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# The [2 + 4] Diels-Alder Cycloadditon Product of a Probable Dialuminene, Ar'AlAIAr' $^{\prime}\left(\mathrm{Ar}^{\prime}=\mathrm{C}_{6} \mathrm{H}_{3}-2,6-\mathrm{Dipp}_{2}\right.$; Dipp $=\mathrm{C}_{6} \mathrm{H}_{3}-2,6-\mathrm{Pr}^{\mathrm{i}}{ }_{2}$ ), with Toluene 

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Heavier group 14 element alkene analogues $\left(\mathrm{R}_{2} \mathrm{MMR}_{2} ; \mathrm{M}=\right.$ $\mathrm{Si}^{1}$ and $\mathrm{Ge},{ }^{2} \mathrm{R}=$ organo or related group) react with dienes to give cycloaddition products in a manner similar to the Diels-Alder reaction. In contrast, the unavailability of potentially double-bonded compounds RMMR ( $\mathrm{M}=\mathrm{B}-\mathrm{Tl}$ ) has prevented the analogous studies for group 13 species. Calculations for the hydrides HMMH $(\mathrm{M}=\mathrm{Ga}, \mathrm{In})^{3}$ and IR data on matrix-isolated species at low temperature, ${ }^{4}$ indicate a trans bent HMMH skeleton and weak $\mathrm{M}-\mathrm{M}$ bonding (ca. $3 \mathrm{kcal} \mathrm{mol}^{-1}$ ). The recently synthesized compounds $\mathrm{Ar}^{\prime} \mathrm{MMAr}^{\prime}\left(\mathrm{M}=\mathrm{Ga},{ }^{5 \mathrm{a}} \mathrm{In},^{5 \mathrm{~b}}\right.$ and $\mathrm{Tl} ;{ }^{5 \mathrm{c}} \mathrm{Ar}^{\prime}=\mathrm{C}_{6} \mathrm{H}_{3}-2,6-$ Dipp $_{2}$, Dipp $=\mathrm{C}_{6} \mathrm{H}_{3}-2,6-\operatorname{Pr}^{\mathrm{i}}{ }_{2}$ ) were also found to have a trans bent structure and $\mathrm{M}-\mathrm{M}$ distances that were longer than single bonds. Moreover, they dissociated to $\mathrm{Ar}^{\prime} \mathrm{M}$ monomers in hydrocarbons at room temperature which is consistent with weak $\mathrm{M}-\mathrm{M}$ bonding. Nonetheless, the "dialuminene" isomer, HA1AIH, was predicted to have a stronger $\mathrm{M}-\mathrm{M}$ bond (ca. $10 \mathrm{kcal} \mathrm{mol}^{-1}$ ) than its heavier congeners, ${ }^{6}$ and the $\mathrm{Al}-\mathrm{Al}$ distance was calculated to be $2.613 \AA$, which is shorter than most $\mathrm{Al}-\mathrm{Al}$ single bonds in the dialanes $\mathrm{R}_{2}-$ $\mathrm{AlAlR}_{2}{ }^{7}$ These data suggested the possibility of isolating an aluminum species of formula RA1A1R and the study of addition reactions to the $\mathrm{Al}-\mathrm{Al}$ double bond. We now show that reaction of $\mathrm{Ar}^{\prime} \mathrm{AlI}_{2}$ (1) with $\mathrm{KC}_{8}$ afforded the 1,2-diiodoalane (2) and probably, the "dialuminene" (3) according to


Thus far, the "dialuminene" $\mathbf{3}$ has not been isolated as a pure species but has been found to crystallize only from toluene. It reacts with this solvent to form the cycloaddition product $\mathbf{4}$ as shown by


Compound $\mathbf{3}$ was generated by the reduction of $\mathrm{Ar}^{\prime} \mathrm{AlI}_{2}$ with 2 equiv of $\mathrm{KC}_{8}$ in $\mathrm{Et}_{2} \mathrm{O}$. Removal of the solvent and subsequent extraction into toluene, followed by separation of $\mathbf{2}$, which is less soluble, and cooling in a ca. $-30{ }^{\circ} \mathrm{C}$ freezer, afforded 4 as red crystals in $17 \%$ yield. ${ }^{8 a}$ Compound 2, an isolable intermediate en route to $\mathbf{3}$ can also be synthesized as a pale yellow solid in $40 \%$ yield from the reduction of $\mathbf{1}$ with 1 equiv of $\mathrm{KC}_{8} .{ }^{8 \mathrm{~b}}$ Yellow crystals of $\mathbf{2}$ were grown from $\mathrm{C}_{6} \mathrm{D}_{6}$ solution, and its structure (Figure 1) ${ }^{9}$ shows that 2 is a unique example of an unsolvated halogensubstituted dialane. ${ }^{10}$ It has a short $\mathrm{Al}-\mathrm{Al}$ single bond 2.609(2) due to the contraction of the effective radius of Al by the iodine substituent. The large Ar' groups are orientated trans to each other, and the $\mathrm{C}-\mathrm{Al}-\mathrm{Al}$ angle is nearly $15^{\circ}$ wider than the $\mathrm{I}-\mathrm{Al}-\mathrm{Al}$ angle.


Figure 1. Selected bond lengths ( $\AA$ ) and angles (deg) for 2. H atoms are not shown. $\mathrm{Al}(1)-\mathrm{Al}(1 \mathrm{~A})=2.609(2), \mathrm{Al}(1)-\mathrm{C}(1)=1.964(4), \mathrm{Al}(1)-$ $\mathrm{I}(1)=2.5020(12), \mathrm{C}(1)-\mathrm{Al}(1)-\mathrm{Al}(1 \mathrm{~A})=128.16(12), \mathrm{C}(1)-\mathrm{Al}(1)-\mathrm{I}(1)$ $=118.25(11), \mathrm{I}(1)-\mathrm{Al}(1)-\mathrm{Al}(1 \mathrm{~A})=113.56(6)$.


Figure 2. Selected bond lengths $(\AA$ ) and angles (deg) for 4. H atoms are not shown. $\mathrm{Al}(1)-\mathrm{Al}(2)=2.5828(7), \mathrm{Al}(1)-\mathrm{C}(1)=2.0004(16), \mathrm{Al}(2)-$ $\mathrm{C}(4)=2.0032(15), \mathrm{Al}(1)-\mathrm{C}(8)=1.9946(15), \mathrm{Al}(2)-\mathrm{C}(38)=1.9990-$ (15), $\mathrm{C}(2)-\mathrm{C}(3)=1.337(2), \mathrm{C}(5)-\mathrm{C}(6)=1.344(2), \mathrm{C}(1)-\mathrm{C}(2)=1.509(2)$, $\mathrm{C}(3)-\mathrm{C}(4)=1.503(2), \mathrm{C}(4)-\mathrm{C}(5)=1.509(2), \mathrm{C}(6)-\mathrm{C}(1)=1.496(2)$, $\mathrm{C}(1)-\mathrm{Al}(1)-\mathrm{Al}(2)=91.95(5), \mathrm{C}(4)-\mathrm{Al}(2)-\mathrm{Al}(1)=93.45(5), \mathrm{C}(8)-\mathrm{Al}-$ $(1)-\mathrm{Al}(2)=142.18(5), \mathrm{C}(38)-\mathrm{Al}(2)-\mathrm{Al}(1)=141.08(5)$.

The air- and moisture-sensitive 4 was characterized by ${ }^{1} \mathrm{H}$ and ${ }^{13} \mathrm{C}$ NMR, and UV-vis. The ${ }^{1} \mathrm{H}$ NMR spectrum featured characteristic alkane and alkene hydrogen signals at 2.63-2.74 and 5.91 ppm that were indicative of localized $\mathrm{C}=\mathrm{C}$ double bonding in a toluene that had undergone cycloaddition to Ar'AlAlAr'. Attempts to observe an ${ }^{27} \mathrm{Al}$ NMR signal were unsuccessful. The absence of a signal is probably a result of the unsymmetric aluminum environment which broadens the signal into the baseline. ${ }^{11}$ The ${ }^{1} \mathrm{H}$ and ${ }^{13} \mathrm{C}$ NMR data were confirmed by X-ray crystallography as shown in Figure 2. The respective bond lengths for $\mathrm{C}(2)-\mathrm{C}(3)$ and $\mathrm{C}(5)-\mathrm{C}(6)$ are $1.337(2)$ and $1.344(2) \AA$ and are characteristic of $\mathrm{C}=\mathrm{C}$ double bonding. ${ }^{12}$ The other four ring $\mathrm{C}-\mathrm{C}$ distances are in the range $1.496(2)-1.509(3) \AA$ which indicated $\mathrm{C}-\mathrm{C}$ single bonding between approximately $\mathrm{sp}^{2}$ hybridized carbons. ${ }^{12}$ The Al(1) $-\mathrm{Al}(2)$ distance, $2.5828(7) \AA$, is shorter than that in 2 and is outside the known range $(2.647(3)-2.751(2) \AA)$ for $\mathrm{Al}-\mathrm{Al}$ single bonds in three-coordinate $\mathrm{R}_{2} \mathrm{AlAlR}_{2}$ compounds. ${ }^{7} \mathrm{The} \mathrm{Al}(1)-\mathrm{C}(1)$ and $\mathrm{Al}(2)-\mathrm{C}(4)$ bond lengths are $2.0004(16)$ and $2.0032(15) \AA$ which are typical for $\mathrm{Al}-\mathrm{C}$ bond distances in trivalent organoalu-
minum species. ${ }^{13}$ The internal angles of the complexed toluene ring are narrowest at the Al-bound carbons $\mathrm{C}(1)$ and $\mathrm{C}(4)$ (109.4(1) and $109.4\left(1^{\circ}\right)$ ) and are in the range $\left(120.8(1)-121.7\left(1^{\circ}\right)\right)$ at $\mathrm{C}(2), \mathrm{C}(3)$, $\mathrm{C}(5)$, and $\mathrm{C}(6)$. The $\mathrm{C}(1)-\mathrm{Al}(1)-\mathrm{Al}(2)$ and $\mathrm{C}(4)-\mathrm{Al}(2)-\mathrm{Al}(1)$ angles are close to $90^{\circ}$, and the external angles $\mathrm{C}(8)-\mathrm{Al}(1)-\mathrm{Al}(2)$ and $\mathrm{C}(38)-\mathrm{Al}(2)-\mathrm{Al}(1)$ involving the terphenyl ligands are wide at $142.18(5)$ and $141.08(5)^{\circ}-$ probably as a result of steric repulsion. The aluminums are almost planar coordinated with angular sums of $359.25(6)^{\circ}$ at $\mathrm{Al}(1)$ and $358.55(6)^{\circ}$ at $\mathrm{Al}(2)$. The $\mathrm{C}(1)-\mathrm{Al}(1)-$ $\mathrm{Al}(2)-\mathrm{C}(4)$ torsion angle is only $24.5^{\circ}$ which indicates the bulky substituents ( $\mathrm{Ar}^{\prime}$ ) are nearly cis with respect to each other.

There are a handful of reactions between unstable boron(I) or aluminum(I) monomers and unsaturated molecules. The first example was the reaction between $\mathrm{BX}\left(\mathrm{X}=\mathrm{F},{ }^{14 \mathrm{a}} \mathrm{Cl}^{14 \mathrm{~b}}\right)$ and acetylene to give 1,4-diboracyclohexadiene. Similarly, the reaction of AlCl with the alkynes, $\mathrm{RC} \equiv \mathrm{CR}(\mathrm{R}=\mathrm{Me}, \mathrm{Et})$, gave the cage species, $(\mathrm{AlCl} \cdot \mathrm{RC} \equiv \mathrm{CR})_{4}$, which are dimers of substituted 1,4 dialuminacyclohexadiene. ${ }^{15}$ In addition, the reaction of AlCl with 2,3-dimethylbutadiene (DMB) produced the cyclic hexamer (AlCl• DMB $)_{6} \cdot{ }^{16}$ More recently, the formal $[1+2]$ cycloaddition product formed from the potassium reduction of $\mathrm{I}_{2} \mathrm{Al}\left[\{\mathrm{DippN}(\mathrm{Me}) \mathrm{C}\}_{2} \mathrm{CH}\right]$ in the presence of $\mathrm{RC} \equiv \mathrm{CR}$; $(\mathrm{R}=\mathrm{Ph}$, or TMS) gave the aluminum cyclopropene analogue, $\mathrm{HC}\{\mathrm{C}(\mathrm{Me}) \mathrm{DippN}\}_{2} \mathrm{Al}(\mathrm{Ph}) \mathrm{C}=\mathrm{C}(\mathrm{Ph}) .{ }^{17}$ However, none of these reactions afforded products with group 13.. 13 element bonds, and it is notable that concentrated toluene solutions of $\mathrm{Ar}^{\prime} \mathrm{MMAr}^{\prime}(\mathrm{M}=\mathrm{Ga}$, In , and Tl ) display no trace of cycloaddition products. The relative inertness of the heavier "dimetallenes" toward $[2+4]$ cycloadditions may be due to their ready dissociation in to monomeric $\mathrm{Ar}^{\prime} \mathrm{M}$ species in solution. ${ }^{5}$

Among heavier main group element compounds, the reactions which most resemble the addition of PhMe to $\mathbf{3}$ is the addition of unstable $\mathrm{Me}_{2} \mathrm{SiSiMe}_{2}$ to aromatic molecules such as benzene, naphthalene, or anthracene to give disilabicyclo[2.2.2]octadiene derivatives with structures similar to that of $4 .{ }^{18}$ However, irradiation with UV (ca. 250 nm ) regenerated the disilene by a photolytic [2 +4 ] cycloreversion. ${ }^{19}$ The analogous generation of Ar'AlAlAr' from 4 via photochemical methods is under investigation. In fact, future work may show that the chemistry of the lighter group 13 "dimetallenes", RMMR ( $\mathrm{M}=\mathrm{B}$ and Al ) will parallel that of the group 14 alkene analogues. Current work is focused on the isolation and characterization of an uncomplexed "dialuminene" and the examination of its reaction chemistry.

Acknowledgment. We are grateful to the National Science Foundation (CHE-0096913) for financial support.

Supporting Information Available: X-ray data (CIF) for 2 and 4. This material is available free of charge via the Internet at http:// pubs.acs.org.

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(8) (a) Under anaerobic and anhydrous conditions, $\mathrm{Ar}^{\prime} \mathrm{AlI}_{2}(1.36 \mathrm{~g}, 2.0 \mathrm{mmol})$ was dissolved in $\mathrm{Et}_{2} \mathrm{O}(85 \mathrm{~mL})$. The solution was added dropwise over 30 min to freshly synthesized $\mathrm{KC}_{8}(0.54 \mathrm{~g}, 4.0 \mathrm{mmol})$ and stirred for 18 h . The deep red solution was allowed to settle ( 4 h ) and was decanted from the graphite. The ether was removed under reduced pressure, and the dark red residue was extracted with toluene $(15 \mathrm{~mL})$. Overnight storage at ca. $-30{ }^{\circ} \mathrm{C}$ afforded red crystals of $4(0.2 \mathrm{~g}, 0.18 \mathrm{mmol})$. The supernatant liquid was removed from the crystals and further concentrated to 10 mL . Storage at $-30^{\circ} \mathrm{C}$ for 9 d gave $\mathbf{4}$ as red X-ray quality crystals. Yield: $0.19 \mathrm{~g}, 17 \% ; \mathrm{mp}=103-107^{\circ} \mathrm{C}$ (upon melting turned from red to pale yellow). Calcd. for $\mathrm{C}_{67} \mathrm{H}_{82} \mathrm{Al}_{2}$ : $\mathrm{C}=85.49, \mathrm{H}=8.78$. Found: C $=85.88, \mathrm{H}=8.03 .{ }^{1} \mathrm{H}$ NMR ( $300 \mathrm{MHz}, \mathrm{C}_{6} \mathrm{D}_{6}, 25^{\circ} \mathrm{C}$ ): $\delta 0.964(\mathrm{~d}, 12 \mathrm{H}$, $\left.o-\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right)^{3} \mathrm{~J}_{\mathrm{HH}}=6.6 \mathrm{~Hz}, 0.985\left(\mathrm{~d}, 12 \mathrm{H}, o-\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right)^{3} J_{\mathrm{HH}}=6.6 \mathrm{~Hz}$, $1.511\left(\mathrm{~s}, 3 \mathrm{H}, \mathrm{Ph}-\mathrm{CH}_{3}\right) 2.645(\mathrm{~m}, \mathrm{C}=\mathrm{C}-\mathrm{CH}), 2.745(\mathrm{t}, \mathrm{C}=\mathrm{C}-\mathrm{CH})^{3} \mathrm{~J}_{\mathrm{HH}}=$ $6.9 \mathrm{~Hz}, 2.909$ (broad mult, $\left.8 \mathrm{H}, \mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 5.907(\mathrm{t}, \mathrm{CH}=\mathrm{CH})^{3} J_{\mathrm{HH}}=$ $7.2 \mathrm{~Hz}, 6.771\left(\mathrm{~d}, 4 \mathrm{H}, m-\mathrm{C}_{6} \mathrm{H}_{3}\right)^{3} J_{\mathrm{HH}}=7.5 \mathrm{~Hz}, 7.081(\mathrm{~m}, 10 \mathrm{H}, m$-Dipp and $p-\mathrm{C}_{6} \mathrm{H}_{3}$ ), $7.197(\mathrm{t}, 4 \mathrm{H}, \mathrm{p} \text {-Dipp) })^{3} J_{\mathrm{HH}}=7.5 \mathrm{~Hz} .{ }^{13} \mathrm{C}\left\{{ }^{1} \mathrm{H}\right\}$ NMR $\left(\mathrm{C}_{6} \mathrm{D}_{6}\right.$, $\left.74.46 \mathrm{MHz}, 25{ }^{\circ} \mathrm{C}\right): \delta 23.66\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 25.66\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 30.92$ $\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 123.75(m$-Dipp $), 127.48\left(p-\mathrm{C}_{6} \mathrm{H}_{3}\right), 128.97\left(m-\mathrm{C}_{6} \mathrm{H}_{3}\right), 129.21$ ( $p$-Dipp), 141.93 (i-Dipp), 147.04 ( $o$-Dipp), $147.14\left(o-\mathrm{C}_{6} \mathrm{H}_{3}\right), 150.91$ (i$\mathrm{C}_{6} \mathrm{H}_{3}$ ). UV/vis (hexanes) $\lambda_{\text {max }} \mathrm{nm}\left(\epsilon \mathrm{mol} \cdot \mathrm{L}^{-1} \cdot \mathrm{~cm}^{-1}\right): 320$ (3400); (b) $\mathrm{Ar}^{\prime} \mathrm{AlI}_{2}(2.5 \mathrm{~g}, 3.69 \mathrm{mmol})$ was dissolved in $\mathrm{Et}_{2} \mathrm{O}(65 \mathrm{~mL})$. The solution was added dropwise over 30 min to $\mathrm{KC}_{8}(0.50 \mathrm{~g}, 3.69 \mathrm{mmol})$ at ca. -78 ${ }^{\circ} \mathrm{C}$ and stirred for 12 h . The red solution was decanted from the graphite. The ether was removed under reduced pressure, and the residue was washed with hexane $(15 \mathrm{~mL})$. The supernatant was removed from the pale yellow product. Yield: $0.81 \mathrm{~g}, 40 \% ; \mathrm{mp}=226-229^{\circ} \mathrm{C}$. Calcd. for $\mathrm{C}_{30} \mathrm{H}_{37}$ AlI: $\mathrm{C}=65.33, \mathrm{H}=6.76$. Found: $\mathrm{C}=65.01, \mathrm{H}=7.01 .{ }^{1} \mathrm{H}$ NMR ( $400 \mathrm{MHz}, \mathrm{C}_{6} \mathrm{D}_{6}, 25^{\circ} \mathrm{C}$ ): $\delta 0.987\left(\mathrm{~d}, 24 \mathrm{H}, o-\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right)^{3} \mathrm{~J}_{\mathrm{HH}}=$ $6.8 \mathrm{~Hz}, 1.151\left(\mathrm{~d}, 24 \mathrm{H}, o-\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right){ }^{3} J_{\mathrm{HH}}=6.8 \mathrm{~Hz}, 3.012(\mathrm{sept}, 8 \mathrm{H}$, $\left.\mathrm{C} H\left(\mathrm{CH}^{3}\right)_{2}\right)^{3} J_{\mathrm{HH}}=6.8 \mathrm{~Hz}, 7.09-7.06\left(\mathrm{~m}, 6 \mathrm{H}, m-\mathrm{C}_{6} \mathrm{H}_{3}, p-\mathrm{C}_{6} \mathrm{H}_{3}\right), 7.146$ (d, $8 \mathrm{H}, m$-Dipp), $7.328\left(\mathrm{t}, 4 \mathrm{H}, \mathrm{p}\right.$-Dipp) ${ }^{3} \mathrm{~J}_{\mathrm{HH}}=7.6 \mathrm{~Hz} .{ }^{13} \mathrm{C}\left\{{ }^{1} \mathrm{H}\right\} \mathrm{NMR}$ $\left(\mathrm{C}_{6} \mathrm{D}_{6}, 100.531 \mathrm{MHz}, 2{ }^{\circ} \mathrm{C}\right): \delta 25.25\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 26.52\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right)$, $30.51\left(\mathrm{CH}\left(\mathrm{CH}_{3}\right)_{2}\right), 124.16\left(m\right.$-Dipp), $p-\mathrm{C}_{6} \mathrm{H}_{3}$ (unobserved, probably obscured by $\mathrm{C}_{6} \mathrm{D}_{6}$ ), $129.87\left(m-\mathrm{C}_{6} \mathrm{H}_{3}\right), 130.10$ ( $p$-Dipp), 139.59 ( $i$-Dipp), $145.85\left(i-\mathrm{C}_{6} \mathrm{H}_{3}\right), 146.93\left(o-\mathrm{C}_{6} \mathrm{H}_{3}\right), 147.809$ (o-Dipp).
(9) Crystal data for 2 at 90 K with Mo $\mathrm{K} \alpha(\lambda=0.71073 \AA)$ radiation: $a=$ 13.5724(12) $\AA, b=19.0587(17) \AA, c=15.5757(14) \AA, \alpha=90^{\circ}=\gamma, \beta$ $=114.603(3)^{\circ}$, monoclinic, space group $P 2_{1} / n, Z=4, R_{1}=0.0426$ for $5199(I>2 \sigma(I))$ data, $w R_{2}=0.1245$ for all (5731) data. Crystal data for 4 at 90 K with $\mathrm{Mo} \mathrm{K} \mathrm{\alpha}(\lambda=0.71073 \AA \AA$ ) radiation: $a=13.9134(15) \AA$, $b=13.9628(18) \AA, c=19.057(2) \AA, \alpha=106.6 .45(3)^{\circ}, b=107.171$ $(4)^{\circ}, c=91.862(5)^{\circ}$, triclinic, space group $\mathrm{P} \overline{1}, Z=2, R_{1}=0.0396$ for $10326(I>2 \sigma(I))$ data, $w R_{2}=0.1114$ for all (13096) data.
(10) The structure of a base-stabilized dialane, $\left[\left(\mathrm{Me}{ }_{3} \mathrm{Si}\right) \mathrm{Si}(\mathrm{Cl})(\mathrm{THF}) \mathrm{Al}_{2}\right.$, has been determined in Klemp, C.; Uffing, C.; Baum, E.; Schnöckel, H. Z. Anorg. Allg. Chem. 2000, 626, 1787.
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## JA034478P

