modes of coordination into four major types: monodentate through a single bonded oxygen (**3a**), monodentate through a carbonyl species (**3b**), chelating (**3c**), or bridging (**3d**).



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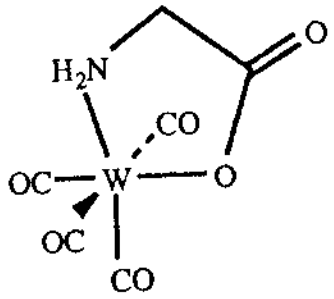
Of these four possibilities, the first and last are those for which the most data are available, and thus these two important situations may be described as asymmetric and symmetric, respectively. One would expect the former to have a large value of $\Delta\nu$(C=O), and the latter to have a small value, and indeed, although a certain amount of controversy has arisen about the cut-off value between the two possiblities,[115,73] the available literature of interest implies that bridging carboxylates give rise to $\Delta\nu$(C=O) values of less than 100 cm^{-1}, while values closer to 200 cm^{-1} are indicative of asymmetric coordination.

Of particular note within the context of this work are the four structures given below in which the O,N-chelating mode observed for the $[W(CO)_4(gly)]^-$ (**4**)[39] and the aluminum-lactate complex (**5**)[73] gives rise to a $\Delta\nu$(C=O) value of 185 and 210 cm^{-1}, respectively; while the bridging carboxylates in complexes (**6**)[90] and (**7**)[88] give rise to a $\Delta\nu$(C=O) of 60 cm^{-1}.

As well as providing information about the nature of the interaction between the carboxylate group and the aluminum, several other features of the infrared spectrum may be utilized in theory. For example, the ν(N-H) in $[W(CO)_4(gly)]^-$ (**4**) in acteonitrile appear



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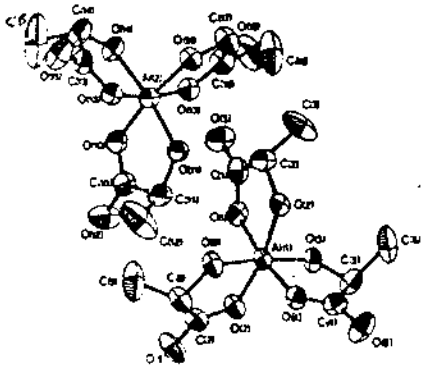

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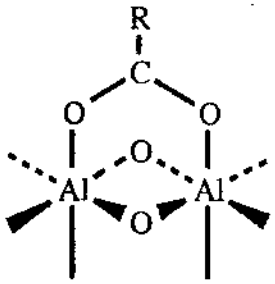

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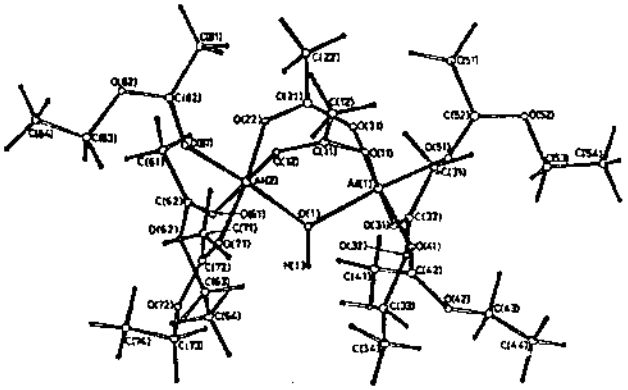

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at 3349 and 3300 cm^{-1} compared to the solid sample in which absorbance bands were observed at 3344 and 3153 cm^{-1}.[39] Changes in the environments of carbon- oxygen single bonds may also be observed in the 1200 to 900 cm^{-1} region of the spectrum. Both of these areas, however, are often obscured by signals arising from different groups or included solvent.

At the onset of the project, we believed that a substantial amount of information could be obtained concerning bonds to aluminum. The presence of an aluminum-oxygen bond can be inferred from ν(Al-O), which are observed in the lower regions of the infrared spectrum. Thus, in complexes of aluminum with pyridinones[116] the ν(Al-O) absorbances were assigned to bands at 705, 580 and 460 cm^{-1}, while the Al-O stretching frequency for THF complexes with $AlCl_3$ were found to be at 439 cm^{-1}.[107]

Bonds between aluminum and chlorine or nitrogen were of particular interest in many reactions, as these had been shown to be fairly sensitive to the nature of the other ligands around the aluminum. Some example data are listed in Table 2-3.

Aluminum alkyls and derivatives of these compounds have been characterized by infrared spectroscopy[117] and these vibrational modes are generally found between 700 and 300 cm^{-1}.

In much of the work reported here, however, the low wavenumber sections of the spectra are of dubious value. While, in theory, the infrared spectrometer used in these studies may be employed to detect peaks as low as 400 cm^{-1}, any assignments between 400 and 600 cm^{-1} may be regarded with skepticism.[119]

Finally, the identification of any bonding between aluminum and functional groups on the side chain of amino acids may be inferred from the absorbances described above and by comparison to a good organic chemistry text.[111]

Table 2-3. Some Selected Al-Cl and Al-N Infrared Signals[107,118]

	$\nu(AlCl_3)$	(Al→N)
$AlCl_3$.THF	546, 537	
cis-$AlCl_3$.2THF	510, 496	
trans-$AlCl_3$.THF	490	
$[AlCl_4]^-$	494	
$[Al(THF)_4Cl_2]^+$	440	
$AlBr_3$.THF	440	
$AlBr_3$.2THF	420	
$Cl_3Al.NH_3$	503, 380	575
$Cl_3Al.NHMe_2$	515, 490, 395	575
$Cl_3Al.NMe_3$	512, 422	565
$Cl_3Al.2NHMe_2$	505, 310	470, 465, 420, 417
$Cl_3Al.NMe_3$	504	

X-ray Crystallography

X-ray crystallography may provide the most useful information regarding the structure of a complex, furnishing information about bond angles and distances as well as the connectivity. Unfortunately, there are several drawbacks to its application. The most obvious problem is that one needs a single crystal that is at least 0.1 mm in every dimension. Some systems do not crystallize, and, even if crystals can be obtained, they may not be of sufficient size or quality. Even if one manages to obtain a crystal, there is no guarantee that it represents the bulk of any precipiate, much less the predominant species in solution.

In cases where crystals were obtained, they were mounted in thin walled glass capillaries with silicone grease by one of three methods, depending on their properties. Moisture sensitive compounds were mounted in a dry box under nitrogen and the open end of the capillary was plugged with modeling clay. The capillaries were then sealed with an oxygen-methane torch as soon as they were removed from the glove box. Where the crystals were solvent-dependent, the lattice solvent depletion was overcome by addition of mother liquor or fresh solvent to the capillary tube and then sealing as described above. Crystals which were not sensitive to either atmospheric moisture or solvent loss were mounted in open air with the aid of a microscope.

A suitable crystal was selected and mounted on the goniometer head of an Enraf-Nonius CAD-4 automated diffractometer which comprised a four-circle kappa axis goniometer with graphite crystal monochromated Mo radiation (λ = 0.71073 Å). The crystal-to-detector distance was 173 mm, and the take-off angle was 2.80°. The

diffractometer was controlled by a Digital Corporation VAXStation 3100/76.

The crystal was first centered visually under the diffractometer microscope and then the program SEARCH[120] was run to find up to 25 reflections and measure their angular settings. These were then used by the INDEX[120] routine to calculate the primitive unit cell. Where appropriate this was transformed, either to higher symmetry or in order to fulfill international conventions.[121] Strong axial reflections were accurately centered and then used to refine the cell parameters.

Where the data were reasonable and did not bear close correspondance to those of structures previously determined, data was collected. This was performed using either a ω-2θ or ω scan (in cases where a cell axis was greater than *ca.* 20 Å) technique with a variable scan width as given in Eq. 2-1 (A was between 0.65 and 0.8°).

$$\text{Scan Width} = A + 0.35 \tan(\theta) \qquad (2\text{-}1)$$

Backgrounds were measured by extending the calculated width on either end of the scan by 25%. A fixed vertical detector aperture (4 mm) and a variable horizontal aperture (3 + tan θ) were used. Every reflection was subjected to a prescan at a rate of 8°/min. Reflections with $I/\sigma(I) < 2$ for this prescan were rejected as weak, and those for which $I/\sigma(I) > 10$ were accepted immediately. Reflections not falling into these two categories were rescanned at speeds ranging from 0.67 to 8°/min for up to 120 s in an attempt to increase $I/\sigma(I)$ to 10. Three reflections were measured every 3600 s of exposure time in order to monitor crystal decay. Crystal alignment was checked using

the same reflections every 250 data points, and, if the scattering vectors deviated by greater than 0.10° from their calculated values at any stage, the unit cell and orientation matrix were recalculated.

The intensity (I) and standard deviation [σ(I)] were calculated using Eqs. 2-2 and 2-3, respectively, where C is the total number of integrated counts, B is the sum of the left and right backgrounds, A is an attenuator factor (either 1 or 14.3), and S is the scan rate.

$$I = AS(C-2B) \tag{2-2}$$

$$\sigma(I) = AS(C + 4B)^{1/2} \tag{2-3}$$

Observed structure factors and their standard deviations were calculated using Eqs. 2-4 and 2-5, respectively, where Lp is a Lorentz-polarization correction term and p = 0.04. No correction was made for extinction.

$$F_o = (I/Lp)^{1/2} \tag{2-4}$$

$$\sigma(F_o) = [\{\sigma(I)^2 + (pI)^2\}]^{1/2}/Lp \tag{2.5}$$

All computations were carried out on a DEC VAXStation 3100/76. Calculations, except where noted, were performed using the MolEN crystallographic software package.[122] The structures were solved using direct methods (MULTAN,[123] SIR,[124] or SHELXS-86[125] and difference Fourier maps. After refinement of the entire model with isotropic thermal parameters, a Fourier absorption correction (DIFABS)[126] was applied. The extent of conversion of certain atoms to have anisotropic thermal parameters was dependent upon the quality and number of data. Hydrogen atoms were generated and allowed to ride on the appropriate carbon [$U(H) = 1.3U_{eq}(C)$]. The function minimized

during refinement was $\Sigma w(|F_o|- |F_c|)^2$ where the weight, $w = [(\sigma F_o)^2 -0.04F_o^2]^{1/2}$.

The results of the final refinement are reported in terms of three parameters: (1) $R = (\Sigma(|F_o|- |F_c|)/\Sigma(|F_o|)$, (2) $Rw = [w\Sigma(|F_o|- |F_c|)^2/w\Sigma(|F_o|)^2]^{1/2}$ and (3) goodness-of-fit (GOF) = $[\Sigma w(|F_o|- |F_c|)^2]$ / (number of reflections - number of least-squares parameters).

Crystallgraphic diagrams were drawn with the aid of ORTEP-II[127]. Scattering factors and corrections for the real and imaginary components of anomalous dispersion were taken from reference 121.

CHAPTER 3

ALUMINUM COMPLEXES OF AMINO ACIDS

3-1. Introduction

The amino acids to be studied are shown in Figure 3-1. As discussed above, these may be divided into two groups: Those that contain coordinating sides chains (figure 3-1b) and those that do not (Figure 3-1a). A large part of the studies reported herein were carried out using the latter category (in order to derive data concerning the binding mode of the carboxylate and amine groups) and only representative examples of the former were investigated.

The primary synthetic approach involved the addition of amino acids to solutions of "reactive" aluminum compounds that contain aluminum-carbon or aluminum-halide bonds. Not only do these reactions take advantage of thermodynamics (the aluminum-oxygen bond being far stronger than that to either carbon or halide)[128] but they may be performed in solvents that do not interact with aluminum to the same extent as water.

3-2. Reactions with Aluminum Halides

In a typical procedure, the amino acid was ground to a fine powder and dried *in vacuo* overnight at a temperature of 80 °C. A solution of AlX_3 in methanol, was further diluted (50 mL), cooled to -77 °C and then transferred to a Schlenk flask containing a

slurry of the amino acid in methanol (*ca.* 50 mL). The mixture was stirred for 24 hours, with gradual warming to room temperature.

The clear, colorless solution was then dried to a powder, which was dissolved in pyridine in order to complex any HCl that may have formed during the course of the reaction (*vide infra*). This solution was evaporated to dryness and the powder was washed with CH_2Cl_2 and filtered. The residue was dissolved in methanol and filtered. Throughout the studies, the methanol fraction was the one shown to contain the aluminum species.

Spectral data are listed in Tables 3-1 (for reactions with aluminum iodide) and 3-2 (for reactions with aluminum chloride). The compounds fall into three general categories:

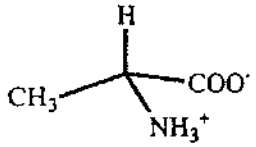
i) a species that gives rise to ^{13}C peaks of *ca.* 173 - 174, upfield peaks in the ^{27}Al NMR, and containing $\Delta\nu$(C=O) values of *ca.* 100 to 170;

ii) a similar species that gives rise to ^{13}C peaks of *ca.* 175 - 179;

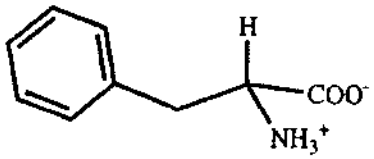
iii) and a third group (of coordinating amino acids) whose infrared spectrum contains an additional strong peak at *ca.* 1730 cm^{-1}.

Assignment of these structures was aided by the results of one repetition of the 3:1 reaction with alanine that was adventitiously performed in base-bath-washed glassware that had been incompletely neutralized. The reaction proceeded in the usual fashion, and the isolated yellow product gave the expected spectroscopic results. After several weeks, however, large yellow crystals of **1** were isolated from methanol.[129,130]

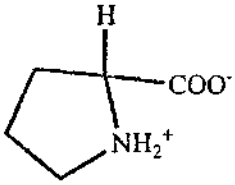
Crystal and data collection parameters and bond lengths and angles are listed in Tables 3-3 and 3-4, respectively. The structure consists of an octanuclear aluminum



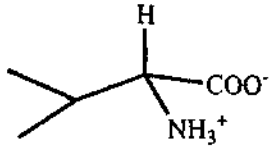
ALANINE



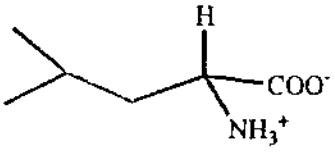
PHENYLALANINE



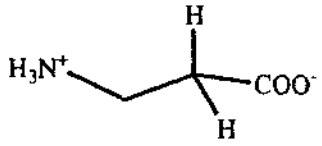
PROLINE



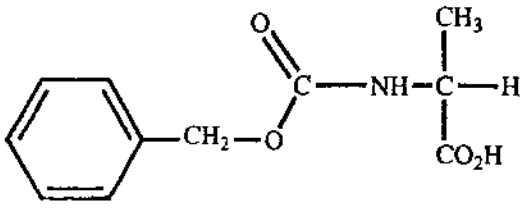
VALINE



LEUCINE

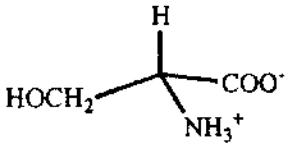


β-ALANINE

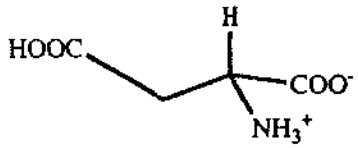


CBZ-ALANINE

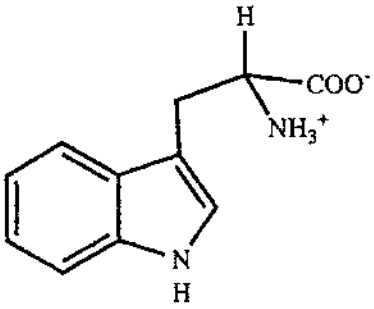
Figure 3-1a. Non-coordinating amino acids utilized in this work.



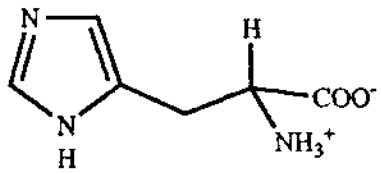
SERINE



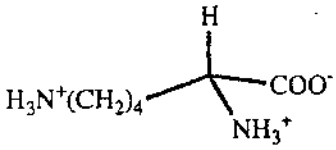
ASPARTIC ACID



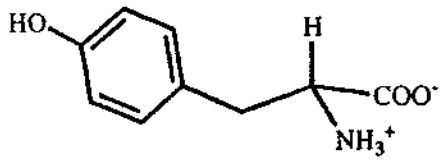
TRYPTOPHAN



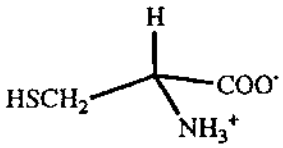
HISTIDINE



LYSINE



TYROSINE



CYSTEINE

Figure 3-1b. Coordinating amino acids utilized in this work.

Table 3-1. Reactions between Amino Acids and AlI_3

Amino Acid	Amino Acid:AlI_3 stoichiometry	^{27}Al NMR ppm	^{13}C NMR 160 - 185 ppm	Infrared Data 1400 - 1800 cm^{-1}
alanine	6:1	4	173.1	1480, 1636
alanine	4:1	3	173.8, 177.5	NA
alanine	3:1	2	172.5	1478, 1632
β-alanine	3:1	4	173.9, 179.0	1467, 1603
cbz-alanine	3:1	*ca.* 5	173.1	1527, 1603, 1720
phenylalanine	6:1	18	172.6, 178.8	1497, 1599
phenylalanine	1:2	8	175.4	1454, 1631
proline	3:1	13	172.8, 176.2	1462, 1632
serine	6:1	16	171.8	1474, 1635
serine	3:1	55	169.0	1479, 1738
aspartic acid	3:1	10	171.9, 169.0	1468, 1656, 1725
aspartic acid	2:1	3	172.7, 171.4, 170.3 169.3	1479, 1737

Table 3-2. Reactions between Amino Acids and $AlCl_3$

Amino Acid	Amino Acid:$AlCl_3$ stoichiometry	^{27}Al NMR ppm	^{13}C NMR 160 - 185 ppm	Infrared Data 1400 - 1800 cm^{-1}
alanine	6:1	7	173, 178	1481, 1646
alanine	3:1	4	172.5, 178	1505, 1649
alanine	1:1	10	172.4, 177.4	1484, 1632
alanine	1:2	10	172.9, 177.1	1481, 1639
β-alanine	3:1	5	173.9, 179	1471, 1607
cbz-alanine	3:1	*ca.* 5	175.5	1529, 1643, 1720
phenylalanine	6:1	19	173.5	1498, 1638
phenylalanine	3:1	20	173.7	1497, 1597
phenylalanine	1:2	16	176.9	1495, 1637
proline	3:1	13	171.1, 173.2, 177.1	1470, 1648
valine	3:1	22	173.7	NA
leucine	3:1	22	172.4	NA
serine	3:1	13	176.0	1500, 1615
serine	1:1	3	177.3	1478, 1639
tyrosine	1:1	11	177.9	1463, 1629
tryptophan	3:1	21	171.8	NA
tryptophan	1:2	5	175.5	1461, 1632
lysine	1:1	11	178.5, 175.1	1472, 1632
aspartic acid	6:1	13	171.2, 173.0	1485, 1639, 1732
aspartic acid	3:1	13	169.7, 170.5	1485, 1732
aspartic acid	1:2	3	173.1, 176.2	1466, 1643

Table 3-3. Crystal and Solution Data for $[Al_8(\mu\text{-ala})_{16}(\mu\text{-OH})_8]\cdot 14\ I^- \cdot 2\ OH^- \cdot 7\ H_2O$ (**1**)

Formula	$C_{48}H_{136}Al_8I_{14}N_{16}O_{49}$
Crystal size (mm)	0.28 x 0.32 x 0.33
Molecular Mass	3714.21
Crystal System	tetragonal
Space Group	I4 bar
Unit cell:	
a (Å)	18.867(2)
c (Å)	20.069(2)
V ($Å^3$)	7145(1)
Z	2
D_c (g/cm^3)	1.726
μ (cm^{-1})	31.16
2θ range	2 - 44
No. data collected	4369
No. unique data	2267
R'_{int}	0.028
No. observed data ($I > 3\sigma(I)$)	1769
R	0.076
R_w	0.087
GOF	2.05
maximum residual electron density	1.34
maximum shift/e.s.d.	<0.01

Table 3-4. Important Bond Lengths (Å) and Angles (°) for $[Al_8(\mu\text{-ala})_{16}(\mu\text{-OH})_8] \cdot 14\ I^- \cdot 2\ OH^- \cdot 7\ H_2O$ (**1**)

Atoms	Length	Atoms	Length
Al1 - O1	1.83(2)	Al1 - O2	1.84(2)
Al1 - O11	1.88(2)	Al1 - O21	1.93(2)
Al1 - O31	1.92(2)	Al1 - O41	1.90(2)
Al2 - O1	1.83(2)	Al2 - O2′	1.84(2)
Al2 - O12	1.88(2)	Al2 - O22	1.97(2)
Al2 - O32	1.94(2)	Al2 - O42	1.88(2)
O11 - C11	1.25(4)	O12 - C11′	1.28(4)
O21 - C21	1.27(3)	O22 - C21	1.18(3)
O31 - C31	1.27(4)	O32 - C31′	1.19(4)
O41 - C41	1.13(4)	O42 - C41	1.30(4)
N13 - C12	1.44(5)	N23 - C22	1.49(4)
N33 - C32	1.53(5)	N43 - C42	1.44(6)
C11 - C12	1.52(5)	C12 - C13	1.52(6)
C21 - C22	1.52(5)	C22 - C23	1.48(5)
C31 - C32	1.51(5)	C32 - C33	1.60(6)
C41 - C42	1.59(4)	C42 - C43	1.27(7)

Atoms	Angle	Atoms	Angle
O1 Al1 O2	92.8(9)	O1 Al1 O11	91.7(9)
O1 Al1 O21	91.3(9)	O1 Al1 O31	176.0(9)
O1 Al1 O41	92.4(9)	O2 Al1 O11	93.2(9)
O2 Al1 O21	91.2(9)	O2 Al1 O31	90.6(9)
O2 Al1 O41	175(1)	O11 Al1 O21	175(1)
O11 Al1 O31	90(1)	O11 Al1 O41	87.9(9)
O21 Al1 O31	86(1)	O21 Al1 O41	87.5(9)
O31 Al1 O41	84.2(9)	O1 Al2 O2′	93.7(9)
O1 Al2 O12	92(1)	O1 Al2 O22	90.7(9)
O1 Al2 O32	174.7(9)	O1 Al2 O42	92.1(9)
O2′ Al2 O12	93(1)	O2′ Al2 O22	90.3(9)
O2′ Al2 O32	90.4(9)	O2′ Al2 O42	174.2(9)
O12 Al2 O22	175(1)	O12 Al2 O32	91(1)
O12 Al2 O42	87(1)	O22 Al2 O32	85.9(9)
O22 Al2 O42	89.6(9)	O32 Al2 O42	83.8(9)
Al1 O1 Al2	128(1)	Al1 O2 Al2"	126(1)
Al1 O11 C11	134(2)	Al2 O12 C11′	136(2)
Al1 O21 C21	134(2)	Al2 O22 C21	131(2)
Al1 O31 C31	135(2)	Al2 O32 C31′	132(2)
Al1 O41 C41	131(2)	Al2 O42 C41	131(2)

′ (x,y,z) → (y,1-x,z)

" (x,y,z) → (1-y,x,z)

species that possesses crystallographically-imposed four-fold symmetry, that has crystallized with iodide and hydroxide ions, and water molecules. The complexity of the system requires that the structure be considered piece-meal. A view of the aluminum-oxygen core is shown in Figure 3-2. The complex is a hollow, cyclic octamer in which each aluminum bridges to two neighboring metal atoms *via* two alanine and one hydroxide. Thus, the structure contains two expected features; complete coordination by oxygen atoms (in agreement with the ^{27}Al), and the amino acid carboxylate present as a bridging species only (as shown by the infrared). Each set of bridging ligands may be considered to consist of an "up" ligand, a "flat" ligand, and a "down" ligand, with respect to the mean plane of the molecule. In each case, the "flat" ligand is an alanine, with the "up" and "down" alternate between hydroxide and alanine, preserving the four-fold symmetry. Each oxygen in the "flattened alanines" is, therefore, *trans* to an oxo group, while the "up" oxygen of one alanine is *trans* to a "down" alanine oxygen of the adjacent bridging set. The presence of iodide ions in the lattice dominated the scattering, thus the precision of the "light atom" part of the structure is not great. One may note, however, the expected disparity between the aluminum bonds to the hydroxy groups (1.83(2), 1.84(2), 1.83(2) and 1.84(2) Å) compared to the carboxylate oxygens (range from 1.88(2) to 1.97(2) Å).

At the time of solution, this structure was unique among metal carboxylates, being approached in form and aesthetic beauty only by the so-called "Ferris wheel" structure found in the decameric iron (III) $[Fe(OMe)_2(O_2CCH_2Cl)]_{10}$.[51] In 1995, however, the octameric titanium carboxylate complex, $[TiO(O_2CC_6F_5)_2]$, was reported, which is

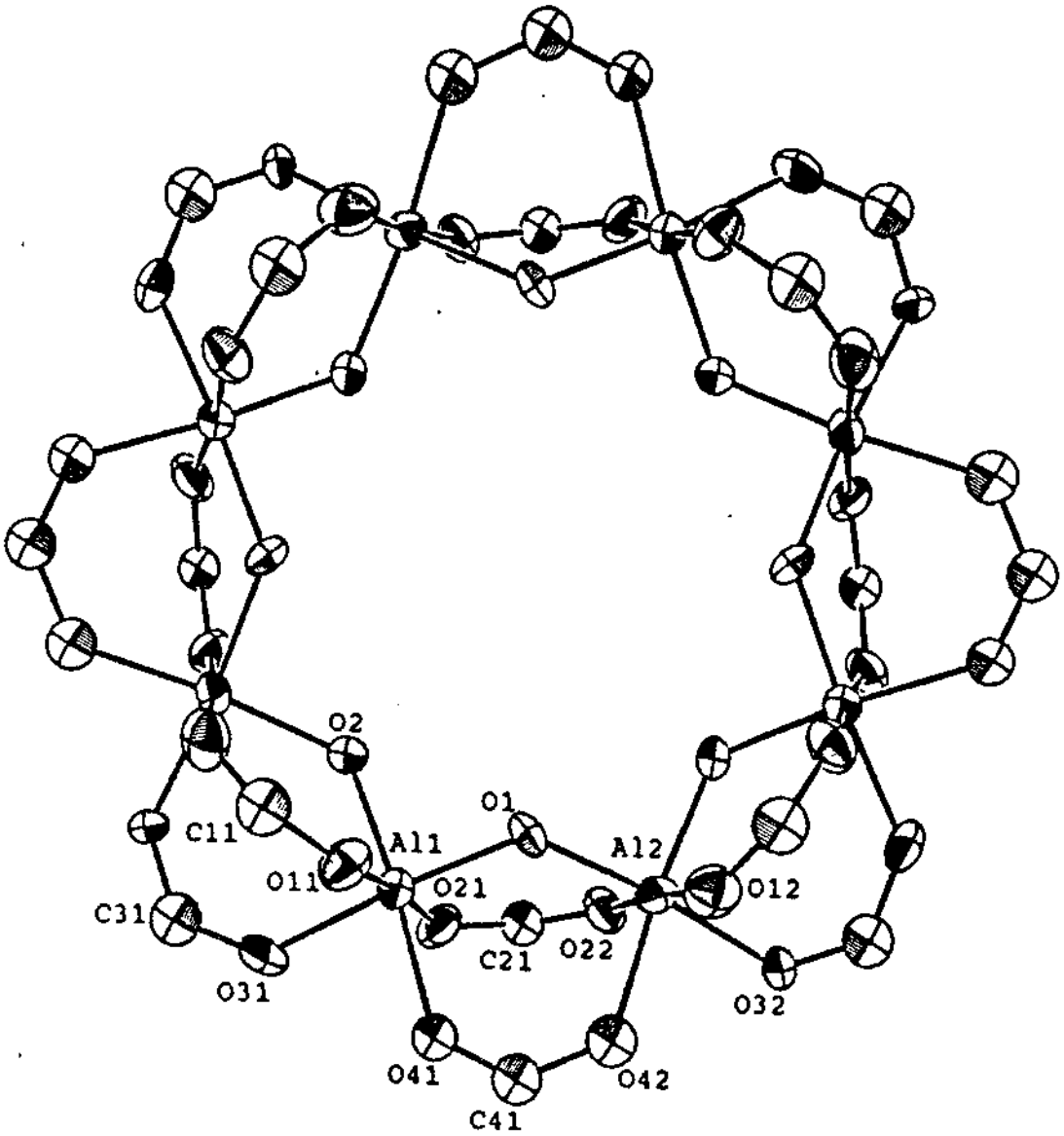


Figure 3-2. Aluminum-Oxygen Framework in $Al_8(\mu\text{-ala})_{16}(\mu\text{-OH})_8$

essentially isostructural as the trifluorobenzoate ligands replace the alanine residues, and there is an oxo bridge instead of a hydroxy bridge (as required by the increase in charge between Al(III) and Ti(IV)).[131]

This latter complex was crystallized with two molecules of toluene inside the cluster, which were held in place by interactions with the pentafluorophenyl substituents. Such inclusion is also present in the aluminum alanine cluster, as shown in Figure 3-3. Two iodide ions (drawn as shaded circles) lie exactly on the four-fold axis and interact with the four hydroxide bridges on either face of the cluster. The distances (3.69(1) Å and 3.68(1) Å) are of a size expected for weak interactions similar to hydrogen-bonding.[132] Of particular note is the I...I separation of 4.21 Å. This is, as would be expected, much greater than the I-I bond length of 2.72 Å in the crystal structure of I_2, but is slightly shorter than twice the ionic radius of I^- (2.2 Å).[133]

The remainder of the lattice consists of several different peaks. There are three other general iodide positions which combine with the two 0.25 occupancy iodides to give a net charge of -14. Three other peaks appeared during the latter stages of refinement, two general and one on a four-fold axis, which refined well as oxygen atoms and had distances from each other and the nitrogen atoms consistent with hydrogen-bonding. All of the iodides interact with the nitrogens of the alanine groups at distances ranging from 3.57 to 3.74 Å and the third interacts with one of the lattice oxygens at a distance of 3.49 Å. Given these distances, and the fact that the complex was crystallized from methanol, it is a reasonable assumption that the amino acid can be considered to be a zwitterion. The aluminum-carboxylate bond distances and geometries are consistent with a formal

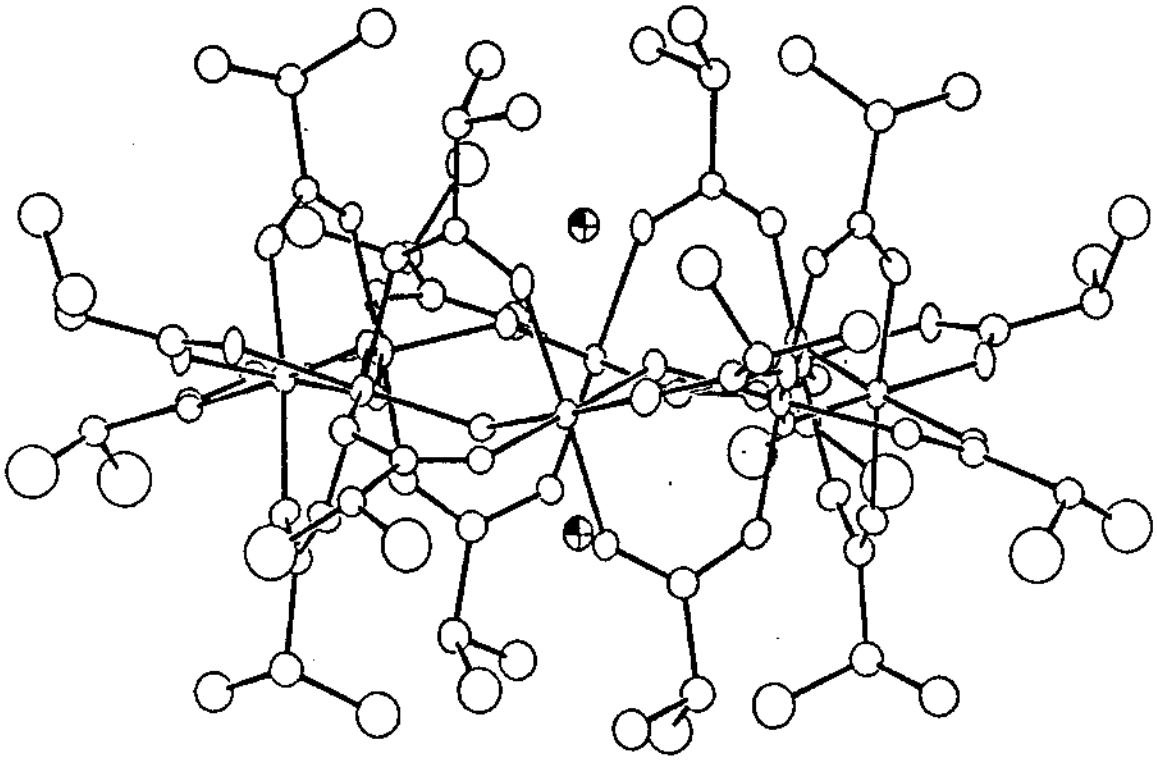


Figure 3-3. Sideways view of $Al_8(\mu\text{-ala})_{16}(\mu\text{-OH})_8$ with the included I^- ions.

charge assignment of -1 to these groups, resulting in a net charge of +16 for the entire complex. It is impossible to distinguish between hydroxide and water in the lattice of a crystal that is so dominated by heavy atom scattering, so it must be assumed that the oxygens species within the lattice represent a composite of two hydroxide ions and seven water molecules.

A view of the unit cell contents is given in Figure 3-4. The cluster packs in a body-centered arrangement, with the various ions and water molecules lying between clusters. There is a considerable amount of "empty space" within the lattice, which could account for the poor crystallinity of the material.

This material could be reproduced by stoichiometric mixing of alanine, AlI_3 and KOH or water in methanol or ethanol. The infrared and ^{13}C NMR shifts were identical to those seen for the reactions between alanine and aluminum halides in methanol, implying the persistence of the basic unit. The ^{27}Al NMR signal, which would be the most sensitive to the nature of bridging groups, appears at 16 ppm.

Given the spectroscopic and structural data for the above complex, therefore, the first, predominant category of product may be readily assigned as an oligomeric aluminum/halide/amino acid cluster of the empirical formula $[Al(\mu\text{-amino acid})_2(\mu\text{-X}]^{2+}$ (**2**). The infrared signals for the complexes are very similar and the ^{13}C carboxylate peak appears between 172 and 174 ppm. The shifts in the ^{27}Al NMR are somewhat varied, although there is a consistent trend. Thus, the iodide complexes appear further upfield than the chloride complexes.

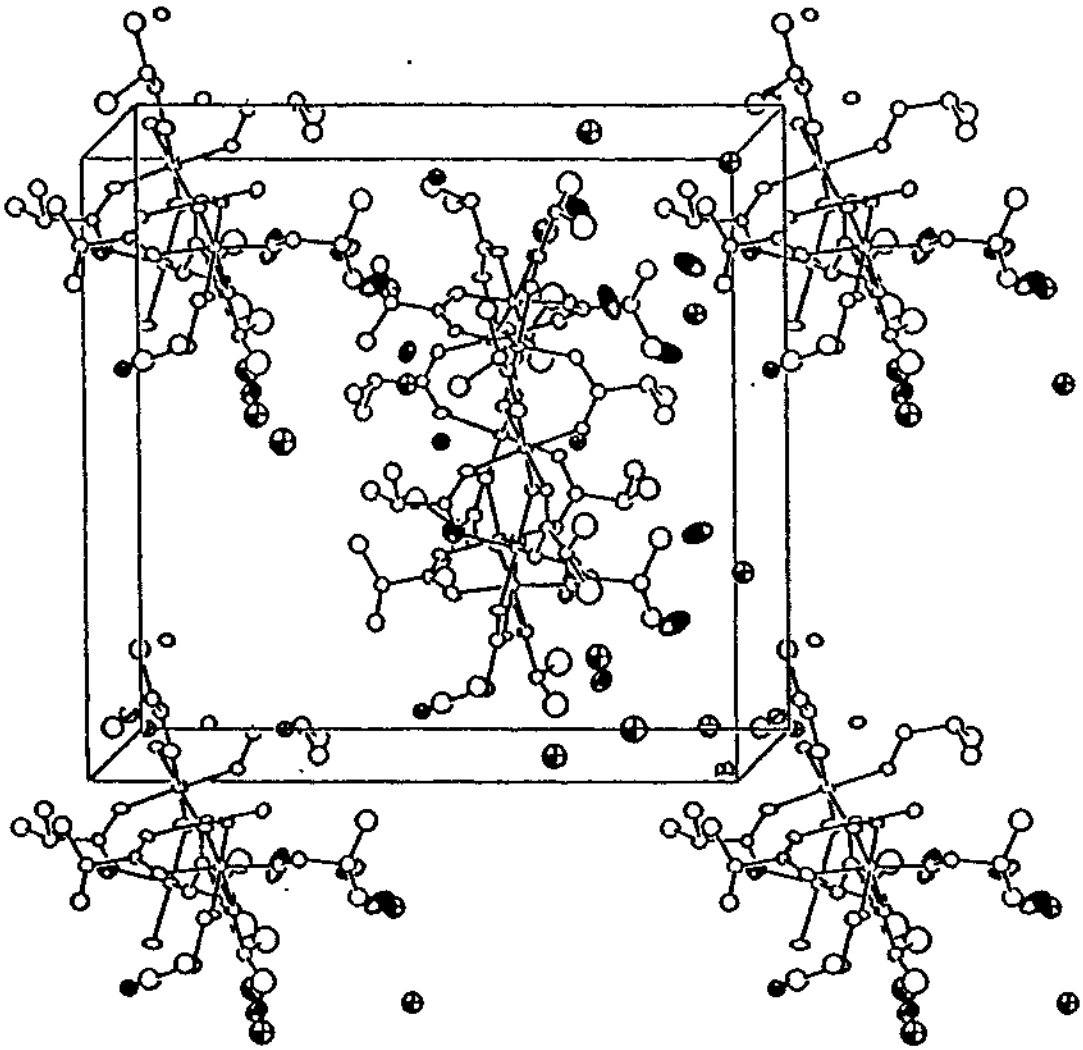
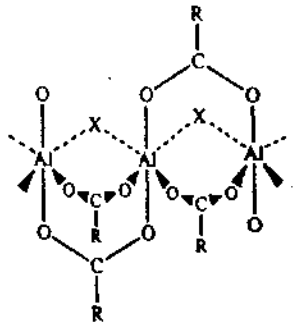


Figure 3-4. Unit cell of $[Al_8(\mu\text{-ala})_{16}(\mu\text{-OH})_8] \cdot 14\ I^- \cdot 2\ OH^- \cdot 7\ H_2O$ (**1**)



2

The appearance of the more downfield peaks in certain of the ^{13}C NMR spectra did not appear to follow any obvious pattern. Given, however, that carboxylate signals are somewhat difficult to observe, it was unclear whether these peaks could have been present in the other spectra. In order to clarify this situation, a series of reactions was performed using phenylalanine ^{13}C-enriched at the carboxylate carbon. This material would lead to both enhanced resolution of the carboxylate peaks in the ^{13}C NMR (which were usually drastically weakened due to negative NOE) as well as isotopically-induced shifts of the carboxylate stretches in the infrared. Phenylalanine was selected because the benzyl substituent imparts increased solubility in a wide range of solvents.

A typical comparison of spectra is given in Figures 3-5 and 3-6. It can seen that the signal strength is dramatically enhanced. In addition, where more than one carboxylate-containing fragment is observed, approximate integrations may be performed (*cf.* Chapter 2), enabling a comparison of abundance of each species.

The spectral data from reactions between aluminum halides and the enriched phenylalanine are listed in Table 3-5. Three distinct types of carboxylate signals are present, depending upon the stoichiometry. When the amino acid is in excess, the dominant signals arise at *ca.* 173 and 179 ppm. As the ratio of amino acid to aluminum

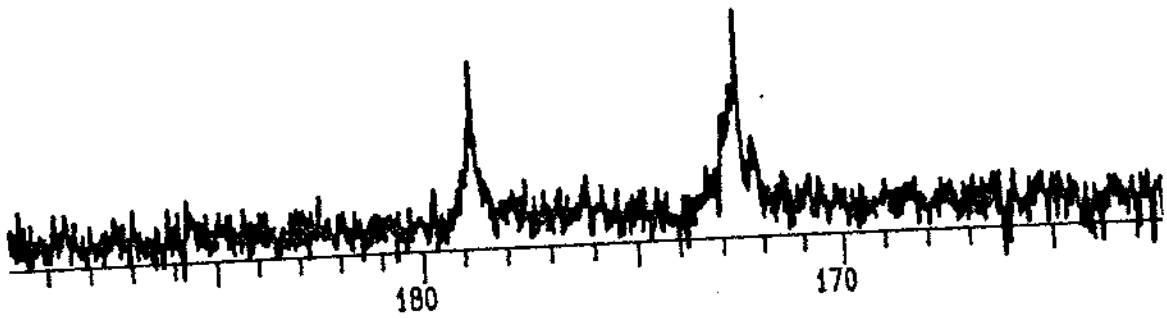


Figure 3-5. ^{13}C NMR of non-enriched phenylalanine + $AlCl_3$ run for 14,735 transients.

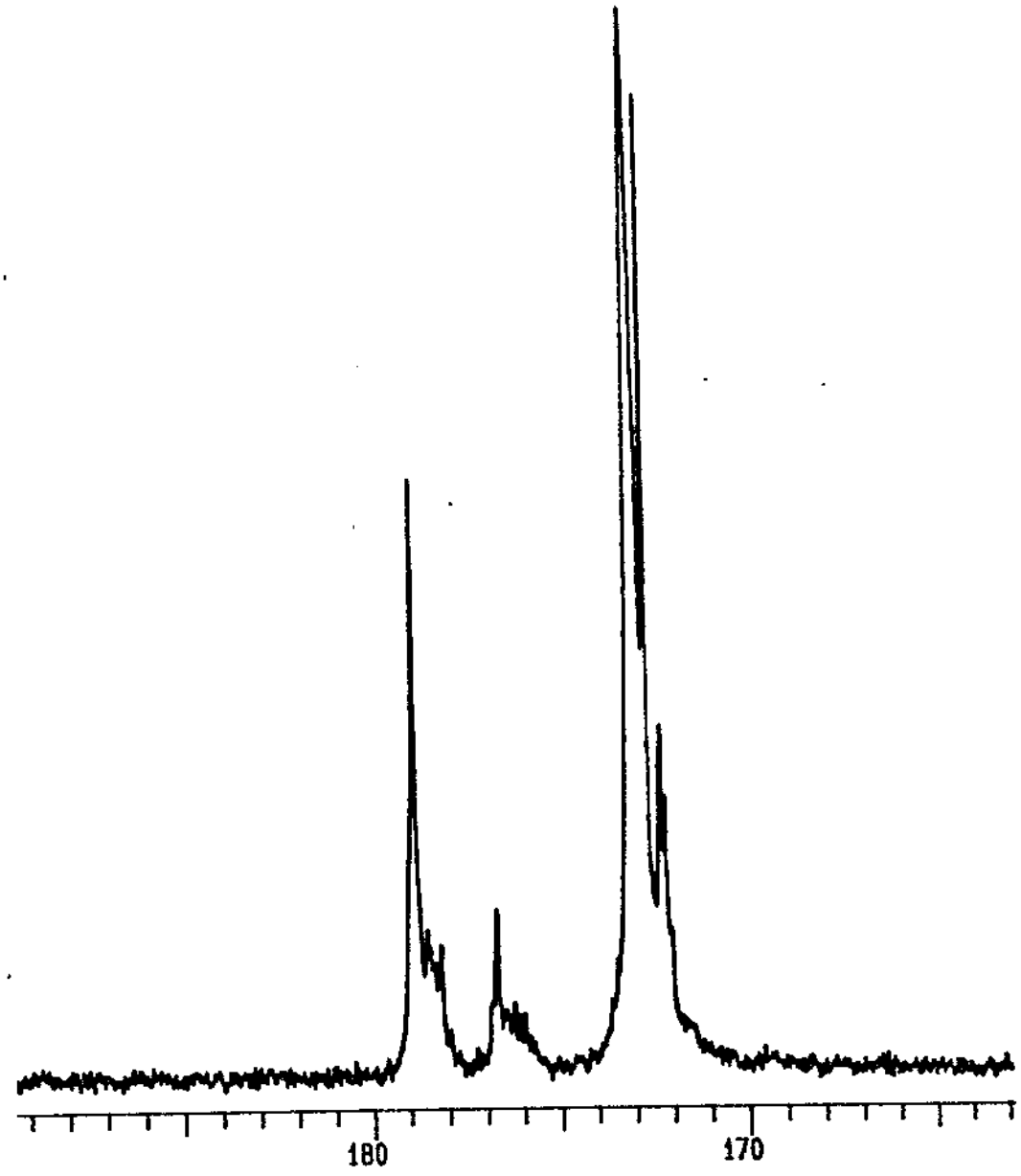


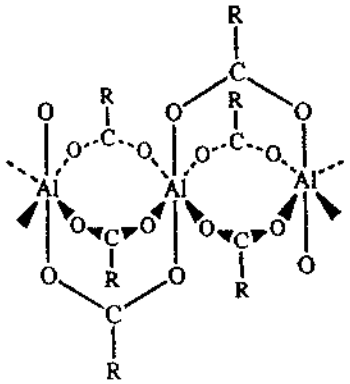
Figure 3-6. ^{13}C NMR of enriched phenylalanine + $AlCl_3$ run for 1,856 transients.

Table 3-5. ^{13}C-enriched Spectral Results

Reaction	^{27}Al δ ppm	^{13}C carboxylate δ ppm (abundance)	infrared (carboxylate) cm^{-1}
6:1 AlI_3	19	178.2, (69%)	1618, 1506
		173.6 (31%)	
5:1 $AlCl_3$	20	178.9, (30%)	1609, 1501
		176.4, (14%)	
		172.4, (56%)	
4:1 $AlCl_3$	20	178.6, (25%)	1618, 1506
		176.6, (15%)	
		172.0, (60%)	
3:1 $AlCl_3$	18	179.4 - 177.6 (20%)	1632, 1484
		177.6 - 175.2 (44%)	
		174.0 - 171.8 (36%)	
1:1 $AlCl_3$	17	176.7 - 176.5 (91%)	1653,1604,1501
		174.7 - 171.9 (9%)	
1:2 $AlCl_3$	16	175.8 (97%)	1606, 1503
1:2 AlI_3	8	176.4 (100%)	1597, 1478

decreases, however, a third signal at *ca.* 176 ppm begins to appear; the downfield signal begins to disappear, and the signals furthest upfield initially increases in intensity and then disappears. These trends agree to a certain extent with the data observed for the non-enriched amino acids. The infrared spectra all indicate the presence of bridging carboxylate species. The signal in the ^{27}Al NMR shifts upfield as the aluminum ratio increases. Although the width of the peaks precludes a detailed analysis, all of them lie in the range expected for octahedral complexes.

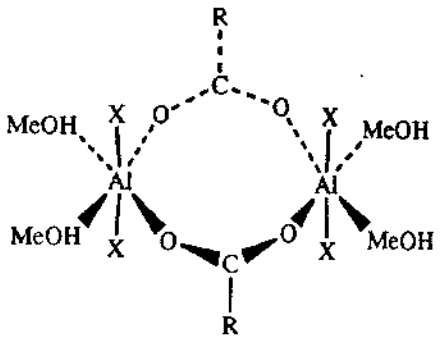
The species that gives rise to the most upfield signals in the ^{13}C NMR may be confidently assigned as the $[Al(phenylalanine)_2X]_n$ species discussed above. The signals furthest downfield in the ^{13}C NMR also give rise to downfield signals in the ^{27}Al NMR, implying a reduction in electron density at the aluminum center. Elemental analysis is consistent with the empirical formula, $Al(amino\ acid)_3X_3$. These species may, therefore, be assigned the structure **3**.



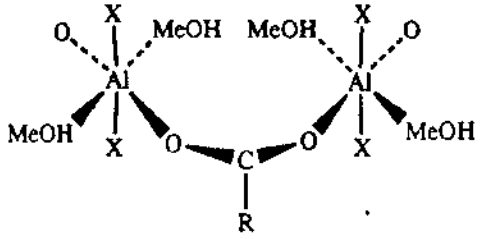
3

The complex that gives rise to the mid-range ^{13}C signals possesses the highest field signals in the ^{27}Al NMR. The elemental analysis is consistent with the formula $AlCl_2(phenylalanine)(MeOH)_2$ (the higher degree of solvation resulting in the higher

NMR shifts). Only two structural types are consistent with this formula and the spectral data (that indicate octahedral aluminum and bridging carboxylate groups): the dimeric species (**4a**) or the oligomeric, single bridged species (**4b**).



4a



4b

The reactions of aluminum halides with the most of amino acids studied, therefore, result in the formation of any of three products **2**, **3**, or **4**, depending upon the stoichiometry. The structural assignments are summarized in Table 3-6.

The spectral data for complexes formed by either aspartic acid or serine lead to the third category described above, in which one or more of the different spectral results are anomalous. That these two amino acids should be capable of different modes of binding is not unexpected, given the data for aluminum complexes with both dicarboxylic acids and hydroxycarboxylic acids that were discussed in the introduction.

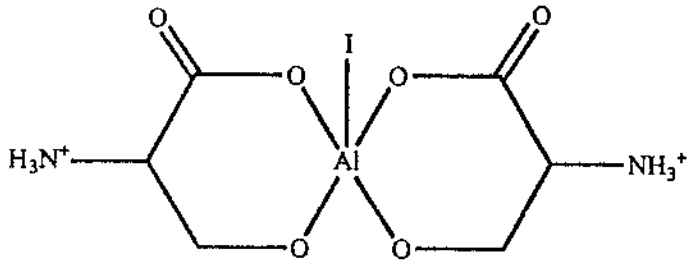
The 3:1 serine:aluminum iodide reaction resulted in a product that was soluble in both THF and CH_3CN, and analysis of this material showed it to differ substantially from that observed in all other cases. A broad signal was observed in the ^{27}Al NMR at *ca.* 50 ppm in THF and *ca.* 70 ppm in CH_3CN, typical of an unsymmetric four- or five-

Table 3-6. Structure Assignments for Reactions of Aluminum Halides with Amino Acids

amino acid	stoichiometry	halide	structure type
alanine	6:1	$AlCl_3$	**2, 3**
alanine	6:1	AlI_3	**2**
alanine	4:1	AlI_3	**2, 3**
alanine	3:1	$AlCl_3$	**2, 3**
alanine	3:1	AlI_3	**2**
alanine	1:1	$AlCl_3$	**2, 4**
alanine	1:2	$AlCl_3$	**2, 4**
β-alanine	3:1	$AlCl_3$	**2, 3**
β-alanine	3:1	AlI_3	**2, 3**
cbz-alanine	3:1	$AlCl_3$	**4**
cbz-alanine	3:1	AlI_3	**2**
phenylalanine	6:1	$AlCl_3$	**2**
phenylalanine	6:1	AlI_3	**2, 3***
phenylalanine	5:1	$AlCl_3$	**2, 3***
phenylalanine	4:1	$AlCl_3$	**2, 3***
phenylalanine	3:1	$AlCl_3$	**2, 3, 4***
phenylalanine	1:1	$AlCl_3$	**2, 4***
phenylalanine	1:2	$AlCl_3$	**4***
phenylalanine	1:2	AlI_3	**4***
proline	3:1	$AlCl_3$	**2, 3**
proline	3:1	$AlCl_3$	**2, 4**
valine	3:1	$AlCl_3$	**2**
leucine	3:1	$AlCl_3$	**2**
tyrosine	1:1	$AlCl_3$	**4**
tryptophan	3:1	$AlCl_3$	**2**
tryptophan	1:2	$AlCl_3$	**3, 4**
lysine	1:1	$AlCl_3$	**2, 3**

*enriched phenylalanine

coordinate species. The infrared contained carboxylate signals at 1738 and 1479 cm^{-1} (1741 and 1480 cm^{-1} in CH_3CN), which should be considered indicative of monodentate coordination. Finally, the ^{13}C NMR contained peaks at 169.0 (168.6), which are further upfield than those observed for bridging, thus adding to the argument for monodentate coordination. In addition, the peaks in the ^{13}C NMR spectrum for the methine and alcohol methylene carbons shift substantially. Crystals of this species were grown from both THF and CH_3CN fractions. These decomposed rapidly at room temperature, so neither elemental analysis nor X-ray data (at UNT) could be obtained. Samples were sent to the University of Texas at Arlington for a low-temperature X-ray structure determination. The unit cell obtained was of a size and symmetry that implied that the structure is a monomeric species containing between 14 and 17 atoms (orthorhmobic, $P2_12_12_1$; Volume = 1165 $Å^3$). Unfortunately, the data set was collected under adverse conditions, and remains unsolved. Nonetheless, there is, therefore, sufficient data available to assign the connectivity as shown in **5** (whether the structure is *cis* or *trans* is undetermined).

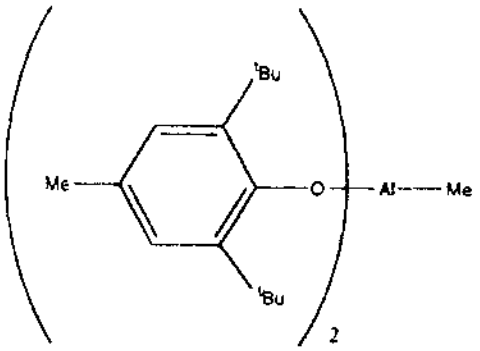


5

The products of reactions with aspartic acid fall into two main categories. In cases where aspartic acid is present in at least an equimolar ratio, peaks indicative of both bridging and monodentate carboxylate groups are present in the infrared. The ^{13}C NMR of the carboxylate region generally contained peaks between 169 and 173 ppm. The ^{27}Al NMR consistently implied one form of octahedral aluminum. When the aluminum reagent was present in excess, however, all traces of monodentate carboxylate groups disappeared in the infrared, downfield shifts were observed for the carboxylate region in the ^{13}C NMR spectrum, and two peaks were observed in the ^{27}Al NMR spectrum. From this one may conclude that, not only does the side chain interact with the aluminum, but that combination of the two groups leads to the availability of multiple coordination modes.

3-3. Reactions with Aluminum Alkyls

The aluminum-carbon bond is highly reactive,[128] thus, while the use of such reagents requires employing extensive inert atmosphere techniques, it is very likely that complexes will be formed. Two aluminum reagents were utilized - trimethylaluminum (TMA) and $(BHT)_2AlMe$ (**6**).[134]



6

Reactions with Trimethylaluminum

A general procedure involved very slow dropwise (70 mL over 5 hours) addition of a dilute (0.01 M) solution of TMA to a slurry of dried amino acid[135] in toluene, THF or ether placed in a dry-ice/isopropyl alcohol bath. This would usually result in effervescence, indicating that reaction had occurred. Variations of this method, involving the use of higher temperatures or more concentrated TMA led to the formation of intractable precipitates or gels, indicating the formation of either aluminum hydroxide or methalumoxane.[136] The product from the low temperature studies usually consisted of a mixture of several species, and structural characterization proved to be impossible.

Reactions with $(BHT)_2AlMe$

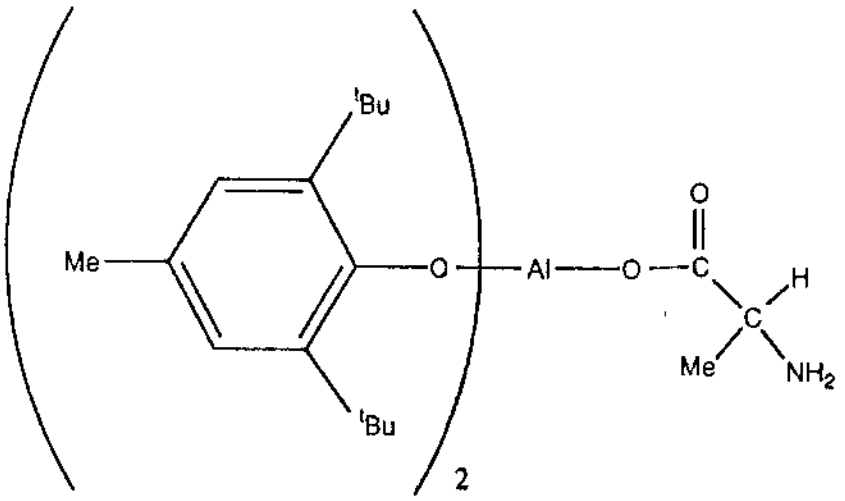
It became apparent that TMA was too reactive to enable the isolation of single, characterizable products. In order to overcome this difficulty, the bulky aluminum aryloxide, $(BHT)_2AlMe$ (**6**) was utilized as the aluminum source. Not only does this species contain fewer reactive sites, but the combination of the steric bulk of the aryloxide ligands together with their strong π-donor ability should decrease the inherent reactivity of aluminum center. Spectroscopic data for reactions with amino acids and **6** (in one case, $(BHT)_2AlH$ was used for solubility reasons) are listed in Table 3-7.

In all three cases, the single product isolated gives rise to a high-field peak in the ^{27}Al NMR, and signals in both the infrared and ^{13}C NMR that correspond to monodentate carboxylate binding.[89] Ordinarily, one would expect the ^{27}Al NMR signals to be indicative of a five- or six-coordinate aluminum center - which is unlikely to be

Table 3-7. Reactions between Amino Acids and $(BHT)_2AlX$

Amino Acid	^{27}Al NMR ppm	^{13}C NMR 160 - 185 ppm	Infrared Data 1400 - 1800 cm^{-1}
X = Me			
alanine	25.7	169.0	1460, 1736
tryptophan	22	172.2	1422, 1658
X = H			
tryptophan	21	NA	1432, 1666

the case given the bulk of the BHT species. However, the monomeric, three-coordinate $(BHT)_3Al$ species gives rise to a signal in the ^{27}Al NMR at a chemical shift of 3.2 ppm,[137] due to the π-donor ability of the BHT ligand. Thus, the general product of these reactions may be assigned the structure shown in **7**.



7

3-4. Summary

Five different complexes of aluminum and amino acids have been synthesized and characterized. Reaction between aluminum halides and amino acids that do not contain either a carboxylate or a hydroxy group in the side chain produce complexes of the general formula, $[Al(\text{amino acid})_n(\text{halide}_{(3-n)})]_m$. The most prevalent form of this form of complex is where n = 2, and an example of this in which the halide is replaced by a hydroxide ligand has been structurally characterized. The complex for which n = 3 may be obtained by employing a large excess of amino acid, and that for which n = 1 may be obtained by employing either equimolar conditions or an excess of aluminum halide.

Reactions of aluminum halides with amino acids that contain either a carboxylate or hydroxy-containing side chain may result in complexes in which the side-chain is also bound. These proved impossible to characterize fully in the case of aspartic acid. For serine, however, a complex in which the amino acid binds in a chelating fashion through both the carboxylate and hydroxy groups was isolated.

It was possible to form complexes when utilizing aluminum alkyls as the metal source. However, these complexes could only be isolated when the reactivity of the species was controlled by the presence of bulky groups. In these cases, the monomeric $R_2Al(\text{amino acid})$ complexes were obtained.

3-5. Experimental

Alanine + AlI_3 (6:1)

A solution of AlI_3 (95%, 0.16 g, 0.37 mmol) diluted with methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and allowed to warm to ambient temperature overnight. After stirring for 24 h at room temperature, the solution was evaporated to a powder under vacuum producing a dark, almost black solid. This was washed with benzene, ether, CH_2Cl_2, THF, CH_3CN, ethanol and methanol.

IR (cm^{-1}) (NaCl): 3442 s, 3030 m, 1723 m, 1636 vs, 1480 s, 1414 m, 1376 m, 1352 m, 1300 w, 1202 m, 1117 m, 1071 w, 998 w, 916 w, 845 w, 770 w, 532 s. $^{13}C\{H\}$ NMR (CD_3OD): δ 173.1, 51.2, 16.6. ^{27}Al NMR (CD_3OD, +18 °C): δ 6 $W_{1/2}$ = 2281 Hz. ^{27}Al NMR (CD_3OD, +50 °C): δ 4 $W_{1/2}$ = 1328 Hz.

Alanine + AlI_3 (4:1)

The previous reaction was repeated with AlI_3 (95%, 0.24 g, 0.56 mmol) and alanine (0.20 g; 2.24 mmol) .

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.5, 173.8 (<u>C</u>OO), (54.9, 53.7) (both <u>C</u>HCOO), 51.5 (<u>C</u>HCOO), 16.8 (<u>C</u>H_3CHCOO); ^{27}Al NMR (CD_3OD): δ 3 $W_{1/2}$ = 2334 Hz.

Alanine + AlI_3 (3:1)

The above reaction was repeated with AlI_3 (95%, 0.24 g, 0.56 mmol) and alanine (0.20

g, 2.24 mmol).

IR (cm^{-1}) (NaCl): 1632 vs, 1478 s, 1419 m, 1384 m, 1351 m, 1304 w, 1195 w, 1119 m, 1082 w, 773 w, 670 m , 606 s, 554 m, 490 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 172.5 (<u>C</u>=O), 58.1, 51.5 (<u>C</u>HCOO), 16.7 (<u>C</u>H_3CHCOO). ^{27}Al NMR (CD_3OD): δ 2.

$Al_8(ala)_{16}(OH)_8 \cdot 14\ I^- \cdot 2\ OH^- \cdot 7\ H_2O$

This compound was isolated from the above reaction, with an aliquot layered with heptane. Adventitious introduction of hydroxide ion led to X-ray quality crystals which were mounted under nitrogen in a sealed capillary.

IR (cm^{-1}) (KBr): 3458 s 3409 s, 3014 vs,2965 vs, 1648 vs, 1480 s, 1381 w, 1351 w, 1312 w, 1262 m, 1200 w, 1114 m, 1105 s, 1052 s, 801 s, 636 m, 593 m, 510 w, 419 w, 406 w.

Alanine + AlI_3+KOH (2:1:1)

A solution of AlI_3 (95%, 0.46 g, 1.13 mmol) diluted with methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C. The reaction mixture was allowed to stir overnight and was then added to a Schlenk containing KOH (63 mg, 1.12 mmol) which had been previously dried under vacuum at -80 °C. The reaction mixture was refluxed overnight and then dried to a powder. This was washed successively with ether, CH_2Cl_2, THF, CH_3CN, acetone and ethanol.

IR (cm^{-1}) (NaCl): 3494 s, 3394 vs, 3147vs, 3065 vs, 2959 vs, 2905 vs, 1637 vs, 1480 s, 1379 w, 1350 w, 1309 w, 1198 w, 1171 w, 1117 w, 992 w, 935 w, 850 w, 770 w, 741

w, 477 s. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 175.6, 173.3, 50.4, 15.9. ^{27}Al NMR (CD_3OD): δ 16.

Alanine + AlI_3+ H_2O (2:1:1)

A solution of AlI_3 (95%, 0.46g, 1.13 mmol) diluted with methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C. The reaction mixture was allowed to stir overnight and then deionized water (1 mL, 2.78 M, 2.78 mL) in methanol was added *via* syringe to the reaction mixture. This was refluxed overnight and then dried to a powder. This was washed successively with ether, CH_2Cl_2, THF, CH_3CN, and methanol.

IR (cm^{-1}) (NaCl): 3479 s, 3394 s, 3144 s, 3065 vs, 3004 vs, 2958 vs, 2908 vs, 1637 s, 1473 s, 1380 m, 1350 m, 1310 w, 1198 w, 1117 m, 1072 w, 992 w, 849 w, 770 m. Crystals of x-ray quality were mounted from this fraction. The X-ray data revealed that it was the octameric structure.

β-*alanine + AlI_3*

AlI_3 (0.1 g, 75 mg) was dissolved in methanol (*ca* 50 mL) and added to a slurry of b–alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and gradually warmed to room temperature overnight. The solvent was removed and the yellow powder was washed with THF, CH_3CN and ethnanol.

IR (cm^{-1}) (NaCl): 1603 vs, 1467 vs, 1412 w, 1400 w, 1386 w, 1335 w, 1088 w, 1049 w, 945 w, 838 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 179.0, 173.9, 36.6, 34.6, 32.0. ^{27}Al NMR

(CD_3OD): δ 4 $W_{1/2}$ = 746 Hz.

Cbz-alanine + AlI_3 (3:1)

AlI_3 (95 %, 0.32 g, 0.75 mmol) in THF (60 mL) was added to a solution of cbz-alanine (0.50 g, 2.23 mmol, previously dried under vacuum at 50 °C overnight) at -77 °C and allowed to warm to ambient temperature overnight. The reaction mixture was stirred at ambient temperature for 24 h after which time the reaction mixture was filtered by frit filter and reduced in volume.

IR (cm^{-1}) (NaCl): 1720 vs, 1603 w, 1527 m, 1455 m, 1378 w, 1341 w, 1297 w, 1218 m, 1177 w, 1114 w, 1072 m, 1004 w, 978 w, 838 w, 740 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 173.1, 170.4 (COO), 158.0 (Cbz-COO), 68.7 ($PhCH_2$), 60.5, 51.2 (both CHCOO), 33.9, 17.4 (CH_3CHCOO). ^{27}Al NMR (CD_3OD): δ 5.

Phenylalanine + AlI_3 (6:1)

AlI_3 (95%, 0.22 g, 0.50 mmol) was dissolved in methanol (70 mL) and added as a partially dissolved brown mixture to a slurry of phenylalanine (0.50 g, 3.01 mmol) at -77 °C. The temperature of the reaction mixture was kept at this temperature for an additional 3 h after the initial mixing of the reagents and then allowed to warm gradually to ambient temperature. The brown solution was then allowed to stir for a further 24 h at ambient temperature, after which time the solvent was removed by evaporation under vacuum. The brown powder was then immersed in pyridine for 3 h which was then removed by evaporation and the residual powder then washed with CH_2Cl_2. After

filtration, the residue was dissolved in methanol and filtered by frit method.

IR (cm^{-1}) (KBr): 3433 w, 3064 s, 3029 s, 2963 s, 2924 s, 1599 vs, 1497 s, 1456 m, 1403 s, 1360 m, 1338 m, 1317 m, 1211 w, 1149 w, 1077 w, 1034 w, 922 w, 854 w, 813 w, 745 m, 708 m, 708 s, 667 w, 599 w, 524 m, 487 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 178.8, (176.1), 172.6 (all $\underline{C}OO$), 136.6, 130.4, 130.0, 128.8 (all Ph), 57.0 ($\underline{C}HCOO$), (39.4) 37.8 ($\underline{C}H_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 18, $W_{1/2}$ = 542.0 Hz.

Phenylalanine + AlI_3 (1:2)

AlI_3 (95%, 1.04 g, 2.42 mmol) was partially dissolved in THF (100 mL) and added as a dark brown slurry to a slurry of phenylalanine (0.20 g, 1.26 mmol) in THF (50 mL) at -77°C. The reaction mixture was kept at this temperature for 3h and then allowed to warm to room temperature overnight. After stirring for 24 h, the THF was removed and the residual powder washed successively with ether, CH_2Cl_2, and THF, in which all the remaining powder dissolved.

IR (cm^{-1}) (NaCl): 3435 vs, 2960 vs, 1631 vs, 1500 m, 1454 vs, 1394 w, 1354 w, 1215 w, 1174 w, 1131 w, 1079 m, 959 w, 921 w, 758 w, 698 w, 612 w. $^{13}C\{^1H\}$ NMR ($\underline{C}DCl_3$ external lock solvent): δ 176.0 to 175.4 br (all $\underline{C}OO$), 135.2, 130.5, 130.1, 128.9, 61.7, 57.7 (both $\underline{C}HCOO$), 36.6 ($CH_2\underline{C}HCOO$), 30.9, 8.2 ^{27}Al NMR (THF): δ 36 $W_{1/2}$ > 5000 Hz, 8 $W_{1/2}$ = 590.9 Hz.

Phenylalanine + AlI_3 + H_2O (2:1:1)

AlI_3 (95%, 0.65 g, 1.51 mmol) was partially dissolved in THF (100 mL) and added as

a dark brown slurry to a slurry of phenylalanine (0.50 g, 3.02 mmol) in THF (50 mL) at -77 °C. The reaction mixture was kept at this temperature for 3h and then allowed to warm to room temperature overnight. After stirring for 24 h, deionized water (1.1 mL, 1.38 M, 1.50 mL) in methanol was added by syringe to the reaction mixture. This was refluxed overnight and then dried to a powder. This was washed successively with ether, CH_2Cl_2, THF, CH_3CN, and methanol.

IR (cm^{-1}) (KBr): 3444 s, 3387 s, 3049 vs, 3000 vs, 2887 vs, 1637 vs, 1497 vs, 1495 vs, 1408 s, 1345 m, 1278 w, 1239 w, 1211 w, 1132 w, 1132 w, 1082 w, 920 w, 749 w, 701 m, 654 w, 599 w, 522 w, 487 w, 479 w, 426 w. $^{13}C\{^1H\}$ NMR (CD3OD): δ 175.1, 171.5 (both $\underline{C}OO$), 134.8, 129.4, 128.7, 127.6 (all Ph-C), 56.0 ($\underline{C}HCOO$), 36.4 ($\underline{C}H_2CHCOO$) ^{27}Al NMR (CD_3OD): δ 6 $W_{1/2}$ = 2397 Hz.

Proline + AlI_3 (3:1)

A mixture of AlI_3 (95 %, 0.66 g, 1.54 mmol) in methanol (100 mL) was added to a slurry of proline (0.50 g, 4.76 mmol) in methanol (60 mL) at -77°C and allowed to warm to ambient temperature overnight. The solvent was removed by evaporation under vaccuum after stirring the reaction mixture for 24 h and the brown powder was washed successively with CH_3CN and ethanol.

IR (cm^{-1}) (NaCl): 3410 s, 3310 s, 2690 vs, 1632 vs, 1462 s. $^{13}C\{^1H\}$ NMR (CD_3CN): δ 176.2, 172.8 (both $\underline{C}OO$), 45.7, 28.3, 22.7, ^{27}Al NMR (CD_3CN): 13 $W_{1/2}$ = 1650 Hz.

Proline + AlI_3 + KOH (2:1:1)

A slurry of AlI_3 (95%, 0.38 g, 0.89 mmol) in methanol (100 mL) was added to a slurry of proline (0.20 g, 1.73 mmol) in methanol (50 mL) at -77°C and allowed to warm to ambient temperature overnight. After stirring for 24 h, the reaction mixture was transfered to a Schlenk containing KOH (0.05g, 0.89 mmol) and the mixture was refluxed for 24 h. The solvent was then removed and the brown powder was washed with CH_3CN; the remaining solid was dissolved in methanol.

IR (cm^{-1}) (NaCl): 3426 s, 2997 vs, 2746 s, 1736 s, 1638 s, 15737 m, 1461 m, 1418 m, 1372 m, 1332 m, 1254 m, 1168 m, 1080 w, 1044 w, 989w, 945 w, 867 w, 817 w, 782 w, 746 w, 676 m. ^{27}Al NMR (CD_3CN): 101 $W_{1/2} > 10^5$.

Proline + AlI_3 + H_2O (2:1 :1)

The previous reaction was repeated using H_2O (2.40 mL, 0.02 M, 48.0 mmol) for KOH.

IR (cm^{-1}) (NaCl): 3426 s, 2997 vs, 2746 s, 1736 s, 1638 s, 15737 m, 1461 m, 1418 m, 1372 m, 1332 m, 1254 m, 1168 m, 1080 w, 1044 w, 989w, 945 w, 867 w, 817 w, 782 w, 746 w, 676 m. ^{27}Al NMR (CD_3CN): 101 $W_{1/2} > 10^5$.

Valine + AlI_3 + H_2O (2:1:1)

The reaction was followed as described for proline except using $AlCl_3$ (0.92 g, 2.14 mmol), valine (0.50 g, 4.27 mmol) and H_2O (1.6 mL, 1.38 mM, 2.22 mmol).

IR (cm^{-1}) (NaCl): 3452 s, 2970 s, 1637 vs, 1505 s, 1386 m, 1115 m. ^{27}Al NMR (CD_3OD): δ 16 $W_{1/2}$ = 536.6 Hz.

Serine + AlI_3 (excess serine)

AlI_3 (95 %, 0.33 g, 0.77 mmol) in methanol (60 mL) was added as a partially dissolved brown mixture to a slurry of serine (0.50 g, 4.76 mmol) in methanol (60 mL) at -77 °C and allowed to warm to ambient temperature overnight. After stirring at room temperature for 24 h, the solvent was removed and the yellow powder was immersed in pyridine for 2 h which was subsequently removed by evaporation. The solid was washed with CH_2Cl_2 and after filtration, the residual solid was dissolved in methanol.

IR (cm^{-1}) (NaCl): 3358 vs, 3052 vs, 3007 vs, 1635 vs, 1474 vs, 1040 m, 952 w.

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 169.8 (COO), 60.2 (CH_2CHCOO), 55.8 (CH_2CHCOO). ^{27}Al (CD_3OD, 18 °C): δ 14 $W_{1/2}$ = 1678 Hz; ^{27}Al NMR (CD_3OD, 50 °C): δ 16 $W_{1/2}$ = 1532 Hz.

Serine + AlI_3 (3:1)

AlI_3 (95 %, 0.66 g, 1.54 mmol) in methanol (70 mL) was added to a slurry of serine (0.50 g, 4.76 mmol) in methanol (60 mL) at -77 °C and allowed to warm to ambient temperature overnight. The brown colored solution that formed was allowed to stir at room temperature and was then dried to a brown powder. This was washed successively with THF, CH_3CN and ethanol. Temperature dependant crystals grew from both the THF and CH_3CN fractions and X-ray quality crystals from the latter fraction were mounted at -80 °C and studied by X-ray crystallography.

THF fraction

IR (cm^{-1}) (NaCl): 3353 s, 3127 vs, 3051 vs, 3004 vs, 2982 vs, 1738 vs, 1579 m, 1479

s, 1397 w, 1295 m, 1262 m, 1248 m, 1128 w, 1075 w, 1046 w, 1014 m, 960 w, 899 w, 817 w, 766 w, 743 w, 705 w. $^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 169.0 (COO), 59.5 (CH_2CHCOO), 55.0 (CH_2CHCOO). ^{27}Al NMR (THF): δ *ca.* 55 $W_{1/2}$ > 5000 Hz.

CH_3CN fraction

IR (cm^{-1}) (NaCl): 3393 s, 3356 s, 3112 vs, 3021 vs, 2914 vs, 1741 vs, 1578 m, 1480 s, 1342 w, 1228 m, 1117 m, 1071 m, 1044 m, 1012 m, 962 w, 895 w, 816 w, 764 w, 708m. $^{13}C\{^{1}H\}$ NMR (CD_3CN): δ 169.8, 168.6 (both COO), 59.6 (CH_2CHCOO), 55.9 (CH_2CHCOO). ^{27}Al NMR (CD_3CN): δ *ca.* 70 $W_{1/2} > 10^5$ Hz.

Serine + AlI_3 + KOH (2:1:1)

AlI_3 (95%, 1.02 g, 2.38 mmol) in methanol (60 mL) was added as a partially dissolved mixture to a slurry of serine (0.50 g, 4.76 mmol) in methanol (60 mL) at -77 °C and allowed to warm gradually overnight to ambient temperature. After stirring at room temperature for 24 h, the brown solution was transfered to a Schlenk containing KOH (0.14 g, 2.50 mmol) and the mixture was refluxed for a further 24 h. The solvent was removed by evaporation and the brown powder was washed with CH_3CN, and then dissolved in methanol.

IR (cm^{-1}) (NaCl): 3449 vs, 3104 vs, 3035 vs, 1629 vs, 1477 s, 1382 m, 1348 m, 1236 w, 1132 m, 1078 m, 1058 m, 972 w, 898 w, 767 w, 665 s. ^{27}Al NMR (CD_3OD): δ 2 $W_{1/2}$ = 1747 Hz.

Aspartic acid+ AlI_3 (3:1)

AlI_3 (95 %,0.54 g, 1.26 mmol) in methanol (70 mL) was added as a partially dissolved mixture to a slurry of aspartic acid (0.50 g, 3.76 mmol) in methanol (60 mL) at -77 °C and the reaction mixture was allowed to warm to ambient temperature overnight. After stirring at room temperature for an additional 24 h, the solvent was removed by evaporation under vacuum and the yellowish-brown powder immersed in pyridine for 3 h. This solvent was also removed by evaporation and the powder was washed with CH_2Cl_2 before being dissolved in methanol

CH_3CN fraction

IR (cm^{-1}) (NaCl): 3419 w, 3003 vs 2970 vs 2871 vs, 1731 vs, 1643 vs, 1561 m, 1455 s, 1421 m, 1371 s, 1333 m, 1276 m, 1185 w, 1106 m, 1075 w, 989 w, 912 w, 877 w, 803 w, 747 w, 672 s. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 172.1, 168.6 (both $\underline{C}OO$), 50.7, 49.5 (both $\underline{C}HCOO$), 35.6 ($\underline{C}H_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 20 $W_{1/2} > 10^5$ Hz.

EtOH fraction

IR (cm^{-1}) (NaCl) 3155 vs, 3101 vs, 1725 vs, 1656 vs, 1587 m, 1468 s, 1407 m, 1188 m, 1134 m, 1092 m, 800 m, 776 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 171.9, 169.0 (both $\underline{C}OO$), 51.5, 48.9 (both $\underline{C}HCOO$), 33.2 ($\underline{C}H_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 10 $W_{1/2} > 10^5$ Hz.

Aspartic acid + AlI_3 (2:1)

The previous reaction was repeated except with AlI_3 (95 %, 0.81 g, 1.89 mmol).

IR (cm^{-1}) (NaCl): 3422 m, 3008 vs, 1737 vs, 1591 m, 1479 s, 1438 s, 1384 m, 1254 m,

1220 m, 1139 m 1085 m, 1010 w, 887 w, 833 w, 772 w, 622. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 172.7, 171.4, 170.3, 169.3 (all <u>C</u>OO), (54.3), 54.2 , 53.2, (both <u>C</u>HCOO), 34.7, 34.6 (<u>C</u>H_2CHCOO). ^{27}Al NMR (CD_3OD): δ 3 $W_{1/2}$ = 2039 Hz.

<u>H_2O fraction</u>

$^{13}C\{^1H\}$ NMR (D_2O): δ COO not detectable, 55.8, 53.4, 37.4. ^{27}Al NMR (CD_3OD): δ 9 $W_{1/2} > 10^5$ Hz, -0.1 $W_{1/2}$ = 68.8 Hz.

Aspartic acid + AlI_3 + KOH (2:1:1)

The previous reaction was repeated except that after stirring for 24 h, the reaction mixture was transfered to another Schlenk containing KOH (0.11 g, 1.96 mmol) and refluxed for another 24 h.

IR (cm^{-1}) (NaCl) 3409 vs, 2960 s, 2919 s, 1725 vs, 1625 vs, 1581 m, 1465 m, 1406 m, 1252 m, 1129 w, 1073 w, 1001 w, 884 w, 747 w, 724 w, 705 w, 670 w. $^{13}C\{^1H\}$ (CD_3OD): δ 171.5, 170.1, 169.2 (all <u>C</u>OO), 51.5, 48.9 (both <u>C</u>HCOO), 33.2 (<u>C</u>H_2CHCOO).

Alanine + $AlBr_3$ (3:1)

A solution of $AlBr_3$ (0.20 g, 0.75 mmol) in methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and stirred overnight at room temperature. The solution was dried to powder and this was washed successively by THF, CH_3CN and methanol and the respective fractions collected on filtration.

$^{13}C\{^1H\}$ (CD_3OD): δ 172.4, 51.6 , 16.5 . ^{27}Al NMR (CD_3OD): δ -5. $W_{1/2}$ = 1623 Hz.

Serine + $AlBr_3$ (3:1)

$AlBr_3$ (0.43 g, 1.61 mmol) in methanol (60 mL) was added to a slurry of serine (0.50 g, 4.76 mmol) in methanol (60 mL) at -77 °C and warmed gradually overnight to ambient temperature. The reaction mixture was then stirred for an additional 24 h after which time the solvent was removed under vacuum. The brown solid was washed successively in THF, CH_3CN, ethanol and methanol.

IR (cm^{-1}) (NaCl): 3379 s, 3043 vs 2964 s, 1614 vs, 1507 m, 1478 m, 1434 m, 1348 w, 1129 w, 1078 w, 1050 m, 971 w, 765 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 174.6, 172.4 (both $\underline{C}OO$), 61.1 ($O\underline{C}H_2CHCOO$) 56.5 ($\underline{C}HCOO$). ^{27}Al NMR (CD3OD): δ 5.

Alanine + $AlCl_3$ (6:1)

Alanine (0.20 g, 2.24 mmol) was ground to a fine powder and dried *in vacuuo* overnight at a temperature of 80 °C. A solution of $AlCl_3$ (12 mL, 0.03 M, 0.36 mmol) in methanol was diluted by a further amount of methanol (50 mL) and then cooled to -77 °C and transfered to the Schlenk containing a slurry of alanine in methanol (*ca.* 50 mL). The mixture was stirred for 24 h, with gradual warming to room temperature. The clear, colorless solution was then dried to a powder which was washed with pyridine. This solution was also dried to a powder which was washed with CH_2Cl_2 and the slurry that formed was filtered by cannula and through a frit and Celite 545® powder. The residue was dissolved in methanol and filtered by frit.

IR (cm^{-1}) (NaCl): 3399 m, 2997 vs, 2931 vs, 2719 m, 1738 w, 1646 vs, 1481 vs, 1377 m, 1348 m, 1377 m, 1348 m, 1299 w, 1119 m, 998 w, 923 w, 852 w, 775 w; ^1H NMR

(CD_3OD, -50°C): δ 7.62 (br, N$\underline{H}_3$), 3.06, (q, C$\underline{H}$COO), 0.62 (d, C$\underline{H}_3$CHCOO). $^{13}C\{^1H\}$ NMR (CD_3OD): *ca.* 178, 173.0 , 50.1, 16.0. ^{27}Al NMR (CD_3OD, +18 °C): δ 7 $W_{1/2}$ = 1453 Hz.

Alanine + $AlCl_3$ (3:1)

A solution of $AlCl_3$ (25 mL, 0.03 M, 0.75 mmol) diluted with methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and the procedure for working up the reaction mixture was as descibed for the previous reaction.

IR (cm^{-1}) (NaCl): 1742 m, 1649 vs, 1601s, 1505 s, 1416 m, 1379 m, 1351 m, 1306 w, 1207 m, 1118 m, 1065 w, 1019 m, 921 w, 847 w, 814 w, 774 w, 668 m, 615 m, 587 s, 511 s, 506 s, 473 vs. NMR: ^1H NMR (CD_3OD, -30°C): δ 7.67 (br, N$\underline{H}_3$), 3.35 (q, C$\underline{H}$COO), 0.51 (d, C$\underline{H}_3$CHCOO). $^{13}C\{^1H\}$ NMR (CD_3OD): δ 178, 172.5 ($\underline{C}$=O), 51.7 ($\underline{C}$HCOO), 16.4 ($\underline{C}H_3CH$). ^{27}Al NMR (CD_3OD): δ 4 $W_{1/2}$ 1817 Hz.

Alanine + $AlCl_3$ (1:1)

A solution of $AlCl_3$ (0.3 g, 2.24 mmol) in methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and the procedure for working up the reaction mixture was as that descibed previously.

IR (cm^{-1}) (KBr): 3434 s, 3084 s, 2903 s, 1632 vs, 1484 vs, 1443 w, 1385 m, 1350 w, 1265 w, 1201 w, 1114 m, 776 w, 750 w, 668 m, 615 m, 470 w. ^{13}C NMR (CD_3OD, -30°C): 177.4, 172.4, 51.3, 16.1. ^{27}Al NMR (CD_3OD): δ 10 $W_{1/2}$ = 858 Hz.

Alanine + $AlCl_3$ (1:2)

A solution of $AlCl_3$ (0.6 g, 2.24 mmol) in acetonitrile (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in acetonitrile (*ca.* 50 mL) at -77 °C and the mixture was stirred for 24 hours, with gradual warming to room temperature. The clear, colorless solution was then dried to a powder which was washed with pyridine. This solution was also dried to a powder which was washed with ether and the slurry that formed was filtered by cannula and through a frit funnel and Celite 545® powder. The residue was washed in this solution was also dried to a powder and was washed with CH_2Cl_2. The slurry that formed was filtered by cannula and through a frit funnel. The remaining residue was dissolved in acetonitrile and filtered by frit as described above. After analysis, the remaining solution was evaporated to dryness, dissolved in methanol and filtered.

CH_3CN fraction : (^1H NMR (CD_3CN):$^{13}C\{^1H\}$ NMR (CD_3CN): δ 177.1, 172.9, 51.6, 15.2. ^{27}Al NMR (CD_3CN): δ 103.8, $W_{1/2}$ = 11.99 Hz, 0, $W_{1/2}$ = 633 Hz.

CH_3CN fraction in MeOH : IR (cm^{-1}) (NaCl): 3360 m, 3063 vs, 1735 w, 1639 vs, 1481 s, 1446 m, 1383 w, 1355 w, 1306 w, 1208 w, 1120 m, 1008 w, 859 w, 771 w, 670 w. ^1H NMR (CD_3OD): δ $^{13}C\{^1H\}$ (CD_3OD): δ 177.1, 172.9, 51.6, 15.2 . ^{27}Al NMR (CD_3OD): δ 10 $W_{1/2}$ = 918.3 Hz, 2.6 $W_{1/2}$ = 23.53 Hz.

β-*alanine + $AlCl_3$ (3:1)*

$AlCl_3$ (0.1 g, 75 mg) was dissolved in methanol (*ca.* 50 mL) and added to a slurry of β–alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and gradually warmed

to room temperature overnight. A fairly insoluble mass formed which was found to be soluble in methanol only.

IR (cm^{-1}) (NaCl): 1726 m, 1607 vs, 1471 vs, 1402 m, 1338 w, 1233, 1103 w, 997 w, 845 w, 797 w, 623 s. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 179.0, 173.9 (<u>C</u>OO), 36.6 ($CH_2\underline{C}H_2COO$), 34.6 , 32.0 (both $\underline{C}H_2CH_2COO$). ^{27}Al NMR (CD_3OD): δ 5.

Cbz-alanine + $AlCl_3$ (3:1)

$AlCl_3$ (0.10 g, 0.75 mmol) in methanol (60 mL) was added to a solution of cbz-alanine (0.50 g, 2.23 mmol, previously dried under vacuum at 50 °C overnight) at -77 °C and allowed to warm to ambient temperature overnight. The reaction mixture was stirred at ambient temperature for 24 h after which time the reaction mixture was filtered by frit filter and reduced in volume.

IR (cm^{-1}) (NaCl): 3323 vs, 3179 vs, 3120 vs, 3027 vs, 2947 vs, 1720 vs, 1643 s, 1529 s, 1455 m, 1378 w, 1340 m, 1293 m, 1218 s, 1218 s, 1177 m, 1115 m, 1071 s, 982 w, 909 w, 839 s, 778 m, 749 s, 740 s. ^1H NMR (CD_3OD): 10.65 - 9.06 (m), 4.10 (br, s), 2.71 (s), 0.37 (d). $^{13}C\{^1H\}$ NMR (CD_3OD): δ 175.5, 158.7, 67.9, 51.4, (53.0), 18.1. ^{27}Al NMR (CD_3OD): δ 2, 4 to 10 (hump).

Phenylalanine + $AlCl_3$ (6:1)

$AlCl_3$ (0.11 g, 0.83 mmol) in methanol (100 mL) was added dropwise to a slurry of phenylalanine (1.0 g, 6.04 mmol) in methanol (50 mL) at -77 °C over a period of 3 h. The reaction mixture was retained at this temperature for a further 3 h and then allowed

to reach ambient temperature overnight. The solvent was then removed and the residual powder immersed in pyridine for several hours before this slurry was again dried to a powder. This was then washed with CH_2Cl_2 and the solid dissolved in methanol and filtered.

IR (cm^{-1}) (KBr): 3418 m, 3065 vs, 3032 vs, 2967 vs, 2932 vs, 1638 vs, 1609 vs, 1568 vs, 1498 vs, 1457m, 1411 s, 1347 s, 1312 m, 1218 w, 1157 m, 1134, w, 1078 w, 1032 w, 1003 w, 945 w, 852 m, 744 m, 700 s, 682 w, 613 w, 528 m, 476 w. $^{13}C\{^1H\}$ NMR (CD3OD): δ 173.5 (COO), 54.6 (CHCOO), 37.5 (CH_2CHCOO) ^{27}Al NMR (CD_3OD): δ 19, $W_{1/2}$ = 664.8 Hz.

Phenylalanine + $AlCl_3$ (4:1)

$AlCl_3$ (0.20 g, 1.50 mmol) in methanol (100 mL) was added dropwise to a slurry of phenylalanine (1.0 g, 6.04 mmol) in methanol (50 mL) at -77 °C over a period of 3 h. The reaction mixture was then treated as described for the previous reaction.

IR (cm^{-1}) (KBr): 3418 m, 3331 m, 3068 s, 3032 vs, 2926 s, 1653 vs, 1604 s, 1501 s, 1455 m, 1400 m, 1345 m, 1137 m, 1082 m, 751 m, 702 s, 604 w, 479 w. $^{13}C\{^1H\}$ NMR (CD3OD): δ 176.0, 172.1 (both COO), 56.6, 55.4, 54.8 (all CHCOO), 37.4 (CH_2CHCOO).

Phenylalanine + $AlCl_3$ (3:1)

$AlCl_3$ (0.13 g, 0.97 mmol) in methanol (100 mL) was added dropwise to a slurry of phenylalanine (0.50 g, 3.02 mmol) in methanol (50 mL) at -77 °C over a period of 3 h.

The reaction mixture was then treated as described for the previous reaction.

IR (cm^{-1}) (NaCl): 1597 vs, 1497 s, 1455 m, 1407 m, 1338 m, 1135 w, 1080 w, 745 m, 701 m. ^{1}H NMR (CD_3OD): δ $^{13}C\{^{1}H\}$ (CD_3OD): δ 173.7 (COO), 57.6 (CHCOO), 38.3 (CH_2CHCOO). $^{27}Al(CD_3OD)$ δ 20, $W_{1/2}$ 1650.

Phenylalanine + $AlCl_3$ (1:2)

$AlCl_3$ (0.13 g, 0.97 mmol) in THF (100 mL) was added to a slurry of phenylalanine (0.50 g, 3.02 mmol) in THF (50 mL) at -77 °C. The reaction mixture was allowed to reach ambient temperature overnight after initially maintaining the temperature of the reaction at -77 °C for 3 h. The reaction was stirred for 24 h after which time the solvent was removed, the powder was washed with CH_2Cl_2 and the residue was re-dissolved in THF.

IR (cm^{-1}) (NaCl): 3063 vs, 1653 vs, 1637 vs, 1495 s, 1469 s, 1357 m, 1278 w, 1122 w, 1082 w, 845 s, 749 s, 700 s. $^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 176.9, (176), 175.0, 174.0) (all COO), 135.9, 134.9, 133.5, 132.6 (all Ph), 56.3 (CHCOO), 37.0 (CH_2CHCOO). ^{27}Al NMR ($CDCl_3$ external lock solvent): δ 90, $W_{1/2}$ = 1294 Hz, 17, $W_{1/2}$ = 705 Hz.

Proline + $AlCl_3$ (3:1)

$AlCl_3$ (0.19 g, 4.34 mmol) dissolved in methanol (60 mL) was added to a slurry of proline (0.50 g, 4.34 mmol) in methanol (60 mL) at -77°C. The reaction was allowed to reach ambient temperature overnight and then stirred for an additional 24 h. The solvent

was removed under vacuum, immersed in pyridine before again evaporating the solvent to dryness under vacuum, and washed with CH_2Cl_2 and the residue re-dissolved in methanol.

IR (cm^{-1}) (NaCl): 3572 s, 3556 s, 2790 s, 1731 m, 1648 vs, 1571 m, 1470 s, 1414 m, 1393 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.1, 173.2, 171.1, 62.3, 60.4, 51.5, 47.0 , 29.4, 24.4. ^{27}Al NMR (CD_3OD): δ 13. $W_{1/2}$ = 1788 Hz

Valine + $AlCl_3$ (3:1)

$AlCl_3$ (0.19, 1.42 mmol) in methanol (60mL) was added dropwise to a slurry of valine (0.50 g, 4.27 mmol) in methanol (50 mL) at -77 °C and after warming to ambient temperature, was stirred for a further 24 h. The solvent was evaporated under vacuum and the solid was immersed in pyridine for 5 h. The solvent was again removed under vacuum an the powder was washed with CH_2Cl_2 and the residual powder was redissolved in methanol.

$^{13}C\{^1H\}$ NMR (CD_3OD): 173.7 (<u>C</u>OO), 61.8 (<u>C</u>HCOO), 30.7 (<u>C</u>HCHCOO), 19.2, 17.7 (both ((<u>C</u>H_3)$_2$CHCH) ^{27}Al NMR (CD_3OD): δ 22 $W_{1/2}$ = 1025 Hz.

Leucine + $AlCl_3$ (3:1)

$AlCl_3$ (0.14 g, 1.04 mmol) in methanol (60mL) was added dropwise to -77 °C to a slurry of leucine (0.50 g, 3.81 mmol) in methanol (60 mL) and allowed to warm to ambient temperature overnight. The reaction was stirred for 24 h and then dried to a powder which was immersed in pyridine for 5 h. The solution was evaporated under vacuum to a

powder which was washed with CH_2Cl_2 and the powder re-dissolved in methanol. $^{13}C\{^1H\}$ (CD3OD): δ 177 (minor), 172.4 (both $\underline{C}OO$), 54.4 (minor), 52.5 ($\underline{C}HCOO$), 40.7 ($\underline{C}H_2CHCOO$), 25.5 ($(CH_3)_2\underline{C}HCH_2$), 22.4 ($(\underline{C}H_3)_2CHCH_2$). ^{27}Al (CD3OD): δ 22 $W_{1/2}$ = 950 Hz.

Serine + $AlCl_3$ (3:1)

$AlCl_3$ (0.21 g, 1.57 mmol) in methanol (60 mL) was added to a slurry of serine (0.50 g, 4.76 mmol) in methanol at -77 °C and allowed to warm to ambient temperature overnight. The reaction was stirred at ambient temperature for 24 h after which time the solvent was removed under vacuum and the solution immersed in pyridine for 5 h. This solution was also dried to a powder and was washed with CH_2Cl_2. The filtrate was dissolved in methanol.

IR (cm^{-1}) (NaCl): 1738 m, 1615 vs, 1500 vs, 1432 m, 1372 m, 1342 m, 1226 m, 1050 m. ^1H NMR (CD_3OD, -60 °C): 8.00 (br, NH_3^+), 3.48 (br,$CH_2C\underline{H}COO$), 3.33 (br, $C\underline{H}_2CHCOO$ $^{13}C\{^1H\}$ NMR (CD_3OD): δ 176.0 (br), 170.1, 169.3, (all $\underline{C}OO$), 60 .7 (major), 57.4 (minor) (both $O\underline{C}H_2CHCOO$), 56.0 (major), 53.7 (minor) (both $OCH_2\underline{C}HCOO$). ^{27}Al NMR (CD_3OD): δ 13 $W_{1/2} > 10^5$.

Serine + $AlCl_3$ (1:1)

$AlCl_3$ (0.64 g, 4.80 mmol) in CH_3CN (60 mL) was added dropwise to a slurry of serine (0.50 g, 4.76 mmol) in CH_3CN (40 mL) at -50 °C and warmed gradually to ambient temperature overnight. After the reaction had stirred at room temperature for 24 h, the

solvent was removed and the slightly brown powder was washed successively with ether, CH_2Cl_2 and CH_3CN before being dissolved in methanol.

IR (cm^{-1}) (NaCl): 3379 s, 3109 vs, 1741 m, 1639 s, 1478 s, 1346 m, 1264 w, 1236 w, 1140 w, 1120 m, 1087 w, 1054 w, 1036 m, 975 w, 860 w, 805 w, 670 m. ^1H NMR (CD_3OD): 9.62 (br, OH), 8.31 (br, NH_3), 3.83 (d, C$\underline{H}_2$CHCOO), 3.41 (t, $CH_2C\underline{H}COO$). $^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.3,173.0, 170.5 (all $\underline{C}OO$), 61.1, 57.8 (both O$\underline{C}H_2CHCOO$), 56.5, 52.9 ($OCH_2\underline{C}HCOO$). ^{27}Al NMR (CD_3OD): δ 2 $W_{1/2}$ = 1408 Hz.

Tyrosine + $AlCl_3$ (3:1)

$AlCl_3$ (0.13 g, 0.97 mmol) in methanol (70 mL) was added as a partially dissolved mixture to a slurry of tyrosine (0.50 g, 2.76 mmol) in methanol (60 mL) at -77 °C and the reaction mixture was allowed to warm to ambient temperature overnight. After stirring at room temperature for an additional 24 h, the solvent was removed by evaporation under vacuum and the yellowish-brown powder immersed in pyridine for 3 h. This solvent was also removed by evaporation and the powder was washed with CH_2Cl_2 with residual solid remaining after filtration dissolved in methanol The reaction mixture continuously precipitated hence obtaining spectral data was not possible.

Tyrosine + $AlCl_3$ (1:1)

$AlCl_3$ (0.37 g, 2.78 mmol) was added to a slurry of tyrosine (0.50 g, 2.76 mmol) in CH_3CN at -30 °C and the reaction mixture was gradually allowed to warm to ambient temperature. After stirring at room temperature for 24 h, the colorless solution was dried

to a powder and washed with CH_2Cl_2, and the washings were discarded. The off-white powder was then dissolved in CH_3CN, in which the solubility had seemingly diminshed, and after filtration, the residual solid was dissolved in methanol. Yield 0.73 g.

CH_3CN fraction

$^{13}C\{^1H\}$ NMR (CD_3CN): δ 176.2, 175.6 to 173.8 (br), (both C̲OO), 157.5, 131.8, 125.7, 116.4 (all Ph), 56.8, 55.3, 51.6 (minor) (all C̲HCOO), 35.3 (CH_2CHCOO). ^{27}Al NMR (CD_3CN): δ 103.8 $W_{1/2}$ = 27.29 Hz; 2 $W_{1/2}$ = 557.4 Hz.

MeOH fraction

IR (cm^{-1}) (KBr): 3378 br, m, 3098 br, vs, 1629 vs, 1516s, 1463 s, 1355 m, 1233 m, 1175 w, 1108 w, 1079 w, 835 w, 613 w. ^{1}H NMR (CD_3OD): δ 9.9 (br, H̲OPh), 8.11 (NH_3^+), 6.93 - 6.45 (mult, Ph), 4.10 (mult., CHCOO), 3.04 (CH_2CHCOO). $^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.9, (175.9), (172.7), 171.2 (all C̲OO), 158.2, 131.6, 125.8, 116.8 (all Ph - C), 57.0, 55.2 (both C̲HCOO), 36.4 (C̲H_2CHCOO). ^{27}Al NMR (CD_3OD): δ 14 $W_{1/2}$ = 1486 Hz; 11 $W_{1/2}$ = 59.90 Hz; 9 $W_{1/2}$ = 375.3 Hz; 4 $W_{1/2}$ = 982.7 Hz; 3 $W_{1/2}$ = 296.0 Hz.

Tryptophan + $AlCl_3$ (3:1)

$AlCl_3$ (0.11 g, 0.82 mmol) in methanol (60 mL) was added dropwise to a slurry of tryptophan (0.50 g, 2.45 mmol) in methanol (50 mL) at -77 °C and after allowing to warm to ambient temperature, was stirred at room temperature for 24 h. The solvent was removed through evaporation under vacuum and the residual powder immersed in pyridine for 5 h. This solvent was also removed by evaporation and the powder was washed with

CH_2Cl_2. The residue after filtration was redissolved in methanol.

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 171.8 (<u>C</u>OO), 138.4, 128.3 (Ph), 125.6 (HN<u>C</u>H indole ring), 122.9, 120.3, 119.0, 112.6 (all Ph), 107.9 (HNCH<u>C</u>(Ph)CH_2), 57.0, 54.6 (both <u>C</u>HCOO), 27.6 (<u>C</u>H_2CHCOO). ^{27}Al NMR (CD_3OD): δ 21.

Tryptophan + $AlCl_3$ (1:2)

$AlCl_3$ (0.26 g, 1.95 mmol) in THF (60 mL) was added dropwise to tryptophan (0.20 g, 0.98 mmol) in THF (50mL) at -77 °C and maintained at this temperature for 3 h after the addition of the $AlCl_3$. The reaction was allowed to warm to ambient temperature overnight and stirred for a further 24 h. The solution was dried to a powder under vacuum and washed in CH_2Cl_2 and filtered. The residual solid was washed in THF and the residue was dissolved and filtered in CH_3CN. The latter fraction was also dissolved in MeOH to observe the effect of the different solvent.

<u>THF fraction</u>

IR (cm^{-1}) (NaCl): 3042 vs, 1642 m, 1473 m, 1459 m, 1358 m, 1240 w, 1103 w, 1050 w, 1015 w, 849 m, 744 m, 596 m, 528 m. $^{13}C\{^1H\}$ NMR (THF): δ 177.2, 175.7, 174.4 (all <u>C</u>OO), 137.2, 128.0 (Ph), 127.0 (HN<u>C</u>H indole ring), 122.0, 121.7, 118.1, 111.7 (all Ph), 108.0 (HNCH<u>C</u>(Ph)CH_2), 56.1, 54.1 (both <u>C</u>HCOO), 27.0 (<u>C</u>H_2CHCOO). ^{27}Al NMR (THF): δ 102 $W_{1/2}$ = 1347 Hz, 69 $W_{1/2}$ = $>10^5$ Hz, 7 $W_{1/2}$ =1408 Hz

<u>CH_3CN fraction</u>

IR (cm^{-1}) (NaCl): 3439 s, 2970 vs, 2931 vs, 1726 m, 1632 s, 1486 m, 1461 s, 1345 m, 1269 m, 1130 m, 1097 m, 1077 m, 746 m, 670 vs $^{13}C\{^1H\}$ NMR (THF): δ 175.4

(COO), 137.4, 128.0 (Ph), 127.0 (HNCH indole ring), 122.0, 121.7, 118.1, 111.7 (all Ph), 108.0 (HNCHC(Ph)CH_2), 55.1 (both CHCOO), 25.8 (CH_2CHCOO). ^{27}Al NMR (CD_3CN): δ 104.0, $W_{1/2}$ = 15.75 Hz, 5 $W_{1/2}$ =1290 Hz

MeOH fraction

IR (cm^{-1}) (NaCl): 3405 br, 3187 vs, 3070 vs, br, 2918 vs, br, 1623 vs, 1460 vs, 1353 m, 1341 m, 1241 w, 1116 m, 1033 m, 942 w, 747 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.7 to 176.1 (all COO), 137.4, 128.0 (Ph), 127.0 (HNCH indole ring), 122.0, 121.7, 118.1, 111.7 (all Ph), 108.0 (HNCHC(Ph)CH_2), 56.1 (CHCOO), 27.5 (CH_2CHCOO). ^{27}Al NMR (CD_3OD): δ 0 $W_{1/2}$ = 2328 Hz.

Histidine+ $AlCl_3$ (1:1)

The reaction procedure was as that described for (1:1) tyrosine/$AlCl_3$, using histidine (0.50g, 3.22 mmol) and $AlCl_3$ (0.43 g, 3.22 mmol).

IR (cm^{-1}) (KBr): 3340 br, 3000 br, 1627 vs, 1503 m, 1464 s, 1350 w, 1145 w, 1085 w, 992 w, 925 w, 811 w, 676 w, 625 m. ^{1}H NMR (CD_3OD): δ 8.82 (NCHNCHCCH$_2$), 7.51 (NCHNCHCCH$_2$), 4.23 (NCHNCHCCH$_2$CH), 3.28 (NCHNCHCCH$_2$).$^{13}C\{^1H\}$ NMR (CD_3OD): δ 177.6, 175.0, 170.1 (all COO), 136.1 (NCHNCHCCH$_2$), 129.0 (NCHNCHCCH$_2$CH), 119.8 (NCHNCHCCH$_2$), 54.7, 52.9 (both CHCOO), 26.8 (CH_2CHCOO). ^{27}Al NMR (CD_3OD): δ 11 $W_{1/2}$ = 1341 Hz.

Cysteine + $AlCl_3$ (3:1)

$AlCl_3$ (0.14 g, 1.05 mmol) in methanol (70 mL) was added as a partially dissolved

mixture to a slurry of histidine (0.50 g, 3.22 mmol) in methanol (60 mL) at -77 °C and the reaction mixture was allowed to warm to ambient temperature overnight. After stirring at room temperature for an additional 24 h, the solvent was removed by evaporation under vacuum and the yellowish-brown powder immersed in pyridine for 3 h. This solvent was also removed by evaporation and the powder was washed with CH_2Cl_2, with residual solid remaining after filtration dissolved in methanol The reaction mixture continuously precipitated, hence obtaining good spectral data was not possible. IR (cm^{-1}) (NaCl): 1644 vs, 1501 s, 1423 s. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 170.0 (COO), 55.8 (CHCOO), 25.1 (SCH_2CHCOO). ^{27}Al NMR (CD_3OD): δ 20 $W_{1/2}$ = 1549 Hz.

Cysteine + $AlCl_3$ (1:1)

The reaction procedure was as that described for tyrosine + $AlCl_3$, using cysteine (0.50 g,4.13 mmol)) and $AlCl_3$ (0.55 g, 4.12 mmol).

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 178.4, 173.1, 169.6, 57.2, 55.6, 25.3. ^{27}Al NMR (CD_3OD): δ 14 $W_{1/2}$ = 1486 Hz; 11 $W_{1/2}$ = 48.16 Hz; 9 $W_{1/2}$ = 737.1 Hz; 8 $W_{1/2}$ = 1017 Hz; 3 $W_{1/2}$ = 916.8 Hz; 3 $W_{1/2}$ = 296.04 Hz;

Lysine + $AlCl_3$ (1:1)

The reaction procedure was as that described for tyrosine + $AlCl_3$, using lysine (0.97 g, 6.64 mmol) and $AlCl_3$ (0.88 g, 6.60 mmol).

IR (cm^{-1}) (KBr): 3420 m, 3126 br, vs, 1632 vs, 1501 m, 1472 s, 1362 w, 1137 w, 1009 w, 808 w, 677 w, 616 w, 426 w. ^1H NMR (CD_3OD): δ 8.52 (NH_3CHCOO), 7.80

($N\underline{H}_3CH_2CH_2$), 4.06 ($C\underline{H}COO$), 3.51 ($NH_3C\underline{H}_2CH_2$), 2.83 ($NH_3CH_2CH_2C\underline{H}_2$), 1.88 ($NH_3CH_2C\underline{H}_2$), 1.59 $C\underline{H}_2CH_2CHCOO$). $^{13}C\{^1H\}$ NMR (CD_3OD): δ 178.5, 177.7, 175.1, 171.6 (all $\underline{C}OO$), 55.3, 53.6 (both $\underline{C}HCOO$), 40.3 ($\underline{C}H_2CH_2CH_2CH_2CHCOO$), 31.2($CH_2CH_2CH_2\underline{C}H_2CHCOO$), 28.0 ($CH_2\underline{C}H_2CH_2CH_2CHCOO$), 23.6 ($CH_2CH_2\underline{C}H_2CH_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 11 $W_{1/2}$ = 73.16 Hz

Aspartic acid + $AlCl_3$ (6:1)

$AlCl_3$ (0.08 g, 0.60 mmol) in methanol (60 mL) was added to a slurry of aspartic acid (0.50 g, 3.76 mmol) in methanol (60 mL) at -77 °C and allowed to warm to ambient temperature overnight. The reaction mixture was stirred at room temperature for 24 h and was then dried under vacuum to a powder which was immersed for 3 h in pyridine. This solvent was then removed and the white powder washed with CH_2Cl_2 and the residual solid dissolved in methanol.

IR (cm^{-1}) (NaCl): 3392 m, 3224 m, 3063 s, 2875 vs, 2794 vs, 2626 s, 2092 w, 1981 w, 1732 vs, 1639 s, 1613 s, 1541 s, 1485 vs, 1400 m, 1331 w, 1246 m, 1195 m, 1058 w, 1002 w, 887 w, 750 vs, 682 vs, 609 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 173.0, 171.2 ($\underline{COO}$), 53.0, 50.7, 49.9(all $\underline{C}HCOO$) , 34.8 ($\underline{C}H_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 13 $W_{1/2}$ = 1384 Hz.

Aspartic acid + $AlCl_3$ (3:1)

The previous reaction was repeated using $AlCl_3$ (0.17 g, 1.28 mmol).

IR (cm^{-1}) (KBr): 3055 s, 2933 vs, 2865 vs, 2797 vs, 2627 vs, 2090 w, 1979 w, 1732 vs,

1636 m, 1618 s, 1540 s, 1485 vs, 1393 w, 1334 w, 1301 w, 1249 m, 1157 w, 1076 w, 1061 w, 1002 w, 880 w, 755 vs, 685 vs, 614 m. ^{1}H NMR (CD_3OD, -60 °C): 7.79 (br, $N\underline{H}_3$), 3.55 (t, $CH_2C\underline{H}COO$), 2.89 (d, $C\underline{H}_2CHCOO$)^{13}C{^{1}H} NMR (CD_3OD): δ 176.2, 173.7, 172.9, 171.6, 170.7, 170.5, , 169.7 ($\underline{C}OO$), 55.8, 53.0 (main), 53.9, 52.0 (all $\underline{C}HCOO$) , 34.7 ($\underline{C}H_2CHCOO$). ^{27}Al NMR (CD_3OD): δ 13 $W_{1/2}$ = 1384 Hz.

Aspartic acid + $AlCl_3$ (1:1)

The previous reaction was repeated with $AlCl_3$ (0.51 g, 3.82 mmol).

IR (cm^{-1}) (NaCl): 3405 m, 3064 vs, 2955 vs, 2866 s, 2649 s, 2083 m, 1736 s, 1636 vs, 1614 vs, 1540 vs, 1485 vs, 1385 w, 1338 w, 1253 w, 1201 w, 1168 w, 1120 w, 1061 w, 1009 w, 932 w, 754 vs, 685 vs, 614 m.

The reaction produced a gel-like material and no NMR data could be obtained.

Aspartic acid + $AlCl_3$ (1:2)

$AlCl_3$ (1.0 g, 7.51 mmol) in THF (60mL) was added to a slurry of aspartic acid (0.50 g, 3.76 mmol) in THF (60 mL) at -77 °C and allowed to warm to ambient temperature overnight. The reaction was stirred at room temperature for 24 h after which time the reaction mixture was filtered and the residual solid dissolved in CH_3CN. The same fraction was also dissolved in methanol to observe changes in speciation.

$\underline{CH_3CN}$ fraction

IR (cm^{-1}) (NaCl): 3419 w, 3003 s 2970 vs 2924 vs 2871 s, 1646 s, 1472 s, 1401 m, 1361

w, 1242 w, 1209 w, 1149 w, 1106 w, 823 m, 672 s. $^{13}C\{^1H\}$ NMR (CD_3CN): δ 179.0, 177.5, 174.6, 170.2 (COO), (73.2, 68.2), 51.6 (CHCOO), 35.6 (CH_2CHCOO). ^{27}Al NMR (CD_3CN): δ 103.7 $W_{1/2}$ = 56.8 Hz, -2 $W_{1/2}$ = 499 Hz.

CH_3OH fraction

IR (cm^{-1}) (KBr): 3402 br, 3127 (br) vs, 1643 vs, 1466 s, 1355 m, 1246 w, 1150 w, 1075 w, 963 w, 857 w, 683 w. $^{13}C\{^1H\}$ NMR (CD_3CN): δ 179.1, 176.2, 173.1 (all COO), 52.3, 51.8, 51.4, 35.6. ^{27}Al NMR (CD_3OD): δ 8 $W_{1/2}$ = 1195 Hz, 2.6 $W_{1/2}$ = 21.1 Hz.

C1-^{13}C - Phenylalanine + $AlCl_3$ (6 (excess):1)

A solution of $AlCl_3$ (2.6 mL, 28.2 mM, 0.073 mmol) in methanol (60 mL) was added dropwise to a slurry of ^{13}C-phenylalanine (0.10 g, 0.60 mmol) in methanol (60 mL) at a temperature of -77 °C over a period of 2 h. The reaction mixture was kept at this temperature for a further 3 h and then warmed to room temperature overnight. After stirring for a further 36 h, the solution was dried to a powder and immmersed in pyridine for 5 h. The solution was again dried to a powder which was dried to a powder and washed with CH_2Cl_2. The residue was dissolved in methanol.

IR (cm^{-1}) (KBr): 3421 m, 3062 vs, 3035 vs 2926 vs, 1605 vs, 1506 s, 1455 m, 1383 m, 1336 m, 1143 w, 1088 w, 1028 w, 853 w, 755 m, 708 m. ^1H NMR (CD_3OD): δ $^{13}C\{^1H\}$ NMR (CD_3OD): δ 178.9, 172.5 (COO). ^{27}Al NMR (CD_3OD): δ 19, $W_{1/2}$ = 646.2 Hz. Anal. Calc: C, 51.6, H, 5.3. Found: C, 52.00, H, 5.01.

C1 -^{13}C - Phenylalanine + $AlCl_3$ (5:1)

The above reaction procedure was repeated except with $AlCl_3$ (4.7 mL, 28.2 mM, 0.132 mmol).

IR (cm^{-1}) (KBr): 3418 s, 3089 s, 3062 s, 3027 vs, 2929 s, 1609 vs, 1501 s, 1461 m, 1387 m, 1335 m, 1137 w, 1087 w, 1040 w, 847 w, 755 m, 706 s, 484 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 178.9 (C00), 176.4 (C00), 172.4 (C00), none. ^{27}Al NMR (CD_3OD): δ 20, $W_{1/2}$ = 490.6 Hz.

C1 -^{13}C - Phenylalanine + $AlCl_3$ (4:1)

The above reaction procedure was repeated except with $AlCl_3$ (4.9 mL, 30 mM, 0.15 mmol).

IR (cm^{-1}) (KBr): 3426 s, 3065 vs, 3035 vs, 2926 vs, 1717 w, 1618 vs, 1506 s, 1392 m, 1220 w, 1165 w, 1084 w, 1037 w, 849 w, 699 m, 669 s, 597 w. ^1H NMR (CD_3OD): δ $^{13}C\{^1H\}$ NMR (CD_3OD, +50°C): δ 178.6, 176.6, 172.0 (all C00), 56.6, 55.4, 54.8 (all CHCOO) ^{27}Al NMR (CD_3OD): δ 20, $W_{1/2}$ = 972 Hz.

C1 -^{13}C - Phenylalanine + $AlCl_3$ (3:1)

The above reaction procedure was repeated except with $AlCl_3$ (2.7 mL, 0.20 mmol).

IR (cm^{-1}) (KBr): 3433 m, 3084 m, 2903 m, 1632 vs, 1484s, 1443 m, 1385 w, 1350 w, 1306 w, 1265 w, 1201 w, 1114 m, 775 w, 750 w, 669 m, 616 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 179.4 to 177.6 (C00); 177.6 to 175.2 (C00); 174.0 to 171.8 (C00). ^{27}Al NMR (CD_3OD): δ 8, $W_{1/2}$ = 1589 Hz.

C1 -^{13}C - Phenylalanine + $AlCl_3$ (1:1)

The above reaction procedure was repeated except with $AlCl_3$ (8.0 mL, 75 mM, 0.60 mmol).

IR (cm^{-1}) (KBr): 3418 m, 3331 m, 3068 s, 3032 vs, 2926 s, 1653 vs, 1604 s, 1501 s, 1455 m, 1400 m, 1343 m, 1137 m, 1082 m, 751 m, 702 s, 604 w, 479 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 176.7 and 176.5, 91.4%; 174.7 to 171.9, 9 %. $^{13}C\{^1H\}$ NMR (d-pyridine): δ 176.3, 100%. ^{27}Al NMR (CD_3OD): δ 17 $W_{1/2}$ = 1594 Hz.

C1 -^{13}C - Phenylalanine + $AlCl_3$ (1:2)

The above reaction procedure was repeated except with $AlCl_3$ (40.0 mL, 30 mM, 1.20 mmol).

IR (cm^{-1}) (KBr): 3421 m, 3062 vs, 2962 vs, 1606 vs, 1503 m, 1434 m, 1344 w, 1291 w, 1157 w, 1085 w, 966 w, 755 m, 709 m, 604 s, 426 w. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 175.8, 96.8 %. ^{27}Al NMR (CD_3OD): δ -2. $W_{1/2}$ = 2321 Hz.

C1 -^{13}C - Phenylalanine + AlI_3 (6:1)

The reaction procedure was the same as that described for the reactions with $AlCl_3$ using AlI_3 (7.30 mL, 10.3 mM, 0.075 mmol) and phenylalanine (75 mg, 0.45 mmol).

IR (cm^{-1}) (KBr): 3440 m, 3032 m, 2929 m, 2228 w, 1724 w, 1605s, 1553 vs, 1498 s, 1455 m, 1391 s, 1331 m, 1310 m, 746 w, 708 m. $^{13}C\{^1H\}$ NMR (C_6D_6): δ 178.8, 173.6. ^{27}Al NMR ($CDCl_3$): δ 20 $W_{1/2}$ = 696.8 Hz.

Cl -^{13}C - Phenylalanine + AlI_3 (1:2)

The above reaction procedure was repeated except with AlI_3 (40.0 mL, 30 mM, 1.20 mmol) and after immersing in pyridine and drying, the powder was washed in ether, CH_2Cl_2 and methanol.

IR (cm^{-1}) (KBr): 3448 m, 3204 vs, 3146 vs, 3092 vs, 3054 vs, 1597 vs, 1530 s, 1478 s, 1460m, 1428 m, 1346 w, 1245 w, 1189 w, 1154 w, 1054 w, 1035 w, 994 w, 956 w, 921 w, 747 m, 703 m, 677 s, 569 m. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 176.4, 100%. ^{27}Al NMR (CD_3OD): δ 8, $W_{1/2} > 10^5$ Hz. Anal. Calc: C, 25.7, H, 4.5 Found: C, 25.6, H, 4.4.

Cl -^{13}C - Phenylalanine + TMA (4:1)

TMA (2.2 mL, 0.05 M, 0.11 mmol) in THF (80 mL) was added dropwise to a slurry of ^{13}C-phenylalanine (75 mg, 0.45 mmol) in THF (60 mL) at -77°C over a period of 3 h. The reaction mixture was maintained at this temperature for an additional 3 h and then allowed to warm to ambient temperature. After stirring at room temperature for another 24 h, the solvent was removed by evaporation and the white powder washed in ether and re- dissolved in THF.

IR (cm^{-1}) (THF, air sensitive cell): 2983 vs, 2871 vs, 2680 w, 2244 w, 2002 w, 1986 w, 1458 w, 1082 vs, 917 s, off scale 500 - 400 cm^{-1}. $^{13}C\{^1H\}$ NMR (d-THF): δ 179.8 to 178.2, 15.7 %, 178.0 to 174, 73.3 %; 173 to 171, 11.5 %. (no others at 167). ^{27}Al NMR (d-THF): δ 14 $W_{1/2}$ = 1070 Hz.

C1 -^{13}C - Phenylalanine + TMA (1:2)

The previous reaction was repeated except with TMA (17.6 mL, 0.05 M, 0.88 mmol). IR (cm^{-1}) (Air sensitive cell, THF): 2983 vs, 2871 vs, 2680 w, 2244 w, 2002 w, 1986 w, 1663 w, 1458 w, 1082 vs, 917 s. $^{13}C\{^1H\}$ NMR (d-THF): δ 66.3 (50 %), 15.7 (50 %). ^{27}Al NMR (d-THF): δ 22 $W_{1/2}$ = 1127 Hz.

Alanine + TMA (1:3) (ether)

TMA (1.7 mL, 10 M, 17 mmol) diluted in ether (*ca.* 60 mL) was added dropwise to a slurry of alanine (0.50 g, 5.61 mmol) in ether (*ca.* 60 mL) at -77 °C over a period of 45 minutes. The reaction mixture was kept at this temperature for several hours after the addition of TMA and then allowed to warm to room temperature overnight. The reaction mixture was filtered by frit filter.

$^{13}C\{^1H\}$ NMR (ether): δ 182.4, 175.3, 53.7, 50.5, 48.1, 19.3, 16.4, -8.7, -9.4, -10.2, (11.4). ^{27}Al NMR (ether): δ 186, 154.

Alanine + excess TMA+ H_2O

The product from the previous reaction was charged with an excess of deionized water over a period of two hours. Great care was taken as this reaction is potentially explosive.

$^{13}C\{H\}$ NMR (D_2O): δ 176.9, 173.5, 171.6, 72.5 57.7, 50.5, 50.0, 27.6, 23.4, 18.0, 17.4, 16.7, 15.0.

Alanine + excess TMA (ether)

TMA (*ca.* 10mL, *ca.* 0.10 mol) was injected at room temperature to a slurry of alanine (1.0 g, 11.2 mmol) and allowed to stir at room temperature. An immediate reaction was observed and the reaction was allowed to subside over a period of 2 hours. The reaction mixture was filtered by frit filter.

IR (cm^{-1}) (Air sensitive cell): 3260 s, 3193 s, 1959 m, 1608 m ,1467 s. $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, external lock solvent): 182.5, 181.9, 175.5 (all $\underline{C}OO$), 58.3, 57.0, 50.6, -9.0. ^{27}Al NMR (ether) δ 187, 175.

Alanine + excess TMA (toluene)

TMA (*ca.* 10 mL, 0.10 mmol) was injected into a slurry of alanine (1 g, 11.2 mmol) in toluene at room temperature and stirred for two hours after which time the alanine had completely reacted.

IR (cm^{-1}) (Air sensitive cell, toluene): 1940, 1872, 1804, 1737, 1209, 1197, 1178, 1157, 1105, 1081. $^{13}C\{^{1}H\}$ NMR (d-toluene): δ 182.4, 175.3, 53.7, 50.5, 48.1, 19.3, 16.4, -8.7, -9.4, -10.2, 11.4. ^{27}Al NMR (toluene) δ 187, 176.

β-*alanine + TMA (1:1)*

TMA (28.0 mL, 0.2 M, 5.60 mmol) in THF was diluted further to *ca* 70 ml with THF and added dropwise to a slurry of b–alanine in THF at -77 °C over a period of 1.5 h. The reaction mixture was kept at this temperature for an additional 5 h and then allowed to warm to room temperature overnight. The product was only slightly soluble in THF.

IR (cm^{-1}) (Air sensitive cell, THF): 3420 vs, 3287 s 3084 s, 2965 s, 1581 s, 1470 m, 1407m, 1337w, 1253 w, 1057 w, 1015 w, 980 w, 889 w, 833m, 701 m, 666 m, 617 m, 428 m.

Alanine + excess TMA + tert-butyl alcohol (toluene)

To the product from the previous reaction was added an excess tert-butyl alcohol (30 mL) which had been previously dried over molecular sieves and distilled under nitrogen.

IR (cm^{-1}) (NaCl): 1653 vs, 1461 m, 1397 s, 1363 m, 1296 m, 1261 w, 1169 m, 1115 m, 1069 m, 1025 m, 934 w, 868 m, 799 w, 869 m, 694 m, 584 m, 517 w, 458 w.

$^{13}C\{^{1}H\}$ NMR (d-toluene): δ 17.4 (only peak detectable). ^{27}Al NMR (d-toluene): δ 23.

Cbz-alanine + TMA (1:1)

TMA (11.2 mL, 0.2 M, 2.24 mmol) in THF (60 mL) was added dropwise to a solution of cbz-alanine (0.50 g, 2.24 mmol) in THF (60 mL) at -77 °C and the reaction mixture was maintained at this temperature for 3 h before being allowed to warm to ambient temperature overnight. After stirring for 24 h, the colorless solution was filtered and reduced in volume. On standing, the solution turned into a gel-like material.

^{1}H NMR ($CDCl_3$): δ 7.24 (m), 4.45 (q), 1.70 (s), 1.25 (d), 0.89 (d). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$): δ 183.3 , 158.4, 155.4, 136.1, 134.5, 131.9, 128.5, 128.3, 70.5, *ca.* 69 (mult.), 68.0, 66.6, 65.9, 54.9, 51.0, 38.7, 30.3, 28.8, 26.4, 25.3, 23.7, 22.8, 18.5, 17.5, 13.9, 10.8, 0.6, -11.0 . ^{27}Al NMR ($CDCl_3$): δ 26, 3. $W_{1/2} > 5000$ Hz.

Phenylalanine + TMA (4:1)

TMA (3.8 mL, 0.2 M, 0.76 mmol) in THF (70 mL) was added dropwise over a period of 3 h to a slurry of phenylalanine (0.50 g, 3.02 mmol) in THF (60 mL) at -77 °C. The reaction mixture was kept at this temperature for 5 h after completing the addition of the TMA. The reaction was then allowed to reach ambient temperature overnight. After stirring for 24 h, the reaction mixture was filtered by frit.

IR (cm^{-1}) (THF, air sensitive cell): 3335 m, 3288 m, 3239 m, 3053 s, 2938 vs, 1619 s, 1455 m, 1304 w, 1266 m, 1194w, 1071 m, 1035 w, 896 w, 849 w, 737 s, 704 s, 666s 542 vs, 496 vs, 463 vs. ^{1}H NMR (d-THF): δ 7.4 to 7.0 (5H, mult., Ph), -0.50 (s, 9H, Al-CH_3). $^{13}C\{^{1}H\}$ NMR (d-THF): δ 182.8, 182.4, 180.9, 179.3, 175.2, (all $\underline{C}OO$), 136.4, 129.9, 129.0, 127.0 (all Ph),55.6 ($\underline{C}HCOO$), 37.6 ($\underline{C}H_2CH(NH_3)$, -9.6 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 110 $W_{1/2} > 10^5$ Hz, 10 $W_{1/2}$ = 833 Hz.

Phenylalanine + TMA (4:1)

The above reaction was repeated with time of addition of TMA to the phenylalanine reduced to 45 minutes.

$^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 174 ($\underline{C}OO$), ($\underline{C}OO$), 138.7, 129.9, 129.0, 126.4 (all Ph), 56.6 ($\underline{C}HCOO$), 37.6 ($\underline{C}H_2CH(NH_3)$, 0.56 . ^{27}Al NMR (THF): δ 20 $W_{1/2}$ 1897 Hz.

Phenylalanine + TMA (7:2)

The reaction was performed as described for the previous one except using TMA (4.4 mL,

0.2 M, 0.88 mmol).

$^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 182.8, 182.4, 179.2, 175.2, (all $\underline{C}OO$), 136.4, 129.9, 129.0, 127.0 (all Ph), 55.6 ($\underline{C}HCOO$), 38.9 ($\underline{C}H_2CH(NH_3)$, 0.9 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 23 $W_{1/2}$ 1060 Hz.

Phenylalanine + TMA (3:1)

The reaction was performed as described above using TMA (5.0 mL, 0.2 M, 1.00 mmol).

$^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 182.9 ($\underline{C}OO$), 136.2, 130.0, 128.4, 127.9 (all Ph), 55.5 ($\underline{C}HCOO$), 37.5 ($\underline{C}H_2CH(NH_3)$, -9.8 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 130 $W_{1/2} > 10^5$ Hz, 16 $W_{1/2}$ = 978 Hz, 10 $W_{1/2}$ 4.24 Hz.

Phenylalanine + TMA (3:1)

The above reaction was repeated with the time of addition of the TMA to the phenylalanine reduced to 45 minutes.

$^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 174 (br), ($\underline{C}OO$), 138.4, 130.2, 129.8, 127.0 (all Ph), 56.3 ($\underline{C}HCOO$), 37.9 ($\underline{C}H_2CHCOO$), 0.9 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 20 $W_{1/2}$ 2530 Hz.

Phenylalanine + TMA (5:2)

The reaction was performed as described previously, using TMA (6.0 mL, 0.2 M, 1.2 mmol).

$^{13}C\{^{1}H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 175.2 (br), ($\underline{C}OO$), 138.3, 131.0,

129.8, 128.0 (all Ph), 55.9 (CHCOO), 38.7 ($\underline{C}H_2CH(NH_3)$, 0.5 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 22 $W_{1/2}$ 1644 Hz.

Phenylalanine + TMA (2:1)

The reaction was performed as described previously TMA (7.56 mL, 0.2 M, 1.51 mmol). $^{13}C\{^1H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 174.1 (br), (COO), 139.1, 132.0, 130.3, 129.2 (all Ph), 56.6 (CHCOO), 38.9 ($\underline{C}H_2CH(NH_3)$, 0.6 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 50 $W_{1/2} > 10^5$Hz.

Phenylalanine + TMA (1:1)

The reaction was performed as described previously, using TMA (15.1 mL, 0.2 M, 3.02 mmol).

$^{13}C\{^1H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 181.4, 177.5, 176.1, 175.1 (all COO), 137.6, 136.8, 129.128.9, 127.0 (all Ph), 56.2 (CHCOO), 38.1 ($\underline{C}H_2CH(NH_3)$, -8.8 (Al-$\underline{C}H_3$). ^{27}Al NMR (THF): δ 9 $W_{1/2}$ = 1641 Hz

Phenylalanine + TMA (1:2)

The reaction was performed as described previously, using (12.1 mL, 0.5 M, 6.05 mmol). $^{13}C\{^1H\}$ NMR (d-py): δ 174.2 (COO), 137.1, 128.9, 126.6, 125.1 (all Ph), 67.8; 56.5, 50.1 (both CHCOO), 38.5 ($\underline{C}H_2CH(NH_3)$, 30.4, 28.6, 23.1, 22.6, 13.6, 10.7. ^{27}Al NMR (THF): δ 22 $W_{1/2}$ = 1165 Hz.

Proline + TMA (1:1)

The previous reaction was repeated except with TMA (21.7 mL, 0.2 M, 4.34 mmol). A gelatinous material formed which was not suitable for analysis by NMR.

IR (cm^{-1}) (Air sensitive cell, pyridine): 3434 vs, 3238 s, 2972 s, 2867 m, 1651 vs, 1379 s. 1322 m, 1316 m, 1295 m, 1266 w, 1197 w, 1071 m, 1064 m, 931 m, 868 m, 798 m, 700 m, 568 m, 421 w. $^{13}C\{^1H\}$ NMR (d-py): δ 67.8, 25.8, -7.2 (Al-$\underline{C}H_3$). ^{27}Al NMR (d-py): δ 8 $W_{1/2} > 10^5$ Hz.

Tyrosine + TMA (3:1)

TMA (4.6 mL, 0.2 M, 0.92 mmol) in CH_2Cl_2 (70 mL) was added dropwise to a slurry of tyrosine (0.50 g, 2.76 mmol) in CH_2Cl_2 (70 mL) at -77 °C over a period of 2 h. The reaction mixture was maintained at this temperature for an additional 3 h before being allowed to warm to ambient temperature overnight. The slurry that was observed after an additional 24 h stirring at this temperature was dried to a powder and dissolved in pyridine in which the product was found to be partially soluble; the product had already been found to be insoluble in THF. The reaction was filtered and concentrated.

$^{13}C\{^1H\}$ NMR (d-py): δ 167.9 ($\underline{C}OO$), 131.8, 131.4, 129.3, 128.6 (all Ph), 68.2, 52.0 ($\underline{C}HCOO$), 39.1 ($\underline{C}H_2CHCOO$), 30.7, 29.2, 24.1, 23.2, 14.2, 11.1, 1.4 (Al-$\underline{C}H_3$). ^{27}Al NMR (d-py): δ 80 $W_{1/2} > 10^5$ Hz.

Tryptophan + TMA (3:1)

TMA (4.1 mL, 0.2 M, 0.82 mmol) in CH_2Cl_2 (70 mL) was added dropwise to a slurry

of tryptophan (0.50 g, 2.45 mmol) in CH_2Cl_2 at -77 °C over a period of 2 h. The reaction mixture was maintained at this temperature for an additional 3 h and after warming to ambient temperature, the slurry was stirred for another 24 h. A slurry was observed after this time and the solvent was removed. The powder was found to be very slightly soluble in THF, pyridine, acetone and CH_3CN.

Pyridine

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 175.7 (COO), 138.0, 128.0 (Ph), 127.0 (HNCH indole ring), 122.5, 121.9, 119.3, 112.0 (all Ph), 108.0 ($HNCHC(Ph)CH_2$), 56.3 (CHCOO), 29.2 (CH_2CHCOO). ^{27}Al NMR (d-py): δ 49 $W_{1/2}$ = 1160 Hz.

CD_3OD

$^{13}C\{^1H\}$ NMR (CD_3OD): δ 179.9, 179.3, 178.8, 169.3 (main) (all COO), 138.3, 133.4, 132.6, 129.8, 128.2 (Ph), 125.1 (HNCH indole ring), 122.8, 120.1, 119.8, 112.4, 111.0 to 109.1 (mult) (all Ph), 108.8 ($HNCHC(Ph)CH_2$), 69.1, 68.8, 55.8 (CHCOO), 40.0, 31.5, 30.0, 27.5 (CH_2CHCOO) 26.4, 24.9, 23.9, 14.4 11.4; 2.1, 0.7 (main) (both Al-CH_3)

Tryptophan + TMA (5:2)

The previous reaction was repeated except that TMA (4.9 mL, 0.2 M, 0.98 mmol) in THF (60 mL) was used. A clear colorless solution was obtained which could not be concentrated sufficiently to obtain good spectral data. On drying to a powder, the product was also found to be insoluble in any other solvent.

Tryptophan + TMA (3:2)

The previous reaction was repeated except that TMA (8.2 mL, 0.2 M, 1.64 mmol) in THF (60 mL) was used.

$^{13}C\{^1H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ 167.7 (COO), 135.8, 132.6, 130.8, 128.8 (Ph), 123.7 (HNCH indole ring), 67.9, 38.8, 30.4, 29.7, 29.0, 25.6 (CH_2CHCOO), 23.0, 22.6, 14.0, 10.9, 1.0 (Al-CH_3); ^{27}Al NMR (d-py): δ 50 $W_{1/2} > 10^5$ Hz.

Histidine+ TMA (3:1)

The reaction procedure was followed as decribed for tyrosine with TMA (3:1) except that TMA (5.4 mL, 0.2 M, 1.08 mmol) and histidine (0.50 g, 3.22 mmol) were used.

$^{13}C\{^1H\}$ NMR (d-py): δ 167.8 (COO), 131.4, 129.2, 122.4 (all imidazole C), 68.1, 54.9 (CHCOO), 38.9 (CH_2CHCOO), 30.6, 29.3, 24.0, 23.1, 14.1, 11.0. ^{27}Al NMR (d-py): δ 70 $W_{1/2} > 10^5$ Hz.

Alanine + BHT_2AlMe (1:1)

BHT_2AlMe (1.21 g, 2.24 mmol), synthesized according to the literature[134] was dissolved in pyridine (*ca.*, 90mL) overnight and added to a Schlenk containing alanine (0.20 g, 2.24 mmol) and refluxed for three days. A gelatinous product emerged (0.07g, 5%) which was washed in CH_2Cl_2, acetone and methanol. However, the product was insufficiently soluble in the first two solvents to provide NMR data.

CH_2Cl_2 fraction

IR (cm^{-1}) (NaCl):1728 vs, 1461 s, 1431 s, 1391 m, 1361 m, 1269 vs, 1233 m, 1216 m,

1151 m, 1120 s, 1074 m.

Acetone fraction

IR (cm^{-1}) (NaCl): 2956 vs, 2874 vs, 1727 s, 1442 vs, 1431 vs, 1391 m, 1361 m, 1268 vs, 1249 vs, 1232 vs, 1215 m, 1199 m, 1156 s, 1121 s, 1073 m, 440-400 vvs (off scale).

MeOH fraction

IR (cm^{-1}) (NaCl): 1736 s, 1460 w, 1274 vs, 1121 m, 1074 m, 867 s, 769 m, 720 m, 710 m, 440-400 vvs, off scale. $^{13}C\{^1H\}$ NMR (CD_3OD): δ 169.0 (COO), 68.3, 39.6, 35.0, 31.1, 34.5, 23.6, 21.2, 14.3, 11.3. ^{27}Al NMR (CD_3OD): δ 26, $W_{1/2}$ >10^5 Hz.

Tryptophan + $BHT_2AlH.OEt_2$ (1:1)

$BHT_2AlH.OEt_2$ (0.53 g, 0.98 mmol) in THF (60 mL) was added to a slurry of tryptophan (0.20 g, 0.98 mmol) in THF (50mL) at -77 °C and warmed gradually overnight to ambient temperature. The solution was dried under vacuum to a powder and was washed with pentane and filtered. The residual solid was dissolved in THF.

IR (cm^{-1}) (NaCl):1666 s, 1625 s, 1432 vs, 1391 m, 1267 s, 1248 s, 1232 s, 1155 s, 861 s. ^{27}Al NMR (CD_3OD): δ 21 $W_{1/2}$ = 1706 Hz.

Tryptophan + BHT_2AlMe (1:1)

The previous reaction was repeated with BHT_2AlMe (0.47 g, 0.98 mmol) prepared according to the literature method.

IR (cm^{-1}) (NaCl): 1658 s, 1458 s, 1422 vs, 1391 m, 1359 m, 1278 s, 1267 m, 1232 m, 1156 m, 886 m, 861 m, 743 m. $^{13}C\{^1H\}$ NMR (THF, $CDCl_3$ external lock solvent): δ

172.2 (br) (<u>C</u>OO), 151.8 (BHT-Ph), 138.2 (trypt- Ph) 137.3, 128.0 (BHT-Ph) 127.1 (tryp - Ph)125.1 (BHT - Ph), 123.5, 121.7, 119.1, 118.7, 111.5, 110.5 (all tryp), 54.6 (<u>C</u>HCOO), 34.8 (BHT), 29.9, 25.9, 25.6 (BHT), 25.2 (tryp - <u>C</u>H_2CHCOO), 24.0, 20.6. ^{27}Al NMR (THF): δ 22 $W_{1/2}$ = 1869 Hz.

[ala][alaH]$^+$. Cl

A solution of $AlCl_3$ (25 mL, 0.03 M, 0.75 mmol) diluted with methanol (*ca.* 50 mL) was added to a slurry of alanine (0.20 g, 2.24 mmol) in methanol (*ca.* 50 mL) at -77 °C and stirred overnight with gradual warming to room temperature. The reaction mixture was dried to a powder which was dissolved in ethanol and filtered by a frit filter adapted for air sensitive work. The solution was layered with heptane and crystallized slowly over a period of *ca* 4 months.

IR (cm^{-1}) (NaCl): 1683 vs, 1478 s, 1409 w, 1364 m, 1339 w, 1300 w, 1256 m , 1202 m, 1103 s, 1000 s, 995 s, 956 m, 937 m, 810 vs, 600 s.

Ph_2B(N-, O-ala)

A solution of $AlCl_3$ (0.25 g, 1.49 mmol) in methanol (*ca.* 50 mL) was added to a slurry of alanine (0.50 g, 4.48 mmol) in methanol (*ca.* 50 mL) at -77 °C and stirred overnight with gradual warming to room temperature. The reaction mixture was then added to a Schlenk containing $NaBPh_4$ (0.20 g, 0.59 mmol) and the resulting clear, colorless solution was filtered by a frit filter. This solution was allowed to stand in a refrigerator at 5 °C for several weeks from which opaque, colorless crystals of x-ray quality

emerged. These were mounted in a sealed glass capillary under nitrogen. (0.044 g, 31.2%)

IR (cm^{-1}) (KBr): 3443 s, 3141 vs, 3049 vs, 2915 vs, 1715 s, 1479 s, 1380 m, 1352 m, 1207 w, 1116 m, 1041 w, 999 w, 853 w, 774 w, 747 w, 705 w. ^{1}H NMR (CD_3OD): δ 7.88 (br), 6.28 - 7.05 (m, 10 H), 3.62 (q, 1 H), 1.16 (d, 3 H). $^{13}C\{^{1}H\}$ (CD_3OD): δ 178.1 (COO), 52.6 (CHCOO), 16.5 (CH_3CH). ^{11}B NMR (CD_3OD): δ 13, –42.

Appendix

Throughout the work, considerable effort was expended in attempting to crystallize the complexes. It was obvious that these would be hampered by both the indeterminate nature of solvation present as well as our inability to determine the charge on the various species. In order to attempt to overcome these problems, various methods were utilized including conventional crystal growing techniques,[138] and numerous added counterions and physical crystallization aids (in particular, Ph_3PO,[139] cigarette ash and hair). In many cases, crystals too small for X-ray analysis were obtained, and the unwanted half from the counterion addition metathesis reactions often crystallized beautifully. Two new species that did not contain aluminum were obtained, and the structures are discussed in this Appendix.

Crystal structure of [alanine][alanine]$^+$.Cl-

A fraction from the 3:1 reaction between alanine and aluminum chloride that was exposed to ether by vapor diffusion produced, after several months, oval-shaped crystals which were suitable for X-ray crystallographic analysis.[140] Crystal and data collection parameters and bond lengths and angles are listed in Tables A-1 and A-2, respectively. The structure was found to consist of two different types of alanine, complexed with chloride. One alanine (alanine 1) is in the expected zwitterionic form while the other (alanine 2) contains a carboxylic acid group, so the structure may be regarded as a mixed alanine-alaninium hydrochloride species.

Table A-1. Crystal and Solution Data for [Ala · HCl][Ala]

Formula	$C_6H_{15}ClN_2O_4$
Crystal size (mm)	0.12 x 0.13 x 0.21
Molecular Mass	214.65
Crystal System	monoclinic
Space Group	$P2_1$
Unit cell:	
a (Å)	10.775(1)
b (Å)	5.0725(6)
c (Å)	10.973(2)
β (°)	115.933(7)
V ($Å^3$)	539.4(4)
Z	2
D_c (g/cm^3)	1.322
μ (cm^{-1})	3.40
2θ range	2 to 50
No. data collected	1109
No. unique data	1062
R_{int}	0.054
No. observed data ($I > 3\sigma(I)$)	341
R	0.0893
R_w	0.0983
GOF	1.06
maximum residual electron density	0.41
maximum shift/e.s.d.	<0.25

Table A-2. Important Bond Lengths (Å) and Angles (°) for [Ala · HCl][Ala]

Atoms	Length	Atoms	Length
O11 - C11	1.24(3)	O12 - C11	1.27(3)
O21 - C21	1.13(3)	O22 - C21	1.33(3)
N11 - C12	1.49(2)	N21 - C22	1.47(3)
C11 - C12	1.52(5)	C12 - C13	1.52(4)
C21 - C22	1.58(4)	C22 - C23	1.48(3)

Atoms	Angle	Atoms	Angle
O11 C11 O12	126(3)	O11 C11 C12	121(2)
O12 C11 C12	114(2)	N11 C12 C11	110(2)
N11 C12 C13	110(2)	C11 C12 C13	115(3)
O21 C21 O22	131(2)	O21 C21 C22	120(2)
O22 C21 C22	108(2)	N21 C22 C21	106(2)
N21 C22 C23	109(2)	C21 C22 C23	107(2)

The crystal quality was sufficiently poor that a full analysis of the finer details of the structure is unwarranted. However, some comparative points may be made. The general structure of alanine 1 is very similar to that of free alanine.[141] Given the intermolecular contacts (*vide infra*) one may claim a slight asymmetry exists in the C-O bond lengths (1.24(3) to 1.27(3) Å), but the difference is within statistical error limits. Alanine 2, on the other hand, may be clearly seen to be the cationic species, even though the hydrogen atoms were not located in the structure solution. The geometry of the OCO group is very asymmetric - the two C-O bonds are 1.13(3) and 1.33(3) Å, corresponding to the C=O and C-O interactions respectively, and, as would be expected by simple VSEPR theory, the angles involving the double bond are enlarged.

The most interesting aspects of the structure are to be found in the interspecies interactions (Table A-3). As would be expected, there is an extensive hydrogen-bonding network, involving seven unique interactions. The chloride ion is involved with four of these (Figure A-1) with distances between the acceptor atom and chloride of between 3.20 and 3.33 Å. Alanine 1 (Figure A-2) is involved in five interactions; one between the nitrogen and a chloride ion, two between the nitrogen and oxygens of neighbouring alanines (an alanine 1 and an alanine 2), and an exceptionally short interaction (2.40 Å)[132] between O12 and the hydroxyl oxygen of alanine 2 (O22). Finally, alanine 2 (Figure A-3) is also involved in five interactions; the two with alanine 1 and with three different chloride ions.

Despite the fact that the hydrogen atoms were not present on difference maps (not an unusual situation for room-temperature structure determinations), the nature of the

Table A-3. Important Interspecies Distances in the Structure of [Ala · HCl][Ala]

Atoms	Length	Atoms	Length
Cl...N11'	3.20	Cl...N21"	3.20
Cl...N21	3.24	Cl...N21"'	3.33
O11...N11""	2.81	O12...O22	2.40
O21...N11""	3.05		

' (x,y,z) → (1-x,y-1/2,1-z)

" (x,y,z) → (1-x,y+1/2,-z)

"' (x,y,z) → (1-x,y-1/2,-z)

"" (x,y,z) → (1-x,y+1/2,1-z)

hydrogen bonding enables the conclusive determination of the charge location on the molecule. The question remains as to why this species, which contains no aluminum, should have been soluble in methanol in the first place. Attempts to redissolve the crystals were, as expected, unsuccessful. However, the NMR spectra of the "decrystallized" solutions contained much weaker alanine peaks, and an increase in solvated aluminum peaks, implying degradation of the product over time.

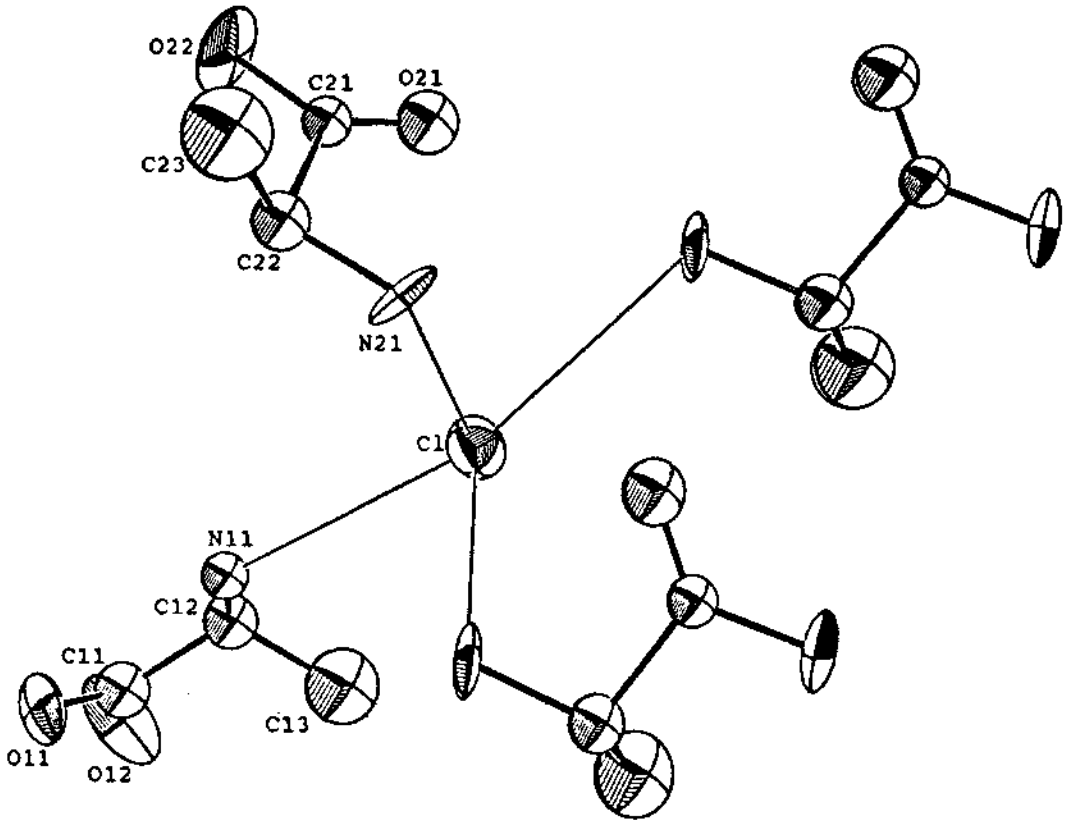


Figure A-1. Coordination Sphere of Cl in [Ala · HCl][Ala]

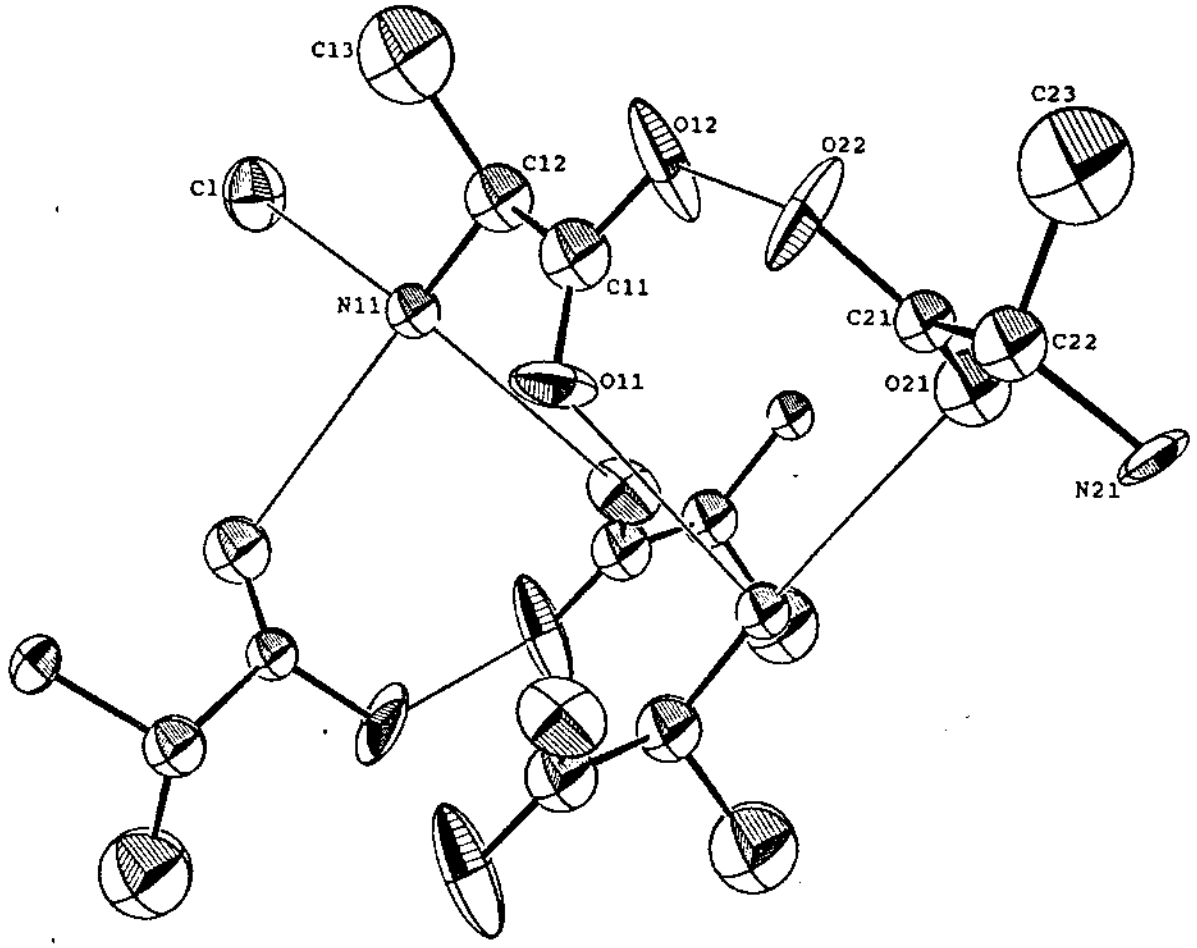


Figure A-2. Coordination Sphere of [Ala] in [Ala · HCl][Ala]

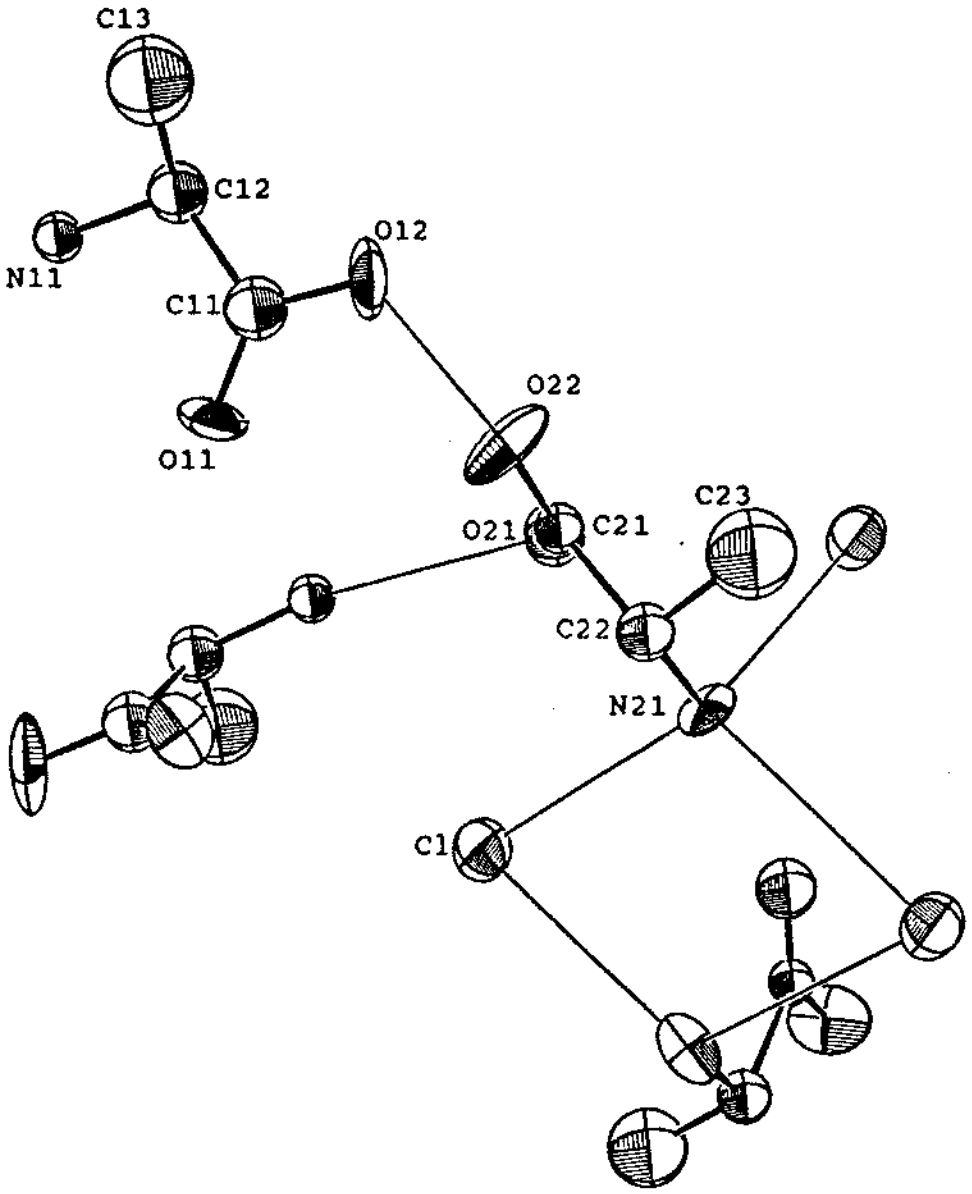


Figure A-3. Coordination Sphere of [Ala · H^+] in [Ala · HCl][Ala]

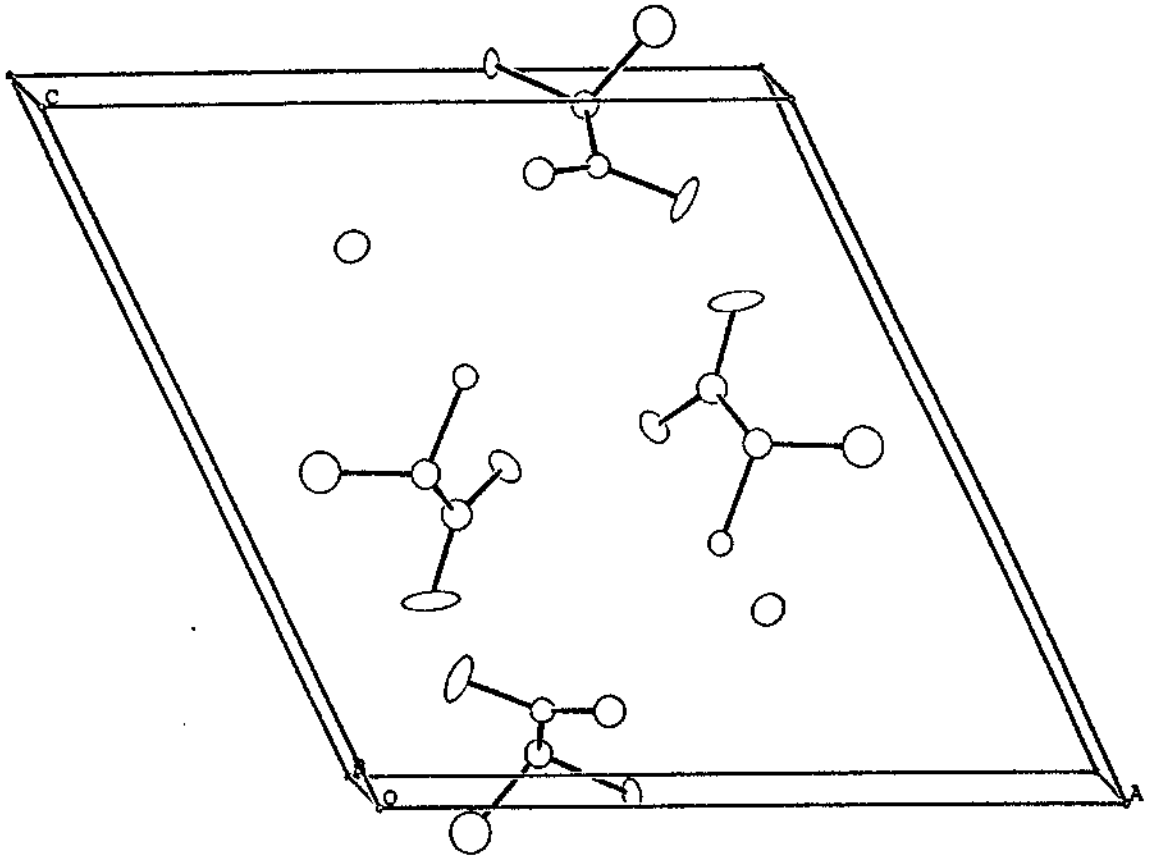


Figure A-4. Unit Cell of [Ala · HCl][Ala]

Crystal Structure of Ph_2B(alanine)[142]

Due to the possibility that the complex might be cationic, certain crystallization attempts involved the addition of tetraphenylborate. As had been the case for some of the attempts to complex alanine to aluminum in acidic solutions (*vide supra*), addition of this anion to reaction mixtures in which the HCl was still present resulted in the formation of a brown color. After storage at 5 °C for three weeks, block-shaped crystals appeared that were suitable for X-ray analysis.[143]

Crystal and data collection parameters and bond lengths and angles are listed in Tables A-4 and A-5, respectively. The analysis revealed that the conditions had been sufficient to lead to acid-promoted attack of alanine on the tetraphenylborate anion, producing the complex (**1**) shown in Figure A-5. This compound was first synthesized by Baum,[144] but only elemental analysis was reported. Given both the potential importance of such compounds (*vide infra*) and the fact that boron is in the same group of the periodic table as aluminum (although possessing very different chemistry),[145] a relatively in-depth discussion is warranted.

The alanine binds to the central boron atom via the nitrogen of the α-amino group and an oxygen of the carboxylate group forming a five membered heterocyclic boroxazolidone. The structures of several similar compounds have been reported and may serve as reference for comparison (Figure A-6 and Table A-6).[146-155]

The key to the remarkable stability of boroxazolidones lies in the strength of B-N bond. The B-N bond length of 1.61(1) Å in **1** is the shortest reported for a four-coordinate boron in a boroxazolidone. Conversely, the B-O length of 1.54(1) Å is the

Table A-4. Crystal and Solution Data for $BPh_2(ala)$

Formula	$C_{15}H_{16}BNO_2$
Crystal size (mm)	0.25 x 0.32 x 0.41
Molecular Mass	253.11
Crystal System	orthorhombic
Space Group	$P2_12_12_1$
Unit cell:	
a (Å)	5.986(1)
b (Å)	12.319(1)
c (Å)	18.169(2)
V ($Å^{3)}$	1339.8(3)
Z	4
D_c (g/cm^3)	1225
μ (cm^{-1})	0.76
2θ range	2 to 44
No. data collected	1002
No. observed data ($I > 3\sigma(I)$)	665
R	0.072
R_w	0.074
GOF	1.38
maximum residual electron density	0.37
maximum shift/e.s.d.	<0.01

Table A-5. Important Bond Lengths (Å) and Angles (°) for BPh_2(ala)

Atoms	Length	Atoms	Length
O4 - C5	1.30(1)	O4 - B3	1.54(1)
O5 - C5	1.19(1)	N2 - C1	1.49(1)
N2 - B3	1.61(1)	C1 - C1a	1.50(1)
C1 - C5	1.54(1)	C6 - B3	1.60(1)
C12 - B3	1.60(1)		

Atoms	Angle	Atoms	Angle
C5 O4 B3	112.9(7)	C1 N2 B3	105.7(7)
N2 C1 C1a	112.2(8)	N2 C1 C5	103.8(7)
C1a C1 C5	110.8(8)	O4 C5 O5	124.6(9)
O4 C5 C1	111.4(8)	O5 C5 C1	123.9(8)
C7 C6 C11	115.9(9)	C7 C6 B3	121.4(9)
C11 C6 B3	122.6(9)	C13 C12 C17	117.5(9)
C13 C12 B3	120.5(9)	C17 C12 B3	122.0(9)
O4 B3 N2	98.6(7)	O4 B3 C6	108.8(8)
O4 B3 C12	110.5(8)	N2 B3 C6	112.6(8)
N2 B3 C12	111.7(8)	C6 B3 C12	113.6(8)

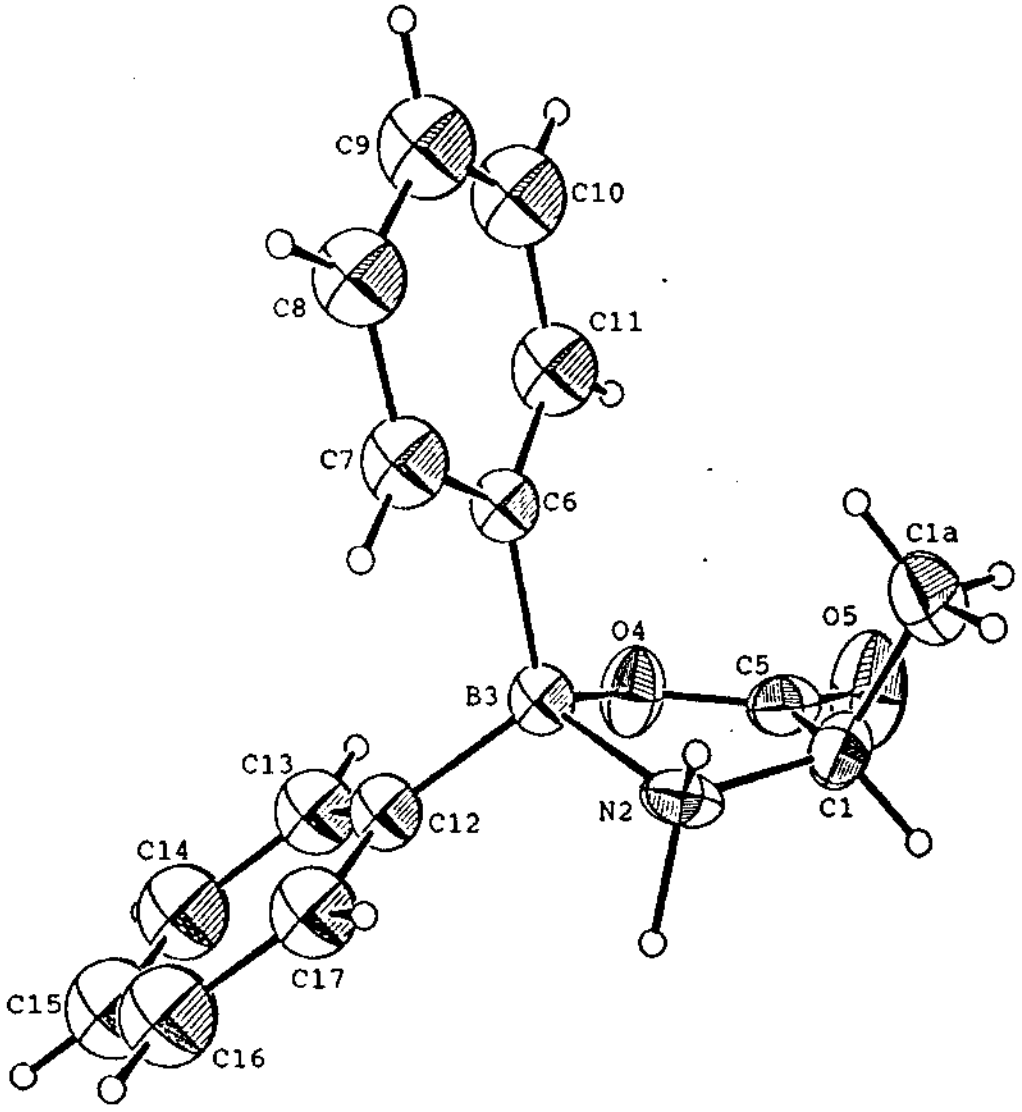


Figure A-5. Molecular Structure of $BPh_2(ala)$

longest example reported. The two parameters may be compared to those in the four-coordinate proline derivative, **5**,[148] and the three-coordinate isoleucine structure **7**.[140] The former contains the second-longest B-O bond and second-shortest B-N bond for four-coordinate structures, and the latter contains the longer three-coordinate B-O bond and shorter three-coordinate B-N bond of the examples given. There is a rough negative correlation between B-O and B-N bonds for all of the structures (except where severe steric effects intrude), thus one may consider the relationship on terms of a constant electronic demand from the boron. Where one atom cannot "fulfill" its share of the demand (such as the oxygen of an the COO group), the bond to the other atom must increase in electron density.

The effects of the carbonyl group may also be observed in a consideration of the C-O bond. For compounds **1**, **5**,[148] **6**,[149] and **7**,[150] the carbon is sp^2 hybridized, whereas it is sp^3 hybridized in the remaining examples. As expected, the increased s-character leads to a shortening of the bond of *ca.* 0.1 Å. It is interesting to note that the C(sp^2)-O bond lengths are closer to those observed for the C-O bond in carboxylic acids (rather than esters), and that the C(sp^3) bond lengths correspond to lengths observed for alcohols rather than ethers.[156] In other words, subtitution of the "other end" of the oxygen by boron is more similar to substitution by hydrogen rather than by carbon, in accordance with the Pauling electronegativities of each atom (B, 2.04, H, 2.20, C, 2.55).[157]

As would be expected for an amino-acid derivative, the cell packing (Figure A-7) is predicated by hydrogen bonding between the carbonyl oxygen and the amine of the molecule related by [(x,y,z) → (x-1,y,z)]. the O...N and O...H distances are 2.88(1) and

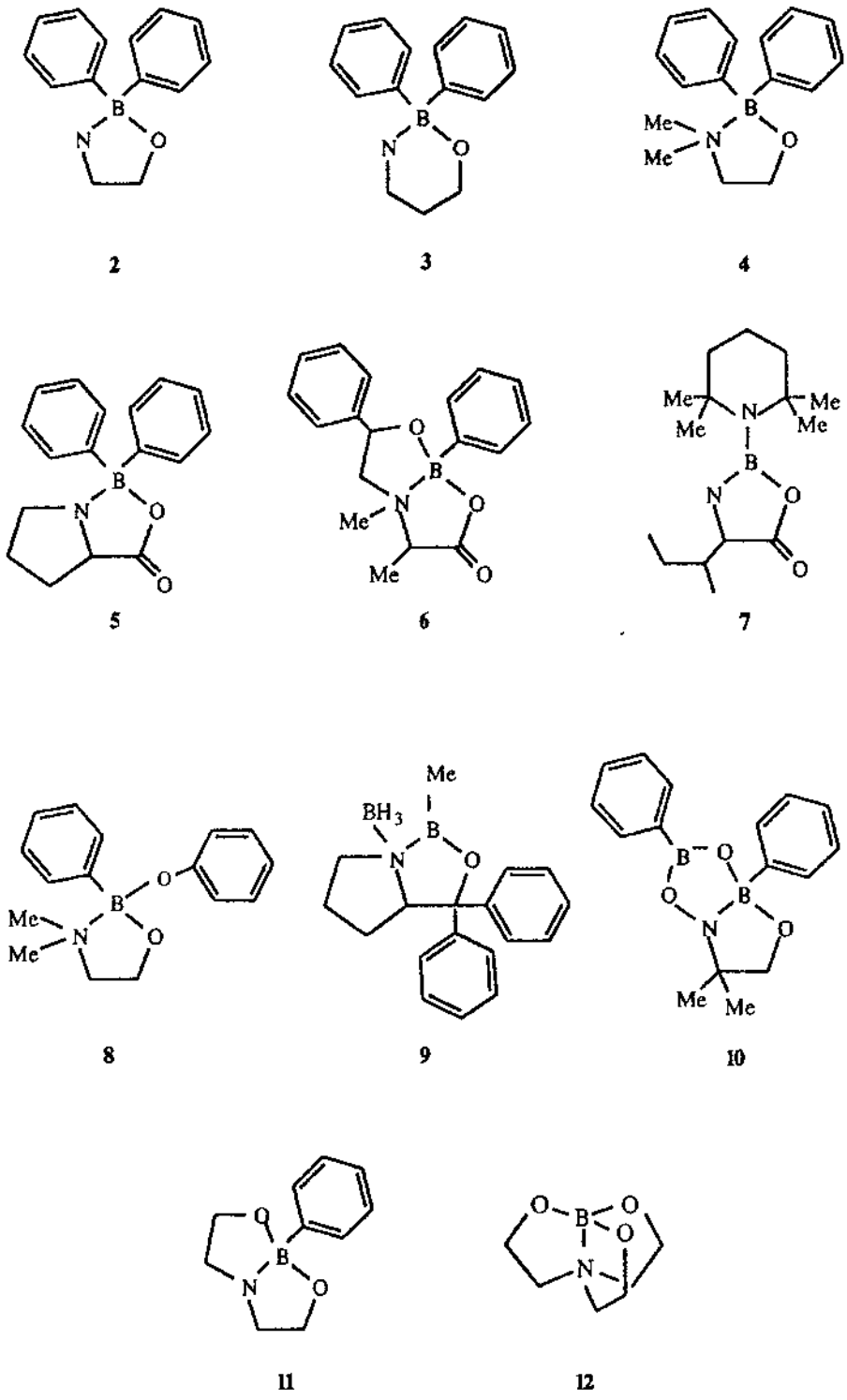


Figure A-6. Boroxazolidone structures.

Table A-6. Bond Distances and Angles in Boroxazolidone Structures

Compound	B-O	B-N	C-O	C=O	C-N	C-C
1	1.54	1.61	1.30	1.19	1.49	1.54
2	1.484	1.653	1.413	---	1.485	1.505
3	1.478	1.638	1.434	---	1.495	1.513
						1.507
4	1.470	1.686	1.415	---	1.501	1.518
5	1.524	1.626	1.297	1.216	1.503	1.513
6a *	1.506	1.713	1.318	1.219	1.503	1.490
6b *	1.422	1.713	1.418	---	1.527	1.526
7	1.432	1.427	1.347	1.213	1.456	1.507
8	1.439	1.676	1.428	----	1.494	1.519
9	1.335	1.486				
10	1.450	1.688	1.423	---	1.511	1.528
11	1.469	1.661	1.417	---	1.482	1.508
	1.457		1.405		1.481	1.520
12		1.647				

*6a represents the heterocycle containing the carbonyl oxygen

6b represents other heterocycle within the structure

1.75(1) Å, respectively, and the O...H-N angle is 157° - all of which values are indicative of a medium strength interaction.[132]

The infrared data shows a peak at 1742 cm^{-1} for the ν_a(C=O) stretch and its position in the spectrum is commensurate with a cyclic structure.[149] Absorption at 1750-1700 cm^{-1} were observed for other boroxazolidones.[149,158,159] The ^{11}B nmr spectrum containing a peak at 13 ppm is typical of a tetrahedral species,[160] with the shoulder at -42 ppm indicating a singly substituted triphenylborate-alanine complex is present in solution,[144] probably in equilibrium with the tetrahedral complex.

Boroxazolidones were synthesized by Skoog as far back as 1954,[161] who predicted correctly their structures despite the limitations of the analytical techniques available to him. These boron compounds are themselves chemically interesting because of their potential use for medical purposes. The most celebrated use is in the field of Boron Neutron Capture Therapy (BNCP) where ^{10}B is administered so that preferential absorption by tumour cells results in their removal on bombardment with neutrons. Only healthy tissue remains.[162] The initial investigations were intended to be the forerunners of trials with polymeric boron complexes in which the number of boron atoms per molecule was greater.

Other agricultural and medicinal properties have been investigated and these include uses as insecticides, herbicides, fungicides, anti-inflammatory and anti-convulsion agents.[150] Similar boron complexes have therefore been the subject of numerous patents.[163]

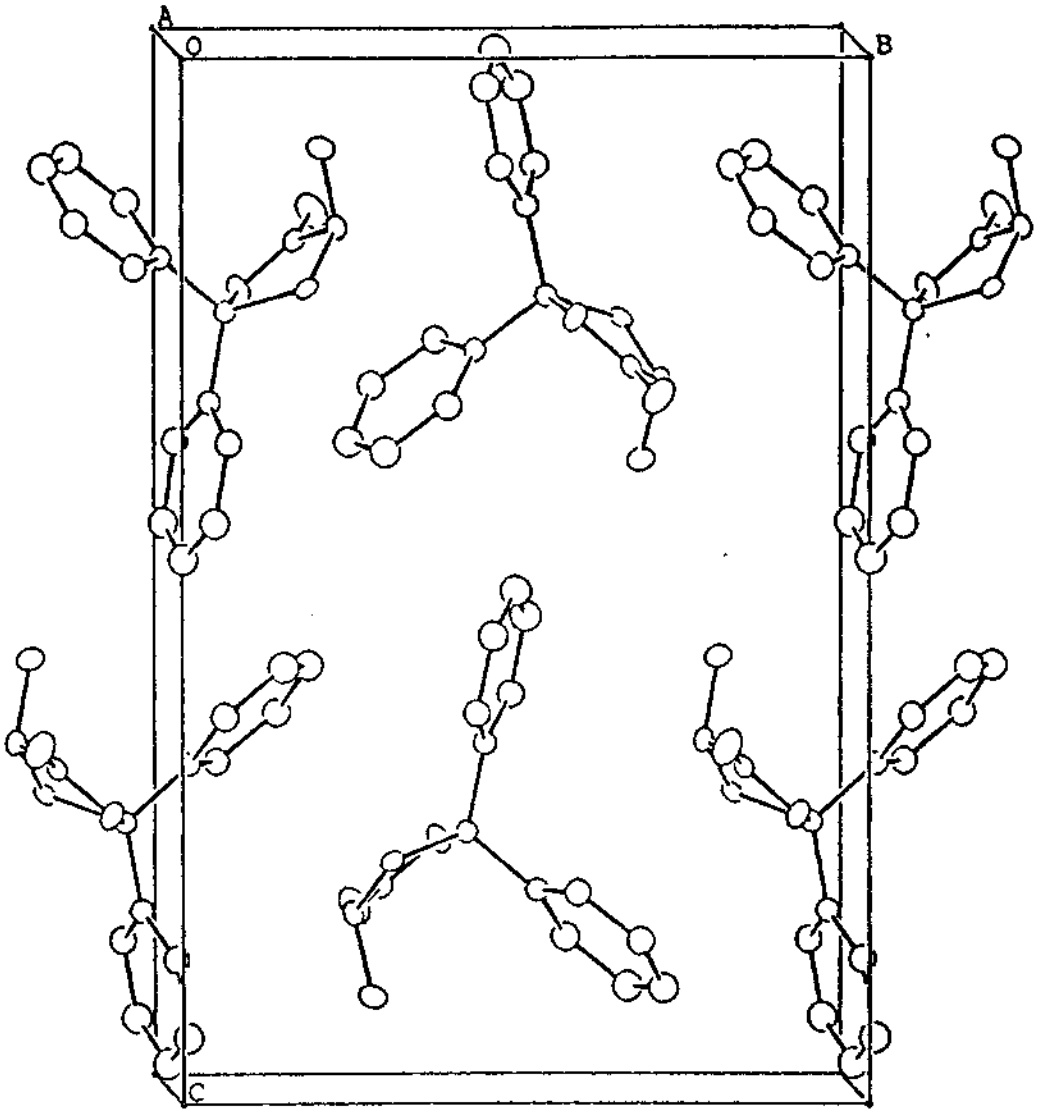


Figure A-7. Unit Cell of $BPh_2(ala)$

Boron complexes of amino acids may also be useful to synthetic chemists. The enantioselective catalytic properties of chiral boroxazolidones have been demonstrated in the reduction of prochiral oximes, imines and ketones.[164] Furthermore, in the alterationof the side chain of amino acids, it is essential that the reactive amino and the carboxyl groups are protected to avoid competing side reactions;[158] complexation of these two groups with boron may be a means for achieving this and may be a useful step in a synthesis as deprotection is easily accomplished through addition of a dilute acid.

CHAPTER 4

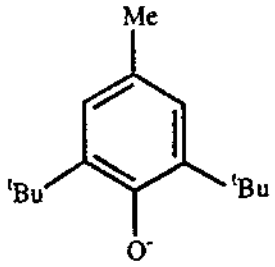
STRUCTURAL STUDIES OF ALUMINUM-CHALCOGEN BONDS

4-1. Introduction

The first part of this dissertation discussed a negative aspect of aluminum chemistry - its role in the environment. As was implied in the introduction, however, aluminum and its compounds are very important in numerous fields, ranging from materials[165] to catalysis of organic transformations.[166] A considerable number of these applications involve aluminum-chalcogen interactions, and complexes containing such bonds are being studied intensively. In this chapter, some structural investigations of such complexes are discussed. All of the compounds were synthesized by the research group of Professor Andrew Barron, formerly of Harvard University, now Professor of Chemistry at Rice University, with whom our group has a long-standing collaboration.

4-2. Sterically Crowded Aryloxide Aluminum Complexes[137]

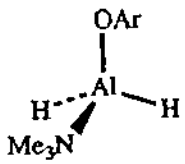
A focus of the Barron group for several years has been the use of the sterically demanding BHT ligand (**1** ≡ OAr) to stabilize otherwise highly reactive complexes and investigate the steric and electronic effects of interactions between aluminum and organic substrates.[167-173]



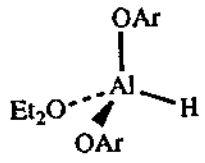
1

One class of compounds that was of interest was the alkoxyalanes, which, in the anionic form, are often used as reducing agents.[174] At the time of the study discussed herein, very few examples of these species had been fully investigated, however,[175] and an extensive study was performed on their synthesis and characterization. In this section, both the structure of one such species, as well as the product of its conversion to a highly substituted alkoxide will be discussed.

Reaction of $[AlH_3(NMe_3)]$[176] with one equivalent of HOAr leads to the formation of the monomeric dihydrido alkoxide aluminum trimethylamine complex, **2**.[137] This was shown to exist in partial equilibrium with the hydride-bridged dimer. As is very common with organoaluminum species, however, disproportionation and ligand exchange occurred in solution,[117] and complex **3** could be isolated from an ether solution of **2**. Complex **3** can also be prepared by reaction of $LiAlH_4$ with three equivalents of HOAr, which produces an equimolar mixture of **3** and $Li(OAr)(OEt_2)$.[167]



2



3

Crystals of **3** were examined as described in Chapter 2.[177] Crystal, data collection and solution parameters are listed in Table 4-1 and important bond lengths and angles are collected in Table 4-2. The structure (Figure 4-1) consists of a monomeric aluminum center bound to two BHT ligands, a hydride and a coordinated ether. The geometry of the aluminum is a distorted tetrahedron, with bond angles ranging from 98(1)° to 118(1)°. If one considers the size of an angle (L-Al-L') to be representative of the steric "bulk" of L and L', angles in **3** imply that BHT is larger than H, which is, in turn, larger than the ether (BHT to BHT angle is 117.2(1), BHT to H angles average 115.5°, BHT to ether angles average 103.3°, and the ether to H angle is 98(1)°). This observation is in agreement with the proximity of the ligand "bulk" to the aluminum center. Thus, while a hydride is obviously much smaller than either BHT or ether, its small "bulk" is much closer than the larger "bulk" of the ligands. The effective "bulk" of the non-hydride ligands is further reduced as they rotate to avoid interligand repulsions. Thus, the two BHT aromatic planes are oriented so that they are close to perpendicular (dihedral angle of 76.1(1)°), and the methyl groups on the ether point away from the closest BHT *t*-butyl group.

One of the most important points to emerge from studies of aluminum-BHT complexes is the concept of Al-O π-bonding.[168] Most BHT complexes have short Al-O bonds and rather obtuse C-O-Al angles. Mono(BHT) complexes display an inverse linear correlation between these two parameters, while bis-BHT complexes, in which steric constraints are more important, usually contain Al-O lengths between 1.71 Å and 1.73 Å regardless of the C-O-Al angle (which ranges from 130 to 175°).[169] The Al-O bonds in

Table 4-1. Crystal and Solution Data for Complex 3

Formula	$C_{34}H_{57}AlO_3$
Crystal size (mm)	0.25 x 0.32 x 0.62
Molecular Mass	540.81
Crystal System	monoclinic
Space Group	$P2_1/n$
Unit cell:	
a (Å)	12.427(5)
b (Å)	11.201(8)
c (Å)	24.866(9)
β (°)	102.64(3)
V ($Å^3$)	3377(3)
Z	4
D_c (g/cm^3)	1.064
μ (cm^{-1})	0.85
2θ range	2 to 44
No. data collected	4600
No. unique data	4382
R_{int}	0.022
No. observed data ($I > 3\sigma(I)$)	2539
R	0.045
R_w	0.045
GOF	1.04
maximum residual electron density	0.18
maximum shift/e.s.d.	<0.01

Table 4-2. Important Bond Lengths (Å) and Angles (°) for Complex **3**

Atoms	Length	Atoms	Length
Al - O1	1.704(3)	Al - O2	1.711(3)
Al - O3	1.907(2)	Al - H	1.47(3)
O1 - C11	1.365(5)	O2 - C21	1.364(4)
O3 - C31	1.465(5)	O3 - C33	1.465(5)

Atoms	Angle	Atoms	Angle
O1 Al O2	117.2(1)	O1 Al O3	102.3(1)
O1 Al H1	118.(1)	O2 Al O3	104.3(1)
O2 Al H1	113.(1)	O3 Al H1	98.(1)
Al O1 C11	165.3(3)	Al O2 C21	162.9(2)
Al O3 C31	124.7(3)	Al O3 C33	117.3(2)
C31 O3 C33	115.3(3)		

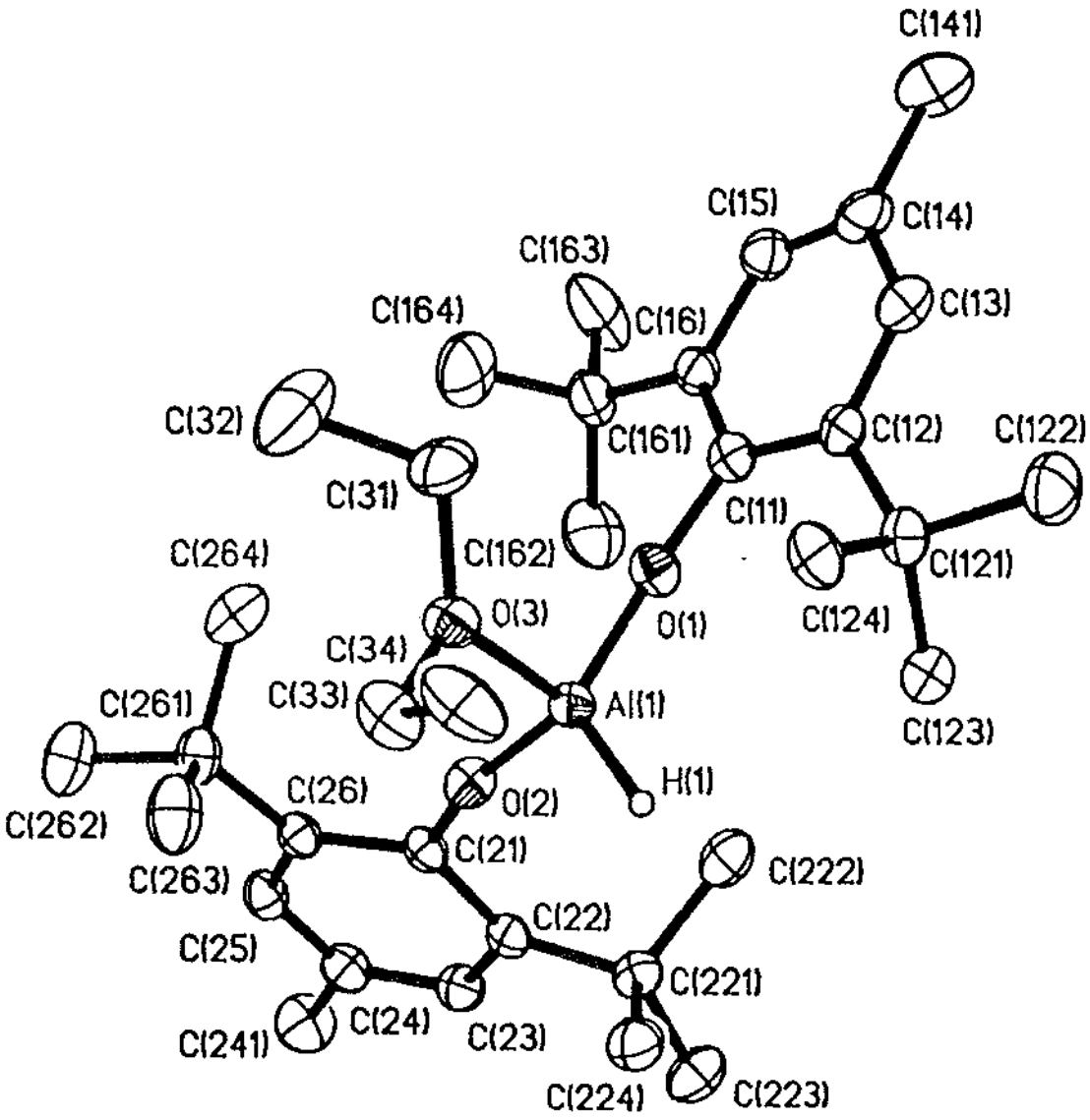


Figure 4-1. Molecular structure of Complex **3**.

3 (1.704(3) Å and 1.711(3) Å) lie at the shorter end of the range, while the angles (165.3(3) and 162.9(2)°) are on the high end of the appropriate range.

The hydride was located from a difference map, and refined to produce an Al-H length of 1.47(3) Å. This is extremely short, compared both to the analogous amine complex, $[AlH(OAr)_2(NH_2Bu^t)]$ in which the Al-H bond length is 1.67(7) Å,[137] as well as *ab initio* calculations which predict values of 1.588 to 1.599 Å.[178] However, neither the location of hydrogen atoms from X-ray data nor *ab initio* calculations on "heavy" atoms are fully reliable, thus extensive conclusions should not be drawn from these disparities. [It should be mentioned that consideration of atomic radii predicts a value of approximately 1.67 Å.][179]

The crystal packing of **3**, shown in Figure 4-2, consists of infinite sheets inclined at about 30° to the *ab plane*. The predominant intermolecular contacts are aromatic perpendicular π-contacts with the expected distances of approximately 3.60 Å.[180]

Reaction of **3** with a further equivalent of HOAr leads to the formation of the previously unknown homoleptic aryloxide, $Al(OAr)_3$.[167] This extremely hindered, three-coordinate monomeric species still possesses sufficient Lewis acidity to bind to certain bases, and the complex (**4**) obtained with 4-*tert*-butylcyclohexanone was characterized by using X-ray crystallography.[181]

Crystal, data collection and solution parameters for **4** are listed in Table 4-3 and important bond lengths and angles are collected in Table 4-4. The structure (Figure 4-3) consists of a distorted tetrahedral aluminum center coordinated to three BHT ligands and a donor *t*-butylcyclohexanone. In general, the repulsion between the three bulky aryloxide

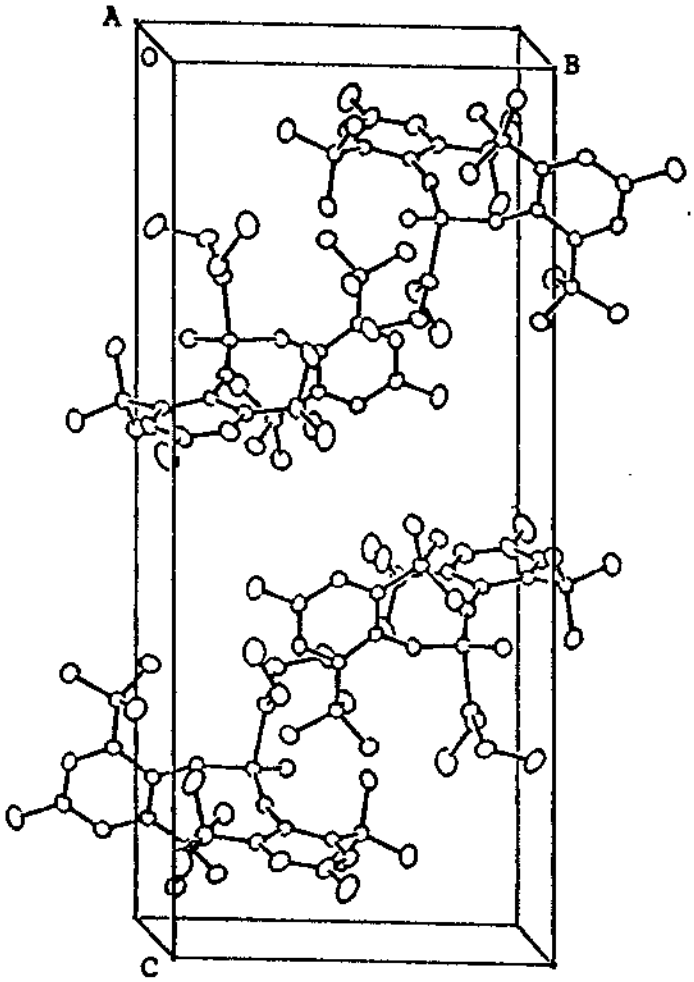


Figure 4-2. Unit cell packing of complex **3**.

Table 4-3. Crystal and Solution Data for **4** · pentane

Formula	$C_{60}H_{99}AlO_4$
Crystal size (mm)	0.4 x 0.42 x 0.38
Molecular Mass	911.44
Crystal System	monoclinic
Space Group	$P2_1/c$
Unit cell:	
a (Å)	11.738(1)
b (Å)	18.618(4)
c (Å)	26.953(5)
β (°)	97.29(1)
V ($Å^3$)	5842(2)
Z	4
D_c (g/cm^3)	1.036
μ (cm^{-1})	0.72
2θ range	2 - 40
No. data collected	6016
No. unique data	5677
R_{int}	0.027
No. observed data ($I > 2.5\sigma(I)$)	2171
R	0.0542
R_w	0.0681
GOF	1.61
maximum residual electron density	0.43
maximum shift/e.s.d.	<0.1

Table 4-4. Important Bond Lengths (Å) and Angles (°) for Complex **4** · pentane

Atoms	Length	Atoms	Length
Al - O1	1.717(5)	Al - O2	1.716(5)
Al - O3	1.691(5)	Al - O4	1.841(6)
O1 - C11	1.359(9)	O2 - C21	1.402(9)
O3 - C31	1.377(7)	O4 - C41	1.25(1)

Atoms	Angle	Atoms	Angle
O1 Al O2	106.3(3)	O1 Al O3	116.4(2)
O1 Al O4	104.1(3)	O2 Al O3	121.8(3)
O2 Al O4	103.6(3)	O3 Al O4	102.2(3)
Al O1 C11	146.7(4)	Al O2 C21	137.2(5)
Al O3 C31	163.9(5)	Al O4 C41	165.8(5)

groups is greater than that to the cyclic ketone, so that two of the BHT-Al-BHT angles are large (116.4(2)° and 121.8(3)°), while all three of the BHT-Al-cyclohexanone angles are very small (102.2(3), 103.6(3), and 104.1(3)°). Probably due to the severe crowding about the aluminum, however, the third BHT-Al-BHT angle is rather cramped, with a value of 106.3(3)°.

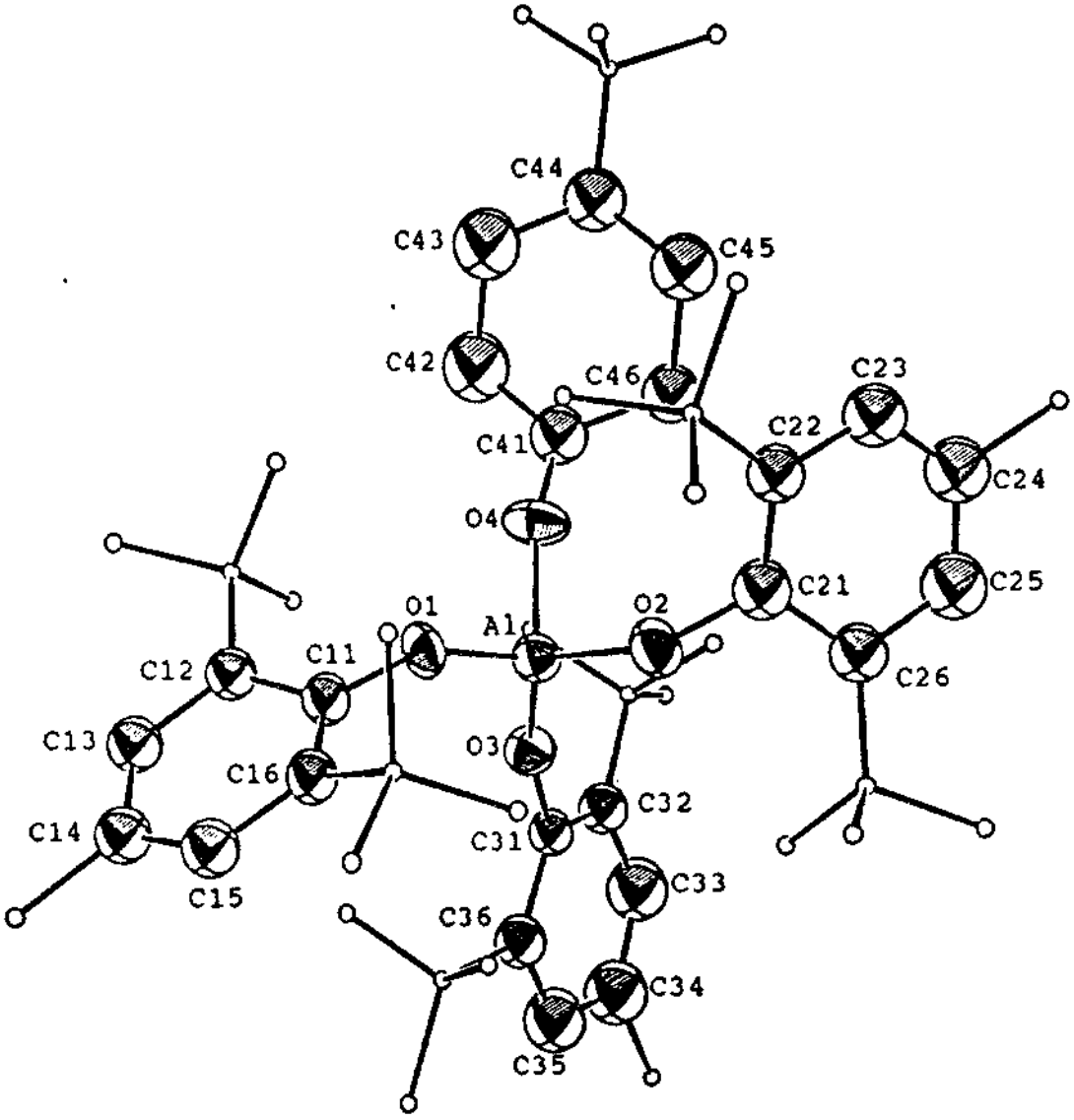


Figure 4-3. Molecular structure of complex **4**.

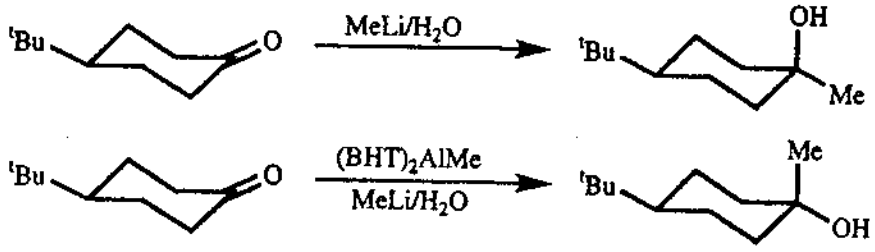
The increase in steric constraints at the aluminum has a very marked effect on the relationship between the Al-O bonds and the C-O-Al angles - namely, as would be expected given the mono- and disubstituted BHT complexes, that there is no relationship. The pairs of parameters are 1.717(5) Å and 146.7(6)°, 1.716(5) Å and 137.2(5)°, and 1.691(5) and 163.9(5)°, for O1 through O3, respectively.

The bonding to the ketone may be compared to mono- and disubstituted BHT aluminum complexes of carbonyl compounds (Table 4-5). In common with the bonds between aluminum and BHT oxygens, there is a general inverse correlation between Al-O bond length and C=O-Al angles. However, there is insufficient data to enable any discussion of the relationship between the geometric parameters and the acidity of the aluminum center or the basicity of the carbonyl group.

Table 4-5. Bond Angles and Lengths to the C=O Group in $Al(BHT)_nXY$ Complexes

X,Y	Carbonyl Compound	Al-O (Å)	C=O-Al (°)	Ref
n = 1				
Me, Me	$O{=}CPh_2$	1.907(8)	153.8(9)	170
n = 2				
Me	$O{=}CPh_2$	1.903(6)	144.0(8)	171
Me	$O{=}C(H)Bu^t$	1.920(3)	136.0(3)	170
Me	O=C(OMe)Ph	1.851(7)	174(1)	170
n = 3				
	O=(4-Bu^tCy)	1.841(6)	165.8(5)	This work

The structure of **4** enabled confirmation of a theory proposed[171] to account for selective axial alkylation of a substituted cyclohexanone by methyllithium in the presence of $(BHT)_2AlMe$ rather than the expected equatorial alkylation:[182]



As may be seen from the view in Figure 4-4, equatorial attack at C(41) is hindered by the *t*-butyl group C(321) through C(324).

The packing of the molecule in the crystalline phase (Figure 4-5) consists of discrete molecules which form loose hexagonal arrays that include the pentane of crystallization. No notably short intermolecular contacts are present.

4-3. Aluminum-Chalcogen Clusters

Clusters formed between elements of groups 13 and 16 are attracting increasing attention for their properties in both materials chemistry and industrial catalytic processes. Of particular interest within the context of this work are the alkyl alumoxanes (of empirical formula, RAlO)[183-185] which have been shown to be very specific co-catalysts for Ziegler-Natta catalysis,[186] and a series of group 13/group 16 cubane materials, which have been shown to produce readily the binary group 13/group 16 materials upon CVD treatment.[187] In this section, the structures of one example of each type of compound will be presented.

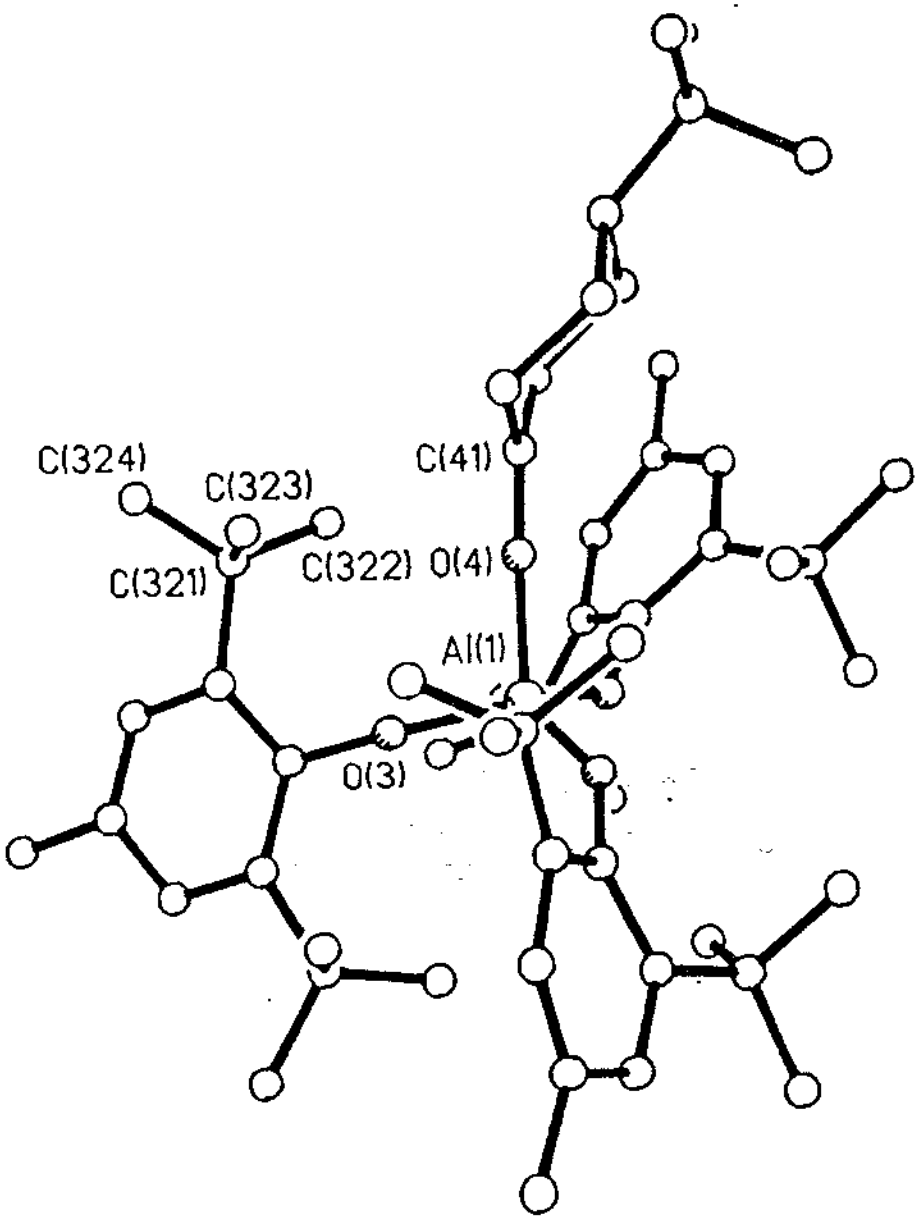


Figure 4-4. Side-on view of complex **4**.

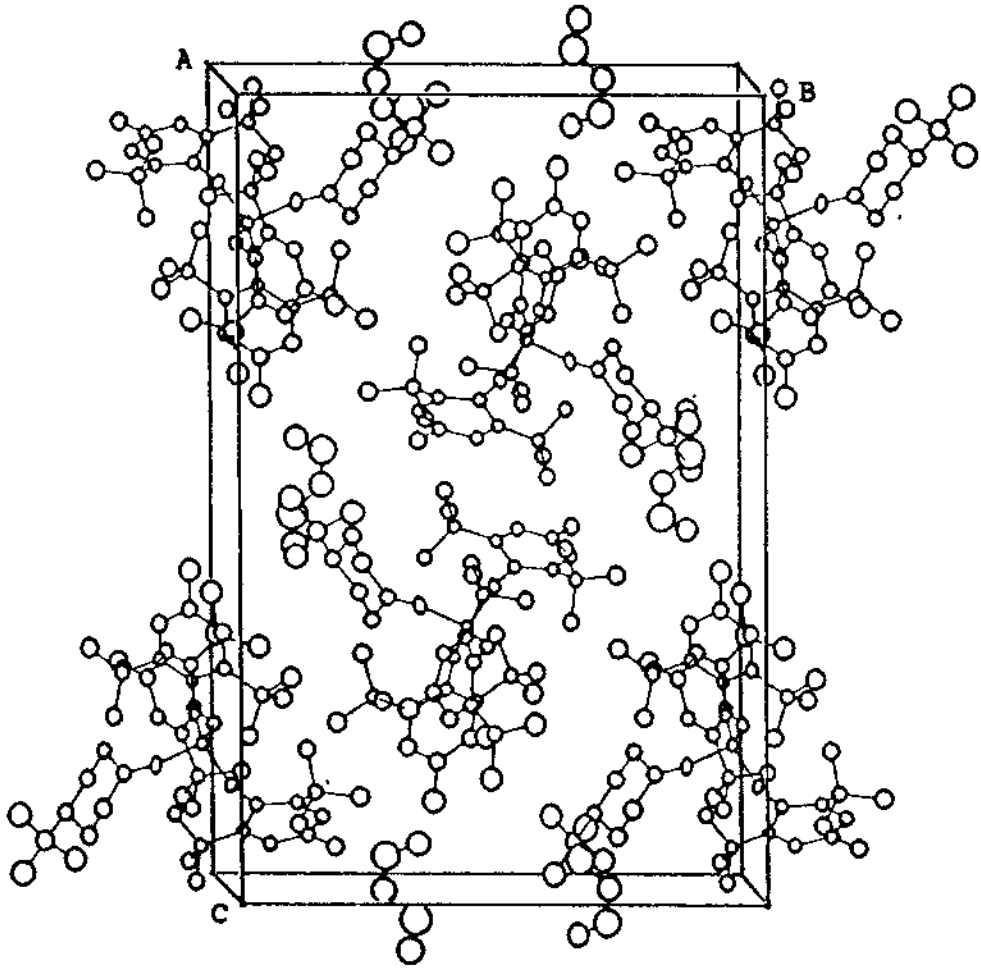
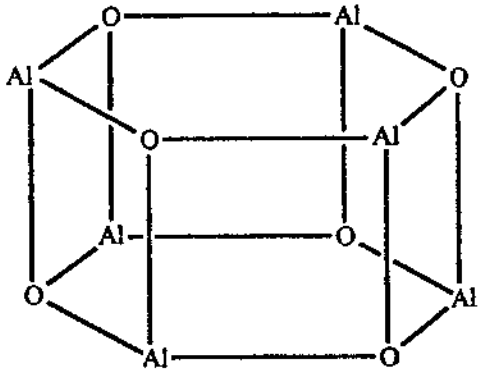


Figure 4-5. Unit cell packing of complex **4** · pentane.

An Alumoxane Amine Complex

Alumoxanes are oligomeric compounds of the general formula $(RAlO)_n$, formed by the controlled (or semi-controlled) hydrolysis of aluminum alkyls. These species are of immense industrial importance as catalysts for the polymerization of epoxides, aldehydes, and olefins.[136] Until recently, however, the exact nature of the catalytically active species was unknown as alumoxanes exist in many different forms which are related by multiple equilibria. In 1993, Barron published the full characterization of a series of *t*-butyl-substituted alumoxanes, which possess catalytic capability similar to that of the industrial mixtures.[183] Access to this system of relatively stable, pure species has resulted in the elucidation of many features of the polymerization processes.

One such process is the polymerization of ethylene and propylene by a mixture of a group 4 metallocene and alumoxane, first introduced by Kaminsky,[186] which has been subject to a detailed investigation by the Barron group.[185] One section of the study addresses the nature of polymer stabilization - currently achieved by addition of primary amines to the system.[188] It had been found, although not explained, that this stabilization requires an amount of added amine that far in excess of what might have reasonably been expected.



5

Addition of *n*-butylamine to a solution of a hexameric *tert*-butylalumoxane (**5**) results in the formation of colorless block-shaped crystals of **6**. These were of sufficient quality to enable study *via* X-ray diffraction.[189] The crystal, data collection and solution parameters are listed in Table 4-6 and important bond lengths and angles are collected in Table 4-7. The structure (Figure 4-6) consists of a hexanuclear aluminum species, in which two aluminum oxygen bonds (Al3...O3) in the alumoxane **5** have been broken, enabling bonding to two molecules of the amine. The gross geometry of the complex, therefore, has changed from a centrosymmetric hexagonal prismatic one, in which two hexagonal Al_3O_3 planar arrays are linked by six aluminum-oxygen bonds (forming six almost square rings) to a centrosymmetric structure in which two boat-shaped Al_3O_3 rings are linked by four aluminum-oxygen bonds (forming two four-membered rings and two boat-shaped six-membered rings). This cluster cleavage results in the release of substantial strain, as may be seen from an analysis of the bond angles at both the aluminum and oxygen atoms. The starting complex, **5**, contains 6 unique angles at the aluminums and 6 unique angles at the oxygens in the range 85.2(2)° to 94.1(2)°. As a result of the reduction in the number of four-membered rings, complex **6** only contains 2 of each type (which range from 85.3(2)° to 96.5(2)°) providing a driving force for the complexation. It should be pointed out that the role of alumoxanes in the catalytic process are as Lewis acids, used to create a vacant coordination site on the metal by complexation of one of the metal ligands. The fact that this complexation to the amine occurs is not, therefore, wholly surprising.

Table 4-6. Crystal and Solution Data for **6**

Formula	$C_{32}H_{76}Al_6N_2O_6$
Crystal size (mm)	0.08 x 0.11 x 0.13
Molecular Mass	746.86
Crystal System	triclinic
Space Group	P1 bar
Unit cell:	
a (Å)	10.637(7)
b (Å)	10.665(4)
c (Å)	11.354(8)
α (°)	65.41(5)
β (°)	87.05(6)
γ (°)	80.55(4)
V ($Å^{3)}$	1155(1)
Z	1
D_c (g/cm^3)	1.074
μ (cm^{-1})	1.70
2θ range	2 - 40
No. data collected	2160
No. observed data ($I > 2.5\sigma(I)$)	1217
R	0.0467
R_w	0.0618
GOF	1.67
maximum residual electron density	0.29
maximum shift/e.s.d.	<0.01

Table 4-7. Important Bond Lengths (Å) and Angles (°) for Complex **6**

Atoms	Length	Atoms	Length
Al1 - O1	1.826(3)	Al1 - O2	1.817(5)
Al1 - O3	1.712(5)	Al1 - C11	1.942(7)
Al2 - O1	1.889(5)	Al2 - O2	1.845(3)
Al2 - O3'	1.785(5)	Al2 - C21	1.993(7)
Al3 - O1	1.761(4)	Al3 - O2'	1.703(5)
Al3 - C31	1.935(5)	Al3 - N41	2.042(7)

Atoms	Angle	Atoms	Angle
O1 Al1 O2	87.9(2)	O1 Al1 O3	103.8(2)
O1 Al1 C11	116.4(2)	O2 Al1 O3	108.5(2)
O2 Al1 C11	119.0(3)	O3 Al1 C11	116.8(3)
O1 Al2 O2	85.3(2)	O1 Al2 O3'	106.7(3)
O1 Al2 C21	118.5(3)	O2 Al2 O3'	105.2(2)
O2 Al2 C21	118.1(2)	O3' Al2 C21	118.0(3)
O1 Al3 O2'	107.7(2)	O1 Al3 N41	96.5(2)
O1 Al3 C31	119.5(3)	O2' Al3 N41	104.0(2)
O2' Al3 C31	117.2(3)	N41 Al3 C31	108.8(3)
Al1 O1 Al2	92.2(2)	Al1 O1 Al3	118.9(2)
Al2 O1 Al3	115.1(2)	Al1 O2 Al2	94.0(2)
Al1 O2 Al3'	115.6(2)	Al2 O2 Al3'	116.3(2)
Al1 O3 Al2'	126.9(2)	Al3 N41 C42	113.6(7)

' (x,y,z) → (1-x,2-y,1-z)

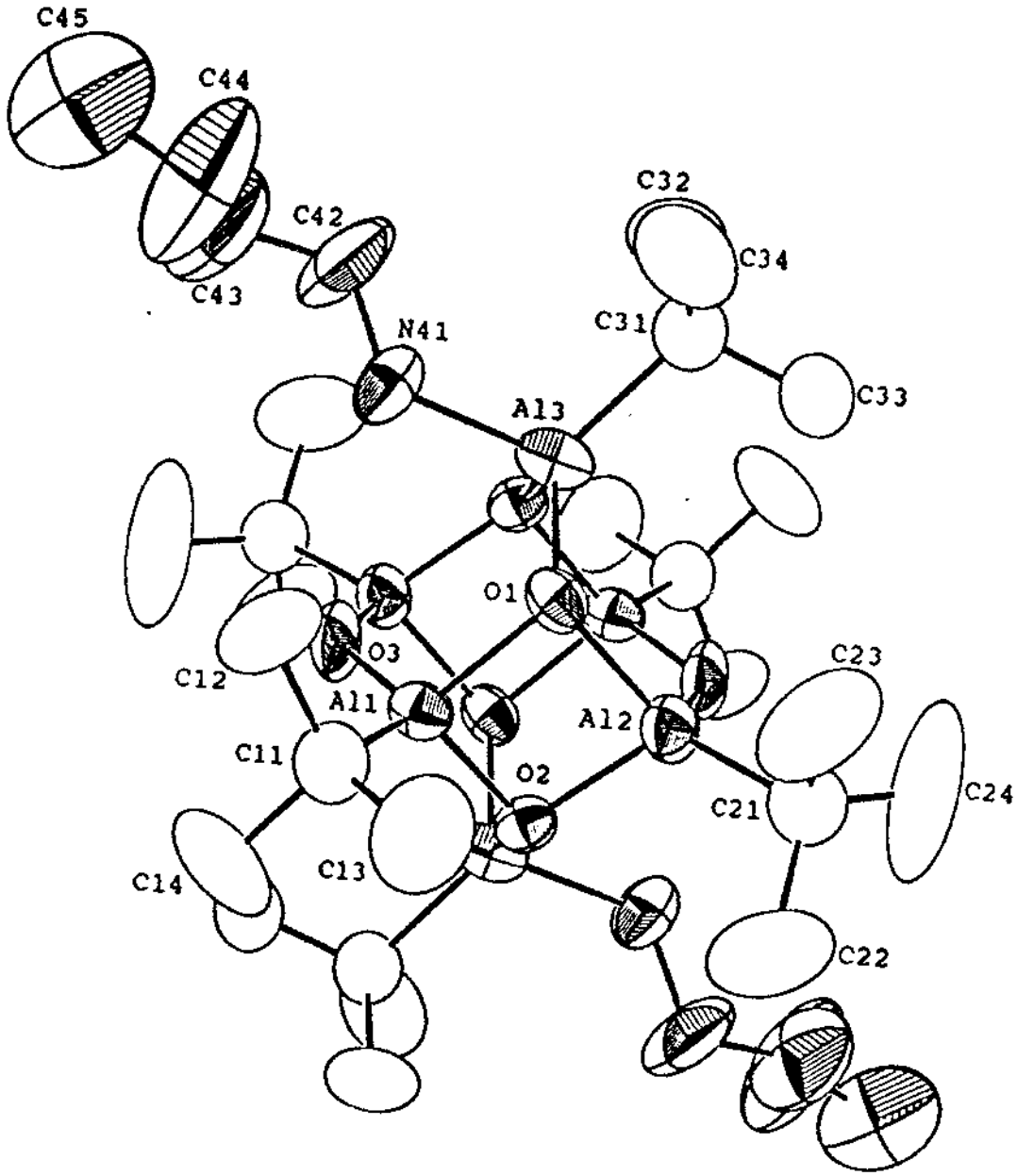


Figure 4-6. Molecular structure of Complex **6**

What is unexpected is the relative stability of the structure. The hexameric starting material is highly unstable in the crystalline form - which would be expected due to the presence of six aluminum-carbon bonds. Indeed, structure solution was accomplished for the hexamer only after combination of three partial data sets from crystals that decayed during data collection (over twenty crystals were required in the whole process).[183,190] In contrast, crystals of **6**, while still sensitive, display much greater stability.

The effect of the cleavage on the geometrical parameters about the aluminum atoms is quite pronounced. In **5**, the aluminum-oxygen bond lengths fall into two categories - those within the planar ring which range from 1.760(6) to 1.795(5) Å, and those that join the two rings, which are much longer due to the constraints of the four-membered rings and range from 1.880(5) to 1.905(4) Å. The situation in **6** is much more complex, due to the presence of a μ^2-oxygen as well as the μ^3-oxygens remaining from the starting material. The bonds to the doubly-bridging oxo group (O3) are short with values of 1.712(5) and 1.703(5) Å, as would be expected. However, the remaining bonds to the μ^3-oxygens, which should be equivalent from steric considerations as each is part of a four- and six-membered ring, show some asymmetry in that the bonds to Al1 are shorter than those to Al2. This asymmetry is also present when considering the aluminum carbons bonds; the bonds to Al1 and Al3 are essentially equivalent with values of 1.942(7) and 1.935(5) Å, which correspond well to the average value found in **5** of 1.94(1) Å, while the bond to Al2 is much longer, having a value of 1.993(7) Å.

The amine group, bound to Al3 suffers from rather high thermal parameters (as one would expect) so detailed analysis of its conformation is not appropriate. The Al3-N41 bond is of the expected length (2.042(7) Å)[191], and is oriented such that it threads through the neighboring *tert*-butyl groups.

The cell packing is unexceptional, as there is only one molecule per unit cell. No short intermolecular contacts are found.

An Aluminum-Sulfur Cubane[192]

Interest in main group cages has increased dramatically in the last few years, primarily due to the facile manner in which they may be converted to binary species.[193] One particular interest of the Barron group involves clusters formed between group 13 and group 16 elements other than the alumoxanes (*vide supra*).

One particular focus of the group has been gallium-sulfur cages, and in particular, different behavior induced by changing the organic substituent on gallium. The $Ga_4S_4(Bu^t)_4$ cube undergoes topological rearrangement upon thermolysis to give higher order clusters,[194] while the analogous *tert*-amyl compound converts smoothly to very pure gallium sulfide.[193] In light of this, the group has begun a program to investigate the properties of the *tert*-amyl complexes of other group 13/group 16 cubanes.

Reaction of $(Amyl^t)_3Al$ with H_2S followed by heating in toluene results in the formation and crystallization of complex **7**.[195] The crystal, data collection and solution parameters are listed in Table 4-8 and important bond lengths and angles are collected in Table 4-9. The structure (Figure 4-7) consists of an aluminum-sulfur cube that resides

on a crystallographic two-fold axis. The cube is distorted in the usual fashion[187] such that the intra-cube angles at the metals are larger than 90° (average 97.3(3)°) and those at the sulfur are smaller (average 82.2(3)°). The aluminum-sulfur distances range from 2.295(8) to 2.319(9) Å, in agreement with those reported previously.[196,197] Although the crystal quality was poor, so that in-depth analysis of other geometrical features is inappropriate, it should be mentioned that the aluminum-carbon distances are *ca.* 0.1 Å longer than in alumoxane clusters, reflecting the lower electronegativity of the chalcogen atom.

The structure solution was hampered by a static disorder in the *tert*-amyl groups, in which the methylene carbons of the ethyl groups occupy two positions in a 1:1 ratio, while the methyl position is not split. This form of disorder is rather rare, and usually occurs when the group furthest from the center of the molecule is involved in strong intermolecular attractions, yet the attached atoms may occupy more than one position.[198] As may be seen from the packing diagram (Figure 4-8), however, the molecules lie in open well-separated positions in the unit cell with no short intermolecular contacts.

Table 4-8. Crystal and Solution Data for Complex **7**

Formula	$C_{20}H_{44}Al_4S_4$
Crystal size (mm)	0.21 x 0.23 x 0.24
Molecular Mass	520.76
Crystal System	monoclinic
Space Group	C2/c
Unit cell:	
a (Å)	19.841(2)
b (Å)	9.561(2)
c (Å)	18.774(2)
β (°)	118.722(8)
V ($Å^3$)	3123.2(8)
Z	4
D_c (g/cm^3)	1.107
μ (cm^{-1})	4.09
2θ range	2 - 44
No. data collected	2111
No. unique data	2055
R_{int}	0.036
No. observed data ($I > 2.5\sigma(I)$)	679
R	0.0868
R_w	0.0900
GOF	1.82
maximum residual electron density	0.36
maximum shift/e.s.d.	<0.5

Table 4-9. Important Bond Lengths (Å) and Angles (°) for Complex **7**

Atoms	Length	Atoms	Length
S1 - Al1	2.316(9)	S1 - Al2	2.319(9)
S1 - Al2'	2.317(5)	S2 - Al1	2.295(8)
S2 - Al2	2.315(8)	S2 - Al1'	2.318(4)
Al1 - C11	2.05(3)	Al2 - C21	2.04(2)

Atoms	Angle	Atoms	Angle
Al1 S1 Al2	81.8(3)	Al1 S1 Al2'	82.0(2)
Al2 S1 Al2'	82.7(2)	Al1 S2 Al2	82.4(3)
Al1 S2 Al1'	82.3(2)	Al1' S2 Al2	82.0(2)
S1 Al1 S2	97.7(3)	S1 Al1 S2'	97.5(2)
S1 Al1 C11	116.2(8)	S2 Al1 S2'	97.1(3)
S2 Al1 C11	120.5(7)	S2' Al1 C11	122.6(6)
S1 Al2 S1'	96.7(2)	S1 Al2 S2	97.1(3)
S1 Al2 C21	117.8(8)	S1' Al2 S2	97.6(3)
S1' Al2 C21	121.6(8)	S2 Al2 C21	120.6(7)

' (x,y,z) → (1-x,y,3/2-z)

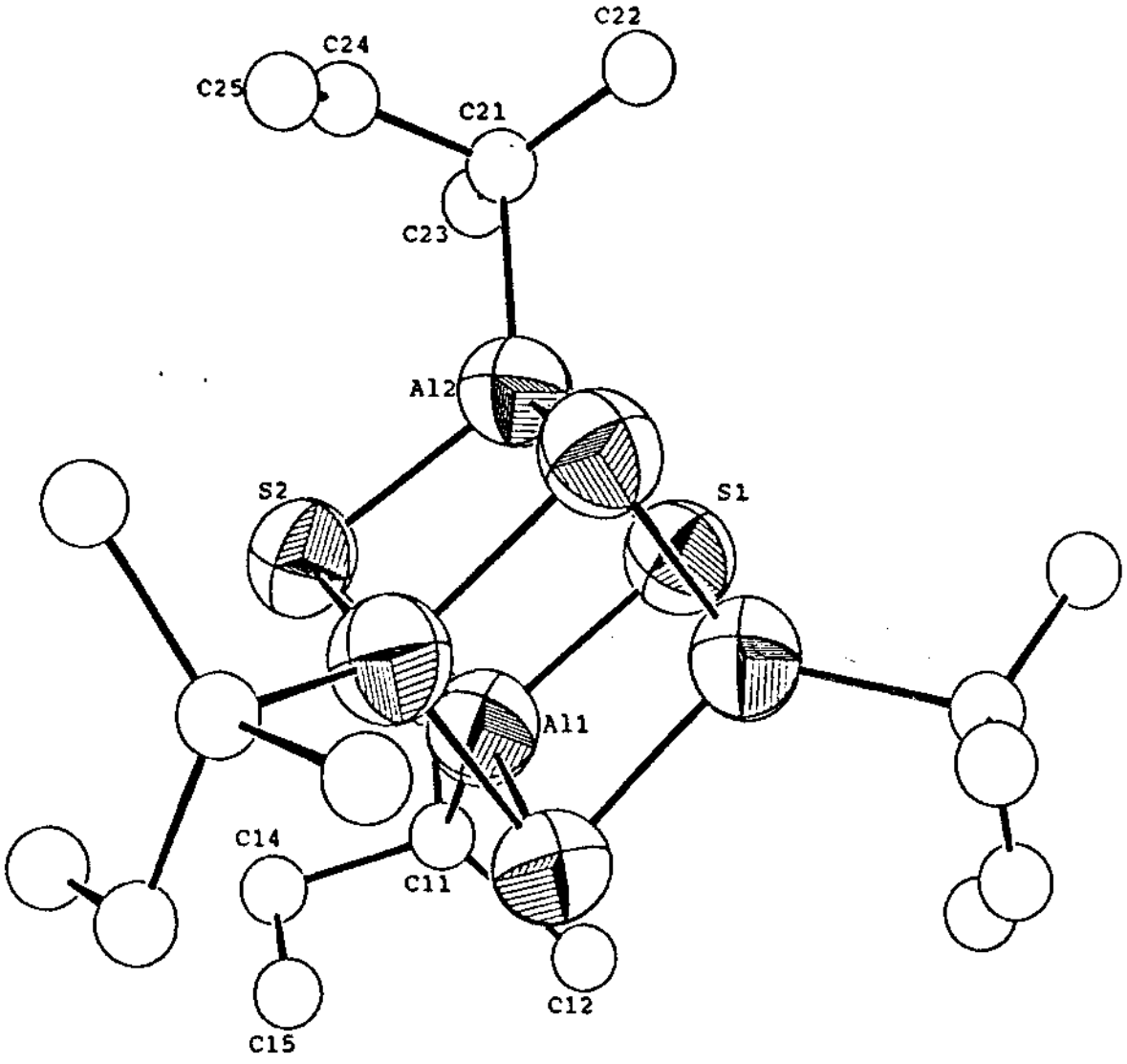


Figure 4-7. Molecular structure of Complex 7

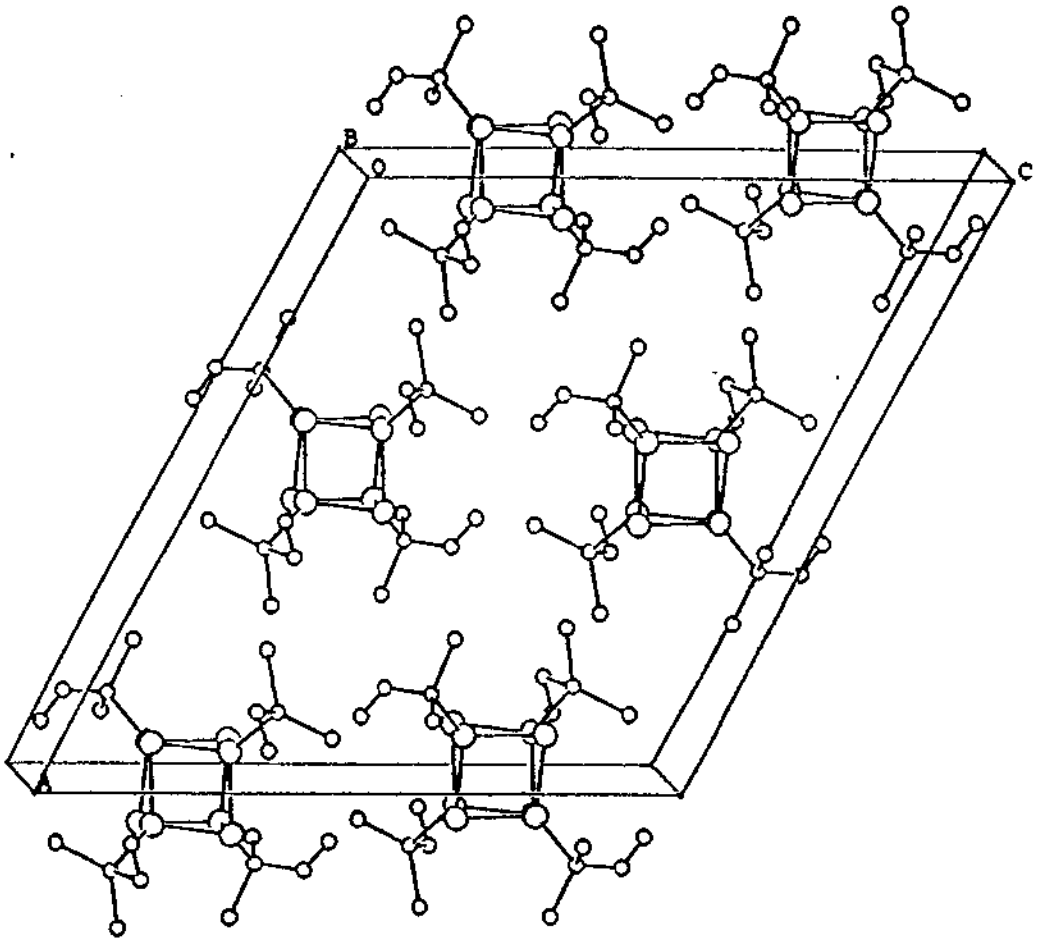


Figure 4-8. Unit cell packing of complex **7**

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