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Reversible Dissociation of a Dialumene

Rosalyn L. Falconer[a], Keelan M. Byrne[b], Gary S. Nichol[a], Tobias Krämer*[b], and Michael J. Cowley*[a]

[a] Dr R. L. Falconer, Dr G. S. Nichol, and Dr M. J. Cowley
School of Chemistry,
University of Edinburgh,
Edinburgh, UK.
E-mail: michael.cowley@ed.ac.uk
[b] Mr K. M. Byrne, Dr T. Krämer
Department of Chemistry,
Maynooth University
Maynooth, Co. Kildare, Ireland
E-mail: tobias.kraemer@mu.ie

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Abstract: Dialumenes are neutral Al(I) compounds with Al=Al multiple bonds. We report the isolation of an amidophosphine-supported dialumene. Our X-ray crystallographic, spectroscopic, and DFT computational analyses reveal a long and extreme trans-bent Al=Al bond with low dissociation energy and bond-order. In solution, the dialumene can dissociate into monomeric Al(I) species. Reactivity studies reveal two modes of reaction: as dialumene or as aluminyl monomers.

Introduction

Like other low oxidation-state main group systems, Al(I) compounds are revealing potential in bond-activation and catalysis.[1] Dialumenes are neutral Al(I) compounds with Al=Al multiple bonds. They sit alongside the prototypical neutral Al(I) compounds (Cp*Al)2 and NacNacAl(I), and the rapidly developing class of anionic aluminyl compounds.[2]

Dialumenes can be divided into two classes: base-coordinated dialumenes (R(L)=Al=Al(L)R), which are isoelectronic with alkene monomers, and “transient” dialumenes (RAI=AIR). Two base-coordinated dialumenes have been reported. The first, silyl substituted I, was reported by Inoue in 2017.[3a] An aryl analogue, II, followed (Figure 1).[5] Though base-free dialumenes (III) are yet to be isolated, “masked” examples that behave as RAl=AIR are known. Power reported the toluene adduct IV.[6] and Tokitoh the related benzene adduct V.[7]

Dialumenes readily activate dihydrogen and other small molecules.[5,6] Inoue’s I and II catalytically reduce CO2 with HBPin.[5b,7] This capability comes from closely spaced frontier molecular orbitals, which confer high reactivity. Even considering the only isolated examples, I and II, it is clear that understanding the interplay between substituents, bonding, and reactivity in dialumenes is critical to their further development.

Base-coordinated and base-free dialumenes are clearly related, but insights from experiment and theory reveal very different pictures of bonding. Dialumenes I and II feature planar or moderately trans-bent Al=Al bonds with double bond character, do not dissociate, and react as dialumenes. Experiment and theory reveal that donor-free dialumenes III feature low Al=Al bond orders and substantially trans-bent geometry.[8] These dialumenes can dissociate readily in solution: V appears to react as either RAl=AIR or RAI=AIR species.[9] Recently, Power showed that a larger terphenyl substituent allows access to an RAl: monomer rather than IV.[10]

A transient N,P-coordinated aluminyl monomer was implicated in our recent studies of reductive elimination in Al(II) dihydride VI (Figure 1c).[11] We thus targeted isolable Al(I) compounds of the same amidophosphine ligand.

Figure 1: a) Base-coordinated dialumenes (R-Si = MeBu:Si; Tip = 2,4,6-trisopropylphenyl); b) ‘masked’ dialumenes (Ar* = 2,6-(2,6-dimethylphenyl)phenyl); Bbp = 2,6-(bis(trimethylsilyl)methyl)phenyl). c) Reversible reductive elimination in VI (Mes = 2,4,6-trimethylphenyl).
Results and Discussion

We prepared dialumene 1 by reduction from the Al(II) precursor diiododialane. Treatment of 2 with 2 equiv. Na/K alloy in THF led to a colour change from yellow to dark purple. After 5 hours, $^{31}$P($^1$H) NMR spectroscopy revealed consumption of 2 and a new broad resonance at $\delta$ 21.3, as well as minor amounts of diolane VI. Crystalline dialumene 1 was isolated as a dark purple solid in 31 % yield from toluene at -30 °C. UV/vis spectroscopy revealed $\lambda_{max}$ 567.0 nm, which we assign to a $\pi$ to $\pi^*$ transition (Figure S3, Table S10). At 293 K, 1 decomposes over 1-2 days in THF, toluene or hexane solutions.

The solid-state structure of dialumene 1, determined by X-ray crystallography, reveals a highly trans-bent Al=Al bond in E configuration (Figure 2). Two-site disorder of the Al positions reveals major and minor isomers of 1 (88/12%) with distinct geometries around the Al2 core. The amidophosphine ligands enforce narrow N1–Al1–P1 angles (83 – 84°). The Al=Al distance in 1 is shorter by 0.1-0.2 Å than in the related Al(II) dihydridodialane VI or in Uhls’s diolane(4) ([SiMe$_3$]$_2$HC)Al–Al(CH(SiMe$_3$)$_2$); (1) 2.5190(14)/2.471(13) Å; VI 2.6586(16) Å; Uhls’s diolane 2.660(1) Å. Nevertheless, the Al=Al distance in 1 is notably longer (~0.1 Å) than in Inoue’s dialumenes [1 2.3943(16); II 2.4039(8)]. Compared to I and II, the Al=Al core of 1 is much less planar (1 $\theta$ = 48.8°/51.2°; I: 0°; II: 17.3°/23.7°). We note that the pyramidalised Al centres in 1 are stereoergic; the major and minor isomers in the solid-state structure have opposite stereochemistry at the Al centres.

DFT calculations reveal that the bonding situation in 1 is distinct from previous base-coordinated dialumenes I and II. Natural Bond Orbital (NBO) analysis of 1 shows natural localised molecular orbitals (NLMOs) representing Al–Al σ- and π-bonds (Fig 3a). Although it retains some apparent π-bond character, the corresponding NLMO of 1 is heavily localised on the aluminium centres; the relevant NLMOs of I or II more closely resemble classical π-orbitals (Fig S19/20). The localisation of the π-orbital in dialumene 1 results from admixture of the Al–Al $\sigma^*$. The extent of this admixture is revealed by the increased s-character of the NLMO of 1 (Al1/Al2 sp$^{1.29}$/sp$^{1.09}$) compared to that in e.g. II (Al1/Al2 sp$^{0.34}$/sp$^{0.23}$), where the π-bond is constructed from essentially pure p-orbitals. Consistent with this picture, the Wiberg bond index for the Al=Al bond of 1 is 1.31, which is increased from that of diolane VI (0.91) but lower than in I or II (1.67, 1.54).

Grützmacher and Fässler have proposed simple topographical criteria for distinguishing classical and non-classical multiple bonds.$^{[13]}$ Their criteria use the Electron Localisation Function (ELF), which identifies regions of localised valence electron density. The ELF of classically π-bonded systems reveals ‘attractors’ – local maxima M in the ELF that correspond to electron pairs – above and below the plane of E=E bonds. Each attractor M is surrounded by a ‘basin’ of electron density. The topology and electron population of such basins is interpretable in familiar terms as covalent bonds or lone pairs. Classical π-bonded systems have ‘dumb-bell’ shaped electron basins, and their populations sum to approximately 4 e$^-$.

Topological analysis of the ELF of 1 (Fig 3b) reveals a quite different picture. The characteristic pattern of attractors and basins for a slipped π-bond is observed. Three valence attractors, M$_1$/M$_2$, are found near the Al$_2$ unit. M$_3$ is centred on the Al–Al bond; its basin population is 1.11 e$^-$. M$_1$ and M$_2$ are above/below an Al centre, ‘slipped’ from their positions in a classical double bond. The basins of M$_1$/M$_2$ are each populated by ~1.30 e$^-$; the summed basin populations (3.76 e$^-$) correspond with the 4 e$^-$ available for bonding from the two Al(II) centres of 1.

The positions of attractors M$_1$/M$_2$ in 1 correspond with those in the base-free dialumene Al$_2$X$_2$. The sigmoidal form of the ELF isosurface of 1 is a feature of bonding in base-free dialumenes, along with low Al–Al bond order (~0.5) and diradical character.$^{[14]}$ Based on the basin population around M$_3$ (1.11 e$^-$), 1 also has low Al–Al bond order. M$_1$ and M$_2$ can be interpreted as non-bonding electron density at Al. In contrast, the ELF of planar
dialamene I reveals features of classical π-bonds: an attractor on each face of the Al–Al bond (Fig S23).

To better determine the Al–Al bond order in 1, we undertook Quantum Theory of Atoms in Molecules (QTAIM) analysis (Figure 3c and SI). The molecular graph reveals Al–Al, Al–N and Al–P bond paths. The Al–P interactions are polar dative bonds, as revealed by the position of their bond critical points (bcp) closer to the more electropositive Al centres and associated QTAIM parameters (\(\sigma_{bcp} = 0.310 \text{ e/Å}^3\), \(\nabla^2\sigma_{bcp} = +1.180 \text{ e/Å}^5\), \(H_{bcp} = -0.107 \text{ E}/\text{Å}^3\), \(G_{bcp}(\sigma_{bcp}) < 1\)).\(^{[15]}\) Meanwhile the Al–N bonds exhibit stronger ionic character (\(\sigma_{bcp} = 0.499 \text{ e/Å}^3\), \(\nabla^2\sigma_{bcp} = +8.410 \text{ e/Å}^5\), \(H_{bcp} = -0.094 \text{ E}/\text{Å}^3\), \(G_{bcp}(\sigma_{bcp}) < 1\)). The Al–Al bond features weak shared-shell covalent character as judged by the charge concentration and topological parameters at its bcp (\(\sigma_{bcp} = 0.349 \text{ e/Å}^3\), \(\nabla^2\sigma_{bcp} = -1.390 \text{ e/Å}^5\), \(H_{bcp} = -0.135 \text{ E}/\text{Å}^3\), \(G_{bcp}(\sigma_{bcp}) < 1\)). In accordance with the ELF results, the values of both \(\sigma_{bcp}\) and \(\nabla^2\sigma_{bcp}\) are rather low, indicating a weak Al–Al bond. The bond ellipticity parameter suggests a small degree of double bond character (\(\epsilon_{bcp} = 0.195\)).

The delocalisation index \(\delta(A,B)\) is a quantitative measure for the number of electron pairs exchanged between two atomic basins. When referenced against a chemically-similar comparator compound with a well-defined bonding situation, the delocalisation index can reflect chemical bond order. Here, we use \(\delta(Al,Al)\) of the bond in dihydrodialanine VI to define an Al–Al bond order of 1. At 0.65, \(\delta(Al,Al)\) in VI is about half that in the planar transition state TS1C–1C (see later) which unequivocally has a planar Al=Al double bond (\(\delta(Al,Al) = 1.21\)). In trans-bent dialamene 1, \(\delta(Al,Al)\) at 0.80 is only slightly higher than that of dialane VI, but much lower than that of the Al=Al double-bond.\(^{[14]}\)

The combined results of our crystallographic and electronic structure analyses indicate small but significant Al–Al multiple bond character in 1. Al–Al bond distance, and computational bond order and delocalisation-index criteria all support the conclusion that the Al=Al bond in 1 is intermediate between single and double bonds, with bond order \(< 1.3\).

Why is dialamene 1 so different from I and II? We used DFT calculations on a set of minimal base-coordinated dialamenes with NHC or PMe3 donors and hydride, phenyl, silyl or amino substituents (Table 1) to answer this question.\(^{[16]}\)

### Table 1. Selected geometrical and thermodynamic properties of model dialamenes calculated at M062X-D3/def2SVP//SMD-B3LYP-D3/6-311G(2d,2p) level\(^{[b]}\)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>Ph</th>
<th>SiMe3</th>
<th>L</th>
<th>Ph</th>
<th>SiMe3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al=Al / Å</td>
<td>2.42</td>
<td>2.44</td>
<td>2.39</td>
<td>2.48</td>
<td>2.45</td>
<td>2.47</td>
</tr>
<tr>
<td>L–Al–R / °</td>
<td>101.7</td>
<td>97.1</td>
<td>112.1/106.9</td>
<td>91.9</td>
<td>95.8</td>
<td>92.7</td>
</tr>
<tr>
<td>(\theta) / °</td>
<td>29.6/47.2(^{[b]})</td>
<td>33.4/53.9(^{[b]})</td>
<td>19.1/16.3(^{[b]})</td>
<td>43.1</td>
<td>46.6</td>
<td>50.5/50.4</td>
</tr>
<tr>
<td>(\Delta G_{bcp}) (disoc., kcal mol(^{-1}))</td>
<td>22.1</td>
<td>20.6</td>
<td>33.2</td>
<td>11.5</td>
<td>19.3</td>
<td>19.7</td>
</tr>
<tr>
<td>(\Delta E_{bcp}) (monomer, kcal mol(^{-1}))</td>
<td>19.2</td>
<td>20.6</td>
<td>12.3</td>
<td>25.5</td>
<td>23.2</td>
<td>25.4</td>
</tr>
</tbody>
</table>

[a] \(L = \text{NHC, Imidazol-2-ylidene (C=H-N)}\). [b] \(\theta\) = trans-bend angle, see Figure 2. Unless otherwise noted, \(\tau = 0°\). Where two values are listed, complexes are unsymmetrically trans-bent. [c] corrected for basis set superposition error (Table S7). [d] \(\tau = 17.8°\). [e] \(\tau = 20.5°\). [f] \(\tau = 7.9°\). [g] \(\tau = 19.8°\).

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The structures of the model dialumenes depend strongly on the substituent and Lewis base (NHC or PMe3). Electropositive substituents (SiMe3) provoke shorter Al=Al bonds, wider R−Al−L angles, and more planar structures. More electronegative (Si < H < Ph < N) or π-donating substituents induce more trans-bending and longer Al−Al bonds. NHC-coordinated dialumenes always have shorter and more planar Al=Al bonds than their PMe3 counterparts (Al=Al = 2.42–2.48 Å vs 2.45–2.60 Å).

These substituent effects mimic those in disilenes, reflecting the isoelectronic relationship between R3Si=SiR3 and R(L)Al=Al(L)R. In disilenes, trans-bend angles and Si=Si bond distances are correlated with the singlet-triplet energy gap (ΔE(σT)) of the notional or real silylene monomers, :Si=Si[17]. We find that the same relationship applies to dialumenes: Al=Al bond dissociation energy increases as ΔE(σT) for the monomeric [R(L)Al]2 fragments decreases (Figure S11). The result is that dialumene bond dissociation energy/geometry can be predicted based on properties of the R(L)Al: (aluminy1) monomer.

We attribute the stronger and more planar Al=Al bonds of NHC- vs PMe3-coordinated dialumenes to the strong donor ability of the NHC, which raises the R(L)Al: HOMO electron density and stabilizes the R(L)Al: fragment (Table S9). The lower dissociation energy for Me3N(PMe3)Al=Al(PMe3)NMe2 (2.1 kcal mol−1) is explained by the large ΔE(σT) for the Me3N(PMe3)Al: fragment (32.4 kcal mol−1).

Returning to dialumene 1, we can assign its extreme trans-bending to the electronegative/π-donating NR2 substituent and narrow 85º N1−Al1−P1 angle enforced by the ligand, which both increase ΔE(σT) in the monomeric aluminy1 fragment (Table S9). Calculations on the full dialumene 1 predict a bond dissociation energy of 7.1 kcal mol−1, vs 25.0 and 19.0 kcal mol−1 for I and II (Table S7). To explore the possible dissociation of 1, we turned to its solution-phase behaviour.

Dialumene 1 is predominantly dimeric in solution. Its 31P{1H} NMR spectrum at 300 K has one broad signal at δ 21.3 (Δν/2 = 134 Hz) (Figure 4a). 1H NMR spectroscopy reveals two ligand environments for 1, in the ratio 54%:46%, indicating at least two (stereo)isomers. The stereogenic Al centres of 1, in combination with its ligand backbone, mean that there are three possible diastereomers of E-1, A-C (Figures 4a, S1), each of which must have distinct 31P signals. [16] 1A and 1B are meso compounds with equivalent phosphorus centres – each will give rise to a singlet. 1C has inequivalent phosphorus centres, so two 31P resonances (potentially doublets with 3Jp,P) are observed. The pattern of DFT-predicted 31P signals confirms our stereochemical analysis (Figure 4c, S15).

At 300 K, the broad 31P{1H} resonance at δ 21.3 indicates diastereomers 1A-C are exchanging. Cooling to 243 K resolves this broad signal into two singlets (δ 20.4 and 20.0). At 203 K, the higher field signal (δ 19.5) broadens and approaches coalescence (Δν/2 = 140 Hz).

The dynamic 31P{1H} NMR behaviour of 1 arises from a combination of intra- and intermolecular exchange process that exchange diastereomers 1A-C. In the low temperature regime (< −300K), only intramolecular fuxional processes are operative. The two singlets observed at 243 K are assigned to 1A/B and 1C. A “trans-flip” process, fast on the NMR timescale at this temperature, simultaneously inverts the stereochemistry at both aluminium centres (Figure 4b). This has the effect of interconverting diastereomers 1A and 1B, generating a (concentration-weighted) time-averaged signal for them. In 1C, the trans-flip is instead a degenerate process that exchanges the two inequivalent phosphorus centres, leading to the observed singlet. At 203 K, we assign the broad signal to 1C, in which the trans-flip is becoming slow on the NMR timescale.

Using DFT calculations we were able to locate the planar transition states TS1A-1B and TS1C-1C for the trans-flip process (Figure 4d). The barriers for this process range from 8 to 11 kcal mol−1. TS1C-1C is higher in energy than TS1A-1B (11.35 vs 9.37 kcal mol−1).

In the higher temperature regime (~300 K), exchange between isomers 1A/B and 1C becomes active through an intermolecular route. Dissociation of dialumene 1 generates monomeric aluminy1 3, which can then recombine to form any of the three diastereomers of 1 (Figure 4c). This process is possible due to the low dissociation energy of 1, (DFT predicts ΔG80 = +7.1 kcal mol−1). 2D 1H EXSY NMR spectroscopy at 300 K reveals exchange cross peaks between resonances for 1A(1B) (time averaged) and 1C (Figures S67). Our DFT calculations place diastereomers 1A-C very close in energy, spanning just 2 kcal mol−1. Experimental measurements are consistent with this. We were able to determine the equilibrium constants for the exchange of [1A+1B] with 1C in the temperature range 188 – 243 K (Figure S5). We can thus estimate ΔG for [1A+1B] → 1C as 0.8 ± 0.2 kJ mol−1 (0.19 ± 0.04 kcal mol−1).

The presence of aluminy1 3 in solution is revealed by dynamic NMR behaviour, but its concentration must be rather low since we did not observe signals for it. Nor did UV-vis spectroscopy in the temperature range 5–65 °C reveal absorptions for 3 (Figure S3). Lacking direct spectroscopic evidence, we sought to trap 3.

Like I and II, 3 can react with alkenes and alkynes to form 4-membered aluminacycles. Treatment of 1 with ethene (1 atm) at room temperature results in rapid (5-20 mins) conversion to dialuminacyclobutane 4 by formal [2+2] cycloaddition of the Al=Al and C=C bonds. Similarly, diphenylacetylene reacts with 1 to form dialuminacyclobutene 5 (Scheme 2). 31P{1H} NMR spectroscopy of 4 and 5 reveals distinct signals for three diastereomers in each case. This is a result of the ‘locking’ of the stereogenic aluminium centres enforced by their cyclic structures (δ 11.6 (d, J3P,P = 12 Hz), 11.5 (s), 11.5 (s), 11.4 (d, J3P,P = 12 Hz); 5 δ 11.0 (br s), 10.7 (s), 10.4 (s), 10.3 (br s); see SI).

X-ray crystallography reveals the geometry of the C2Al2 rings of 4 and 5. The Al−Al distances in 4 and 5 are not notably longer than in 1, despite destruction of the Al=Al π bond (1, 2.519(1) Å; 4, 2.558(1) Å; 5, 2.512(1) Å, see SI). This is rather different to the behaviour of dialumenes I or II in comparable reactions with alkenes/alkynes. The resulting analogues of 4/5 exhibit substantial Al−Al bond elongation (0.20–0.25 Å) compared to VII. The difference reflects the lower Al=Al bond order in 1 vs II/III.

When dialumene 1 is treated with the bulkier alkyl Me3SiC≡CSiMe3, the observed product is derived not from 1 but rather from its monomer, 3. On addition of Me3SiC≡CSiMe3, purple solutions of 1 become yellow within three hours. 31P{1H} NMR reveals a broad signal at δ 9.8, characteristic of amidophosphate-coordinated Al(III) compounds.[19]

X-ray crystallography shows that the product from 1 and Me3SiC≡CSiMe3 is aluminacyclop propane 6 (Figure 5). 6 has the narrow C1–Al−C2 angle expected for aluminacyclopropanes.
Figure 4. a) $^{31}$P($^1$H) NMR spectra of $^1$ (161 MHz, d$_8$-toluene) recorded at 203-300 K. b) Inversion at aluminium exchanges $1\text{A}$ and $1\text{B}$, but is degenerate for $1\text{C}$. c) Intermolecular dissociation/recombination exchanges diastereomers $1\text{A}$/$1\text{B}$ and $1\text{C}$. d) Reaction energy profile for the 'trans-flip' isomerisation in $1$. 

$\Delta G^1 1\text{A} \rightarrow 1\text{B} = 7.46 \text{ kcal mol}^{-1}$
$\Delta G^1 1\text{B} \rightarrow 1\text{A} = 9.37 \text{ kcal mol}^{-1}$
$\Delta G^1 1\text{C} \rightarrow 1\text{C} = 10.07 \text{ kcal mol}^{-1}$
The reaction of dialumene 1 with alkynes directly with NacNacAl(I) is also a viable.

The characteristic reaction for neutral aluminyls is A NacNac (1.367(2) Å). Cycloaddition reactions with alkynes are a RESEARCH ARTICLE

Structurally, the AlC2 core of 5 and its NacNac analogue are closely comparable.

Conclusion

In summary, we have prepared the first isolable dialumene that dissociates in solution. The donor properties of the amidophosphine ligand generate a large ΔEtrans on the transient aluminyl monomers. This large ΔEtrans is the origin of the low bond order, high trans-bending, and weak Al=Al bond in 1. We continue to explore the reactivity of 1 and related systems.

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Keywords: aluminium • low-valent • dialumene • multiple bonds • Al(I)

By calculating $\delta$(Al,Al)$_{1}$/\delta$(Al,Al)$_{VI}$ we can estimate the Al–Al bond order in 1 as 1.24. For details see: D. B. Chesnut, Chem. Phys. 2006, 321, 269–276.


$Z$ isomers of 1 are ruled out on the basis of their higher energy, see SI.

Deposition Numbers 2100531 (1) and 2100549-51 (4-6) contain the crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service www.ccdc.cam.ac.uk/structures.
A highly trans-bent dialumene has marginal Al=Al double bond character and, in solution, can dissociate into monomeric aluminyl fragments. Reactivity studies reveal that both the dialuminene and aluminyl monomer can be trapped by varying the reaction partner. DFT calculations elaborate the origins of the extreme trans-bending, weak Al=Al bond, and define substituent effects in dialumenes.

Institute and/or researcher Twitter usernames: @cowley_group @RosalynFalconer @TobiKraemer @keelan542