Small Molecule Activation

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Addition of Ethylene or Hydrogen to a Main-Group Metal Cluster under Mild Conditions**

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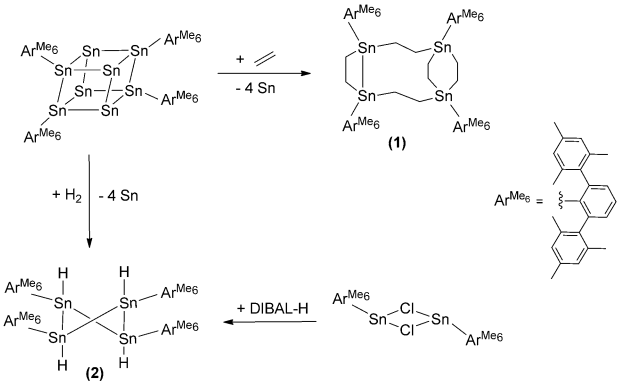
Abstract: *Reaction of the tin cluster $Sn_8(Ar^{Me_6})_4$ ($Ar^{Me_6} = C_6H_2$-2,6-(C_6H_3-2,4,6-Me_3)$_2$) with excess ethylene or dihydrogen at 25 °C/1 atmosphere yielded two new clusters that incorporated ethylene or hydrogen. The reaction with ethylene yielded $Sn_4(Ar^{Me_6})_4(C_2H_2)_5$ that contained five ethylene moieties bridging four aryl substituted tin atoms and one tin–tin bond. Reaction with H_2 produced a cyclic tin species of formula $(Sn(H)Ar^{Me_6})_4$, which could also be synthesized by the reaction of $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$ with DIBAL-H. These reactions represent the first instances of direct reactions of isolable main-group clusters with ethylene or hydrogen under mild conditions. The products were characterized in the solid state by X-ray diffraction and IR spectroscopy and in solution by multinuclear NMR and UV/Vis spectroscopies. Density functional theory calculations were performed to explain the reactivity of the cluster.*

In 2005 it was shown that a main-group molecule could react with dihydrogen at room temperature and atmospheric pressure.[1] Since then a wide variety of main-group compounds have been investigated for their reactions with small molecules under mild conditions.[2–5] Such reactions are dependent on the existence of donor and acceptor orbitals of suitable symmetry and modest energy separation.[6] Thus, multiply bonded or unsaturated main-group species have commonly been used. For example, heavier Group 14 alkyne, $Ar^{iPr_4}EEAr^{iPr_4}$, and carbene, $:E(Ar^{iPr_4})_2$, analogues (E = Ge or Sn; $Ar^{iPr_4} = C_6H_3$-2,6-(C_6H_3-2,6-iPr_2)$_2$) react readily with hydrogen, ethylene, and other small molecules under mild conditions.[7–10] Activation of small molecules can also be effected by stable carbenes such as $:C(tBu)(iPr)_2N$[5,11] or frustrated Lewis pairs using a phosphine or related electron donor and $B(C_6F_5)_3$ as the acceptor.[12] Several reactions have been shown to be reversible, which also has generated widespread interest.[13–15] The reactivity of these main-group compounds toward small molecules can resemble that of transition-metal complexes, and thus, may have use in catalytic applications.[16]

The reactivity of main-group clusters towards small molecules under ambient conditions has remained virtually unexplored.[17] There have been a few theoretical studies on dihydrogen activation by aluminum clusters[18] and the activation of ammonia–borane by a gallium nitrogen cage compound.[19] Main-group molecular clusters are also of interest because the coordination of their constrained atoms may resemble that of atoms at elemental surfaces.[20–23] Herein we report the reactions of the tin cluster $Sn_8(Ar^{Me_6})_4$ ($Ar^{Me_6} =$ 2,6-(2,4,6-$Me_3C_6H_2$)$_2C_6H_3$)[20] with excess ethylene or dihydrogen to afford the products **1** and **2** as depicted in Scheme 1.



Scheme 1. Reactions of $Sn_8(Ar^{Me_6})_4$ with excess ethylene or H_2, and a reaction of $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$ with DIBAL-H in 1:4 molar ratio.

The product **1** shows that the initial cluster has absorbed five ethylene molecules. A reaction between the tin cluster and dihydrogen yields the tin hydride **2**. Significantly, both reactions involve the loss of the unsubstituted tin atoms in the cluster. The syntheses of **1** and **2** are described as well as their characterization by NMR spectroscopic methods and X-ray crystallography. Computational investigations of model systems for **1** and **2** are also described.

Compound **1** was synthesized by treating $Sn_8(Ar^{Me_6})_4$[20] in THF with ethylene under ambient conditions (Scheme 1). The initially dark purple mixture was stirred for 2.5 days at 25 °C to afford a dark red solution and a metallic precipitate, assumed to be elemental tin. After work-up, compound **1** was isolated in 14% yield. Colorless crystals were grown from diethyl ether at 6 °C overnight. Compound **1** crystallizes in a triclinic $P\bar{1}$ space group with two diethyl ether solvent molecules.[24] Figure 1 depicts the solid-state structure of **1** and it can be seen that the initial tin cluster, $Sn_8(Ar^{Me_6})_4$, has

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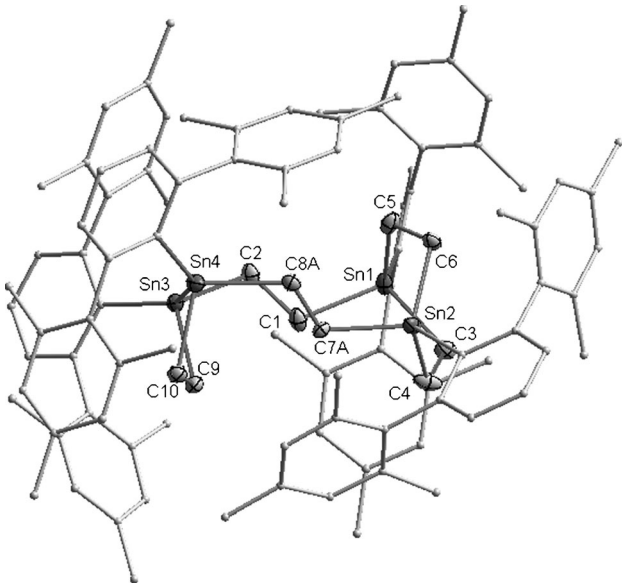

Figure 1. X-ray crystal structure of **1**·2 Et_2O. One of the disordered ethylene (C7B–C8B) positions, solvent molecules, and hydrogen atoms are not shown for clarity. Ellipsoids are set at 30% probability. Selected bond lengths [Å] and angles [°]: Sn3–Sn4 2.8549(5), Sn1–C1 2.181(4), C1–C2 1.538(6), Sn3–C9 2.208(4); C1-Sn1-C3 108.82(17), C1-Sn1-C5 106.15(17), C2-Sn3-C9 110.36(16).

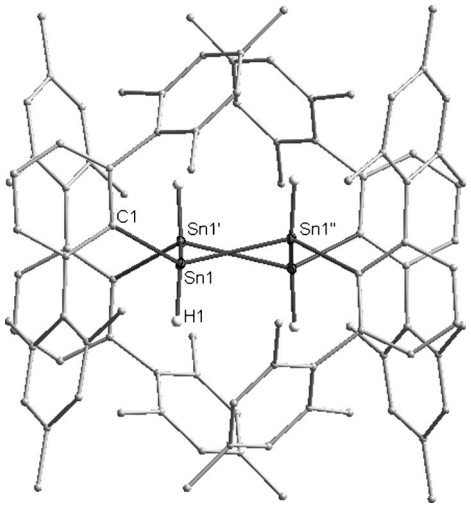

Figure 2. X-ray crystal structure of **2**·2 Et_2O. Solvent molecule and aryl hydrogen atoms are not shown for clarity. Ellipsoids are set at 30% probability. Selected bond lengths [Å] and angles [°]: Sn1–Sn1′ 2.8433(4), Sn1–Sn1″ 2.8050(3), Sn1–C1 2.173(3), Sn1–H1 1.47(5); C1-Sn1-Sn1′ 130.89(7), Sn1-Sn1′-Sn1″ 87.030(3).

incorporated five ethylene molecules and the four unsubstituted tin atoms have been eliminated. One C_2H_4 moiety is disordered over two positions, each with 50% occupancy and only one of these sites (C7A and C8A) is shown in Figure 1.

Each tin is tetrahedrally coordinated and carries one Ar^{Me_6} ligand. Two tin atoms, Sn1 and Sn2, are bound also to three carbon atoms from different CH_2CH_2 moieties, whereas Sn3 and Sn4 are bonded to two carbon atoms from bridging CH_2CH_2 moieties as well as to each other. Thus there is one intact Sn–Sn bond (Sn3–Sn4, 2.8549(5) Å), similar in length to the CH_2CH_2 bridged tin–tin single bond in $Ar^{iPr_4}Sn(\mu_2{:}\eta^1{:}\eta^1\text{-}C_2H_4)_2SnAr^{iPr_4}$, formed by reversible addition of ethylene to the distannyne $Ar^{iPr_4}SnSnAr^{iPr_4}$.[3] The average Sn–CH_2 and CH_2CH_2 C–C bond lengths in **1** are 2.177 Å and 1.527 Å, respectively. These are normal for Sn–C and C–C single bonds.[25,26] Interligand angles at the tin atoms are near 109.5°, indicating tetrahedral geometry, although disorder at the C7–C8 moiety and the Sn–Sn bond cause deviation from the ideal value. The ^1H and ^{13}C NMR spectra of compound **1** indicate the presence of symmetry in the molecule in solution as only two unique sets of signals corresponding to Ar^{Me_6} ligand environments are observed. The ^{119}Sn NMR spectrum reveals two signals at 336.0 (Sn3 and Sn4) and 1.1 ppm (Sn1 and Sn2), indicating two tin environments, the chemical shifts of which are consistent with reported values.[8]

The reaction of $Sn_8(Ar^{Me_6})_4$ with excess of H_2 was conducted similarly and yielded the tetrameric tin(II) hydride **2** (Figure 2) in low yield. It was characterized by single-crystal X-ray diffraction.[24] The low yield is due probably to the reaction conditions that required mild heating in THF, which decomposes the majority of the starting cluster with deposition of elemental tin. Hence, the tin hydride **2** was synthesized in a more straightforward manner by the reaction of the precursor $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$[27] with diisobutylaluminum hydride (DIBAL-H) (Scheme 1). A solution of DIBAL-H in hexanes was added dropwise to a diethyl ether solution of $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$. The initially yellow solution turned orange and after workup compound **2** was collected as yellow crystals in 21% yield.

Compound **2** crystallizes in an orthorhombic *Fddd* space group. The asymmetric unit consists of a $Sn(H)(Ar^{Me_6})$ moiety and one half of an Et_2O solvent molecule, with the rest of the molecule generated by symmetry. The structure consists of a puckered ring of four tin atoms each σ-bonded to a hydrogen and an Ar^{Me_6} ligand along with to the neighboring tin atoms. The tin atoms are tetrahedrally coordinated. The overall tetrameric structure may be contrasted with that of the more sterically encumbered hydrogen bridged dimer $\{Ar^{iPr_4}Sn(\mu\text{-}H)\}_2$[28] or that of the asymmetric stannylstannylene $Ar^{iPr_8}SnSn(H)_2Ar^{iPr_8}$[29] and related species.[30] The orientation of the hydrogens alternate on either side of the Sn_4. The Sn–Sn bond lengths (2.8433(4) and 2.8050(3) Å) are slightly shorter than the tin–tin single bonds in the other terminal tin hydrides,[29,30] but within the range of typical tin–tin single bonds. There are a few structures in the literature that incorporate a Sn_4 ring, but none have Sn–H bonds. The known species have formulas Sn_4L_8 (L = alkyl ligand) or $Sn_4L'_4$ (L′ = bidentate ligand).[31–33] The ^1H NMR spectrum of **2** shows a hydride signal at 3.97 ppm, and the ^{119}Sn NMR spectrum displays a doublet at −324.3 ppm, $J_{Sn\text{-}H} = 1590$ Hz.[34]

The reactivity of the tin cluster towards H_2 and ethylene was investigated computationally using the PBE0 hybrid functional[35–38] with def2-TZVP basis sets.[39] A model compound Sn_8Ph_4 was used to lower the computational cost. The calculations show that the reaction of dihydrogen with the Sn_8Ph_4 cluster yields an addition product $Sn_8(H_2)Ph_4$ (Figure 3) initially, whose formation is slightly disfavored in

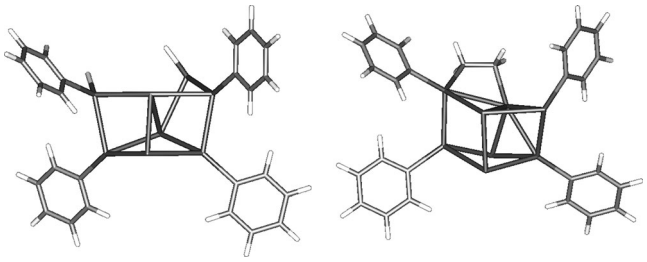

Figure 3. Optimized structures for the addition products of Sn_8Ph_4 with H_2 (left) and ethylene (right).

the gas phase ($\Delta H = 4\ kJ\,mol^{-1}$; $\Delta G = 39\ kJ\,mol^{-1}$). The Gibbs energy of activation was found to be $134\ kJ\,mol^{-1}$, consistent with the fact that the reaction with H_2 required mild heating and an excess of hydrogen gas to proceed. A similar addition product was located for the reaction of Sn_8Ph_4 with ethylene (see Figure 3). However, the gas-phase reaction is exothermic and only slightly disfavored by entropy ($\Delta H = -33\ kJ\,mol^{-1}$; $\Delta G = 22\ kJ\,mol^{-1}$). In this case, the Gibbs energy of activation is also significantly smaller, $86\ kJ\,mol^{-1}$, consistent with experimental observations.

The frontier orbitals of Sn_8Ph_4 have both electron donating and accepting features (see the Supporting Information), which rationalizes the relatively facile formation of $Sn_8(H_2)Ph_4$ and $Sn_8(C_2H_4)Ph_4$. The modeling of mechanisms for the formation of $\{Sn(H)Ph\}_4$, $Sn_4Ph_4(C_2H_4)_5$, and elemental tin is beyond the scope of this work. However, the peculiar structure of **1** with an unreacted tin–tin bond prompted us to investigate the possible insertion of a sixth ethylene to $Sn_4Ph_4(C_2H_4)_5$ to form $Sn_4Ph_4(C_2H_4)_6$. The structures of ethylene, $Sn_4Ph_4(C_2H_4)_5$, and $Sn_4Ph_4(C_2H_4)_6$ were optimized (see the Supporting Information) and their energies compared, which revealed that the addition of a sixth equivalent of ethylene is thermodynamically favored ($\Delta G = -12\ kJ\,mol^{-1}$), though the reaction could be prevented by kinetic factors. Unfortunately, we could not locate a transition state for the addition of the sixth ethylene molecule, and thus the magnitude of the activation barrier remains unknown.

In summary, we have described the syntheses and characterization data for two new insertion products of small molecules to a tin cluster under mild conditions. Further studies on the reactivity of $Sn_8(Ar^{Me_6})_4$ towards other small molecules and attempts to prepare $Sn_4(Ar^{Me_6})_4(C_2H_4)_6$ are ongoing.

Experimental Section

All manipulations were carried out under anaerobic and anhydrous conditions by using modified Schlenk line techniques under a dinitrogen atmosphere or in a Vacuum Atmospheres HE-43 drybox. Solvents were dried and stored over sodium. Physical measurements were performed under anaerobic and anhydrous conditions. ^1H, $^{13}C\{^1H\}$, ^{119}Sn, and $^{119}Sn\{^1H\}$ NMR spectra were obtained on Varian 400 or 600 MHz spectrometers and referenced to known standards. IR spectra were recorded as Nujol mulls between CsI plates on a PerkinElmer 1430 Infrared Spectrometer. UV/Vis spectra were recorded as dilute toluene solutions in 3.5 mL quartz cuvette using an Olis 17 Modernized Cary 14 UV/Vis/NIR Spectrophotometer. Melting points were determined on a Meltemp II apparatus using glass capillaries sealed with vacuum grease, and are uncorrected. All starting materials were obtained from commercial sources and used as received. $Sn_8(Ar^{Me_6})_4$[20] and $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$[27] were prepared by previously reported procedures.

$Sn_4(Ar^{Me_6})_4(CH_2CH_2)_5$ (**1**): $Sn_8(Ar^{Me_6})_4$ (0.700 g) was dissolved in THF (ca. 40 mL). The flask was flushed with ethylene gas for ca. 45 min at 25 °C and then stirred under an ethylene atmosphere for another 48 h. The initially dark purple solution became dark red with a gray precipitate (assumed to be elemental tin). The mixture was allowed to settle and filtered. The filtrate was evaporated and the residue was dissolved in Et_2O (ca. 20 mL). Filtration followed by reduction in volume to ca. 6 mL, and storage at 6 °C overnight yielded colorless crystals of **1**, which were dried under vacuum. Yield 0.080 g (14 %). ^1H NMR (25 °C, C_6D_6, 600 MHz): $\delta = -0.10$ (t, $^3J_{HH} = 8.0$ Hz, 4H, Sn-CH_2CH_2-Sn), 0.11 (m, $^3J_{HH} = 8.0$ Hz, 4H, Sn-CH_2CH_2-Sn), 0.52 (t, $^3J_{HH} = 24.0$ Hz, 8H, Sn-CH_2CH_2-Sn), 0.74 (t, $^3J_{HH} = 8.0$ Hz, 4H, Sn-CH_2CH_2-Sn), 2.04 (s, 24H, Mes-CH_3), 2.07 (s, 24H, Mes-CH_3), 2.29 (s, 12H, Mes-CH_3), 2.34 (s, 12H, Mes-CH_3) 6.83, 6.84, 6.87, 6.91, 7.19 ppm (aromatic H, 28H); $^{13}C\{^1H\}$ NMR (25 °C, C_6D_6, 151 MHz): $\delta = 6.5$, 9.2, 9.5, 13.9, 14.4, 19.8 (CH_2CH_2), 21.4, 21.6, 21.6, 23.1 (Mes-CH_3), 31.9 (CH_2CH_2), 128.4, 128.4, 128.6, 129.0, 129.2, 129.3, 136.2, 136.5, 141.9, 142.7, 147.2, 150.2 ppm (aromatic C), three *ipso*-C signals were not observed; $^{119}Sn\{^1H\}$ NMR (25 °C, C_6D_6, 149 MHz): 336.0 (*Sn*-*Sn*) and 1.1 ppm (*Sn*-CH_2CH_2). Melting point: 152–155 °C (decomp.). IR in Nujol mull (cm^{-1}) with CsI plates: 650, 520, 475, 335, and 315 (Sn-C, stretching and bending). UV/Vis (toluene, nm): 307, 321, and 330.

$\{Sn(H)(Ar^{Me_6})\}_4$ (**2**), method A: $Sn_8(Ar^{Me_6})_4$ (0.661 g) was dissolved in toluene (ca. 25 mL) and warmed to 60 °C. The mixture was stirred under an H_2 atmosphere for 3.5 h and then cooled to room temperature. Stirring was continued overnight without any color change but a significant amount of gray precipitate (elemental tin) was formed. The precipitate was allowed to settle and the solution was filtered. The volume was reduced to ca. 10 mL and 5 mL of THF was added. The mixture was placed in a ca. 6 °C fridge. Crystals of compound **2** were collected from the mixture which contained mainly unreacted $Sn_8(Ar^{Me_6})_4$. Method B: A solution of diisobutyl aluminum hydride in hexanes (3.2 mL, 1M, 3.2 mmol, diluted with 2 mL of hexanes) was added dropwise to the diethyl ether solution of $\{(Ar^{Me_6})Sn(\mu\text{-}Cl)\}_2$ (0.708 g in ca. 30 mL of diethyl ether) at −78 °C. The solution became orange and was stirred for ca. 2 h. A green precipitate was formed and removed by filtration. Storage of the diethyl ether solution at −30 °C overnight yielded yellow crystals of **2**. Yield 0.135 g (21 %). ^1H NMR (25 °C, C_6D_6, 600 MHz): $\delta = 1.66$ (s, 12H, Mes-CH_3), 1.80 (s, 12H, Mes-CH_3), 2.07 (s, 12H, Mes-CH_3), 2.15 (s, 12H, Mes-CH_3), 2.33(s, 24H, Mes-CH_3), 3.97 (s, 4H, Sn-*H*), 6.73, 6.77, 6.82, 7.07, 7.10, 7.12 ppm (aromatic H, 28H); $^{13}C\{^1H\}$ NMR (25 °C, $CDCl_3$, 151 MHz): $\delta = 21.5$, 21.8, 22.0, 22.4, 23.7 ppm (Mes-CH_3), 128.4, 128.5, 128.7, 128.8, 128.9, 129.0, 129.3, 135.1, 135.3, 135.5, 135.7, 135.9, 136.0, 141.7, 142.0, 144.5, 150.0, 150.2 ppm (aromatic C); ^{119}Sn NMR (25 °C, $CDCl_3$, 149 MHz): $\delta = -324.3$ (d, $^1J_{Sn\text{-}H} = 1590$ Hz, Sn-H). Melting point: > 300 °C. IR in Nujol mull (cm^{-1}) with CsI plates: 1845 (Sn-H stretching), 730 (Sn-H bending). UV/Vis (toluene, nm): 296 and 308.

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