# Communications

Organometallic Reagents

Structurally Stimulated Deprotonation/Alumination of the TMP Anion**

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Derived from the cyclic secondary amine 2,2,6,6-tetramethyl-piperidine [TMP(H)] by removal of its nitrogen-attached hydrogen atom, the TMP anion **1** has had a 40 year career[1] in the business of selective proton abstraction.[2] Possessing attributes of high steric bulk and low nucleophilicity, without any β-hydrogen atoms (the presence of which often disadvantages its diisopropylamido analogue[3] through β-hydride decomposition), **1** is usually employed as its lithium salt, LiTMP, which exists as a cyclotetramer in the crystal.[4] NaTMP is a cyclotrimer,[5] whereas KTMP remains still to be crystallographically characterized. Besides being strong Brønsted bases, these alkali metal TMP compounds are strong Lewis acids. Adding the Lewis base TMEDA (*N,N,N′,N′*-tetramethylethylenediamine) to them causes steric inflation of the alkali metal coordination sphere, concomitantly reducing the TMP complex aggregation state. Tetrameric LiTMP is reduced to the hemisolvated open dimer [(TMEDA)Li(μ-TMP)Li(TMP)];[6] whereas the larger alkali metal complexes become fully solvated cyclodimers [{(TMEDA)M(μ-TMP)}$_2$][7] (M = Na or K). Since such structural changes can modify the reactivity of the "TMP anion", accommodating it within a more altered mixed-metal (and/or mixed-anion) environment can exert a strong influence on reactivity. This idea has stimulated much current research into TMP-based bimetallic reagents including TMP-magnesiates,[8] TMP-zincates,[9] TMP-cadmates,[10] TMP-chromates,[11] TMP-manganates,[12] and TMP-ferrates,[11] which can show significant improvements in, for example, functional group tolerance or kinetic stability compared to that of LiTMP. Of particular interest in this study are TMP-aluminates. Uchiyama and co-workers introduced the first TMP-aluminate "*i*Bu$_3$Al(TMP)Li" in 2004[13] showing its high chemo- and regioselectivity in proton abstraction reactions of functionalized aromatic substrates. In these and subsequent reactions of this type, the TMP anion is invariably the sole active (or most active) base ligand executing deprotonation upon the substrate and disembarking the assembly as

TMP(H). The prospect of deprotonating this most powerful of bases to generate a TMP-based dianion would seem a challenge too far. However, here we present a rational structurally controlled approach that has met this challenge.

Recent inorganic structurally focused studies[14] have elaborated the design characteristics of a TMP-bimetallic complex that can render it a powerful metalating (magnesiating, zincating, aluminating etc.) agent. Commonly, the two distinct metals connect through a TMP bridge, with the di- or trivalent metal carrying two or three additional anions (alkyls and/or amides), while a neutral aggregation-blocking capping ligand (for example, multiple THF molecules or TMEDA) binds terminally to the alkali metal. With "*i*Bu$_3$Al(TMP)Li", organic substrates such as benzamides can undergo *ortho* deprotonation/alumination with evolution of TMP(H) (Scheme 1).[15] While such reactions are intermolecular, it is
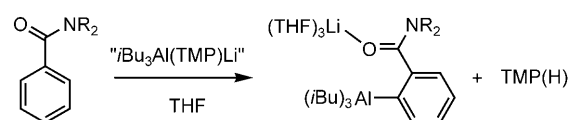
Scheme 1. Example of an *ortho*-alumination using a TMP-aluminate.

thought that the organic substrate coordinates to the bimetallic assembly (probably at the alkali metal site) prior to its deprotonation, so in effect the aluminum–hydrogen exchange reaction is intramolecular in origin.[16] Building on this idea, we demonstrated that it was possible to effect deprotonation of the neutral cap by tuning the relative steric profiles of the cap, the alkali metal, and the anionic bridges.[17] This was achieved by using a cap (TMEDA) that when bound to the smallest alkali metal (lithium) might encroach into bridging-anion territory. Thus we showed that merging together LiTMP, diisobutylaluminum(TMP), and TMEDA in hexane solution in the absence of an organic substrate, forced deprotonation/alumination of a terminal Me group on TMEDA to generate a methylenic CH$_2$–Al bond (Scheme 2). Two molecules of TMEDA (within the same bimetallic assembly) and its tridentate analogue PMDETA (*N,N,N′,N″,N″*-pentamethyldiethylenetriamine) can be simi-
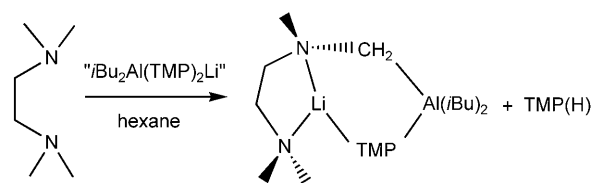
Scheme 2. α-Methylalumination of TMEDA.

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larly deprotonated α to nitrogen, which generally is a position challenging to metalate in tertiary amines.[18]

Having successfully applied this intramolecular alumination trapping methodology to both added organic substrates and in their absence attached neutral caps, we pondered whether it could be extended to the considerably more taxing challenge of deprotonating an attached anion. This task proved surprisingly straightforward in practice. A simple plan was devised to combine a larger alkali metal (potassium) with a smaller fitting cap (TMEDA instead of tridentate PMDETA) in the hope of encouraging closer intramolecular contact between incipient anion bridges as two distinct metal compounds approach each other to generate a bimetallic assembly. Experimentally this meant reacting KTMP with *i*Bu₂Al(TMP) and TMEDA in a 1:1:1 stoichiometry in hexane solution. X-ray crystallographic studies[19] supported by solution NMR spectroscopic studies established the crystalline product to be the new potassium aluminate [(TMEDA)K(μ-TMP*)(μ-*i*Bu)Al(*i*Bu)] (**2**) where TMP* represents a unique CH₃-deprotonated as well as an NH-deprotonated dianionic variant of the bulky cyclic amine. Thus the planned "intramolecular" alumination strategy has been successful with the TMP anion undergoing a second deprotonation to form TMP* which has been trapped in the new bimetallic assembly.

The molecular structure of **2** (Figure 1) varies from the common structure of TMP-bimetallic assemblies.[14] Potassium connects to aluminum through an amido N bridge and an alkyl C bridge, with a bidentate TMEDA cap and an isobutyl ligand attached terminally to the respective metals. The new feature is an irregular, highly puckered four-atom (Al1-N3-C34-C37) ring, which closes through the making of the Al1−C37 bond involving the methylenic CH₂ unit that originates from deprotonation of one Me group on the α-C
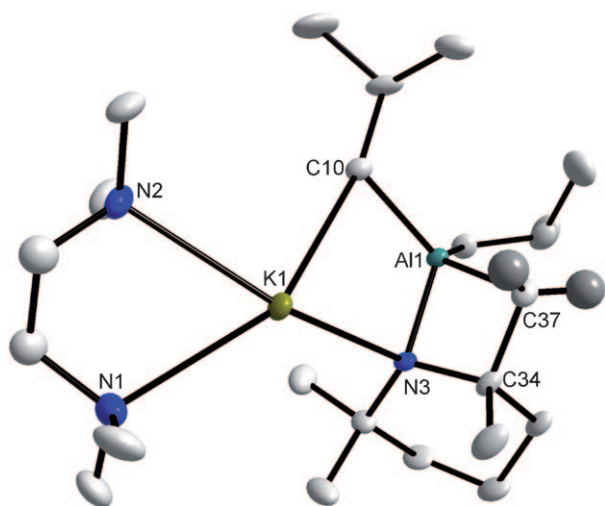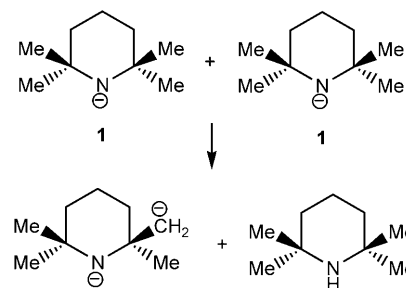
atom of TMP. Three other Me groups of TMP* retain their full complement of hydrogen atoms. Therefore TMP* functions in a new role as an N,C-bidentate, dianionic ligand towards Al. Consequently, both N3 and C34 become stereogenic centers. As the space group is centrosymmetric, these atoms exist as (*S,R*) and (*R,S*) enantiomeric pairs within the crystal. Selected dimensions in **2** are in the legend to Figure 1. TMP* makes an acute bite angle (N3-Al1-C37) of 73.55(9)°, which contributes to the marked distortion from tetrahedral of the Al center [widest bond angle: C37-Al1-C40 120.77(9)°; mean bond angle 108.87°]. There is little discrimination between the bond lengths of the three Al−C bonds [largest difference 0.011 Å; mean value 2.016 Å], with the Al−N bond being shorter at 1.897(2) Å. Potassium occupies a highly irregular four-coordinate CN₃ geometry. All K−N bond lengths are similar (mean value, 2.849 Å). The intramolecular K1−C10 bond length is 3.184(3) Å, and there is also a moderately close intermolecular K1−C37* contact [3.413(2) Å] with the methylenic CH₂ of a neighboring molecule, giving a loose dimeric arrangement (see Supporting Information).

Recorded in [D₁₂]cyclohexane solution, ¹H and ¹³C NMR spectral data of **2** support the structure observed in the crystal. Most informatively, the methylenic CH₂ unit is diastereotopic giving rise to two inequivalent ¹H resonances (one doublet at δ = 0.38 ppm; the other obscured by an overlapping *i*Bu CH₂ resonance spanning δ = −0.17 to −0.28 ppm), coupled to the same ¹³C resonance (at δ = 32.9 ppm).

Formally the reaction leading to **2** can be regarded as a self-deprotonation, with one TMP anion reacting with another (Scheme 3). This unusual reactivity emphasizes the greater scope of mixed-metal chemistry as TMP self-deprotonation/metalation is unlikely to be reproduced (in a controlled manner) in a homometallic system. While this reaction is unprecedented, TMP dispensed as Mg(TMP)₂ has been reported[20] to deprotonate LiHMDS (HMDS is 1,1,1,3,3,3-hexamethyldisilazide) at a Si(CH₃) site, though this is a much less challenging task as several examples of Si(CH₃) deprotonation have appeared.[21] In general, C−H activation of CH₃ groups is a well-known, somewhat random phenomenon across organometallic chemistry.[22] The reaction reported herein represents a special and surprising case of C−H bond activation which introduces a novel modified form of TMP. As a bonus, the structurally well-defined bimetallic approach that made it possible could offer model systems with which to study systematically special intramolecular deprotonations, especially in cases where C−H

Figure 1. Molecular structure of **2** with hydrogen atoms (except those of NCCH₂Al) and the minor disordered component omitted for clarity. Thermal ellipsoids are drawn at 50% probability. Selected bond lengths [Å] and angles [°]: K1–N1 2.897(2), K1–N2 2.825(2), K1–N3 2.825(1), K1–C10 3.184(3), Al1–C10 2.022(2), Al1–C37 2.011(3), Al1–N3 1.897(2); N1-K1-N2 64.29(6), N1-K1-N3 122.17(5), N2-K1-N3 146.26(6), C37-Al1-C40 120.77(9), N3-Al1-C37 73.55(9), Al1-N3-C34 92.9(1), Al1-C37-C34 87.1(1), N3-C40-C37 100.4(1).

Scheme 3. Self-deprotonation of the TMP anion.

bonds have exorbitantly high pK_a values, and are normally resistant to conventional bases.

Experimental Section

The reaction was carried out under a protective argon atmosphere using standard Schlenk techniques. Full details are given in the Supporting Information.

Synthesis of **2**: Hexane (10 mL) was added to an oven-dried Schlenk tube. Next, 1.6 M nBuLi (1.25 mL, 2 mmol) was added, followed by TMP(H) (0.34 mL, 2 mmol) at room temperature. The reaction mixture was left to stir for 30 min and then iBu$_2$AlCl (0.38 mL, 2 mmol) was injected into the Schlenk tube, producing a white suspension almost immediately. The reaction was left to stir for 45 min and was then filtered through Celite and glass wool, which was then washed with more hexane (10 mL). To a separate Schlenk tube containing a suspension of freshly prepared KTMP in hexane (10 mL) [from a mixture of KCH$_2$SiMe$_3$ (0.24 g, 2 mmol) of and TMP(H) (0.34 mL, 2 mmol)], the solution was added through a cannula to give a tan-colored suspension. Finally, TMEDA (0.30 mL, 2 mmol) was injected, and the reaction mixture quickly turned into a homogeneous solution which was left to stir for 30 min before the Schlenk tube was left in the refrigerator at −4 °C. A crop (0.43 g, 49 %) of colorless crystals formed in solution that were suitable for X-ray crystallographic analysis. ^{1}H NMR (400.13 MHz, 298 K, C$_6$D$_{12}$): $\delta = 2.34$ [4 H, s, 2 × CH$_2$ of TMEDA], 2.24 [12 H, s, 4 × CH$_3$ of TMEDA], 1.98–1.82 [2 H, m, 2 × CH of iBu], 1.75–1.60 [1 H, m, 1 × γC(H)$_2$ of TMP], 1.58–1.24 [5 H, m, 1 × γC(H)$_2$ of TMP and 2 × βCH$_2$ of TMP], 1.23 [3 H, s, 1 × CH$_3$ of TMP], 1.01–0.91 [18 H, m, 2 × CH$_3$ of TMP and 4 × CH$_3$ of iBu], 0.38 [1 H, d, ^2J(H,H) = 12.5 Hz, 1 × metal-C(H)$_2$ of metalated TMP-Me], 0.11–(−0.04) [2 H, m, CH$_2$ of iBu], −0.17–(−0.28) [2 H, m, 1 × metal-C(H)$_2$ of metalated TMP-Me, ^2J(H,H) = 11.8 Hz, and 1 × C(H)$_2$ of iBu], −0.42–(−0.49) ppm [1 H, m, 1 × C(H)$_2$ of iBu]. ^{13}C{^{1}H} (100.62 MHz, 298 K, C$_6$D$_{12}$): $\delta = 58.1$ [2 × CH$_2$ of TMEDA], 57.2 [1 × quaternary C of TMP], 50.6 [1 × quaternary C of TMP], 46.1 [4 × CH$_3$ of TMEDA], 40.6 [1 × βCH$_2$ of TMP], 39.6 [1 × βCH$_2$ of TMP], 36.9 [1 × CH$_3$ of TMP], 36.6 [1 × CH$_3$ of TMP], 32.9 [1 × metal-CH$_2$ of TMP], 31.8 [1 × CH$_2$ of iBu], 31.5 [1 × CH$_3$ of TMP], 30.2 [1 × CH$_3$ of iBu], 29.5 [1 × CH$_3$ of iBu], 29.3 [1 × CH$_3$ of iBu], 28.8 [1 × CH$_3$ of iBu], 28.5 [1 × CH of iBu], 28.4 [1 × CH of iBu], 27.3 [1 × CH$_2$ of iBu], 20.9 ppm [1 × γCH$_2$ of TMP].

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[19] Crystal data for **2**: C$_{23}$H$_{51}$AlKN$_3$; A colorless block gave triclinic space group $P\bar{1}$, $a = 11.5698(9)$, $b = 11.9773(9)$, $c = 12.2821(10)$ Å, $\alpha = 80.845(7)$, $\beta = 68.551(8)$, $\gamma = 62.341(8)°$, $V = 1403.0(2)$ Å^3, $T = 123$ K, $Z = 2$, $\rho_{calcd} = 1.031$ Mg m^{-3}, $2\theta_{max} = 122.9°$, Cu$_{K\alpha}$ $\lambda = 1.5418$ Å. The structure was solved and refined to convergence on F^2 (SHELXS and SHELXL-97; G. M. Sheldrick, *Acta Crystallogr. Sect. A* **2008**, *64*, 112). C- and H-atoms of the TMEDA chelate were modelled as disordered over two sites, site occupancy ratio 2:1. $R1 = 0.0463$ (for 3890 reflections with $I > 2\sigma(I)$) $wR2 = 0.1263$ and $S = 1.074$ for 306 parameters and 4263 unique reflections. Minimum/maximum residual electron density −0.533/0.640 e Å^{-3}. CCDC 760700 (**2**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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