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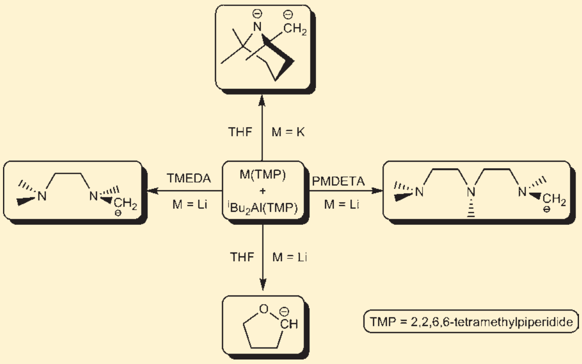
Structurally Powered Synergic 2,2,6,6-Tetramethylpiperidine Bimetallics: New Reflections through Lithium-Mediated *Ortho* Aluminations

Robert E. Mulvey,* David R. Armstrong, Ben Conway, Elaine Crosbie, Alan R. Kennedy, and Stuart D. Robertson*

WestCHEM, Department of Pure and Applied Chemistry, University of Strathclyde, Glasgow G1 1XL, U.K.

S *Supporting Information*

ABSTRACT: Recent times have witnessed many notable advances in metalation chemistry with halide salt supported strategies and alkali-metal mediated metalation being particularly prominent. This article begins with a brief account of both of these avant garde metalation methods focusing on selected recent examples not covered previously in a review. New results in the area of Alkali-Metal Mediated Alumination (AMM*Al*) are also presented. Thus, the putative lithium aluminate base THF·$Li(\mu\text{-}TMP)_2Al(^iBu)_2$ (**4**) is shown to act via TMP basicity to efficiently *ortho* deprotonate a variety of functionalized aromatic molecules at room temperature, tolerating carboxamide and halide functionalities. These metalated species are electrophilically quenched with elemental iodine. Crystal structure determinations of the metalated intermediates confirm unequivocally that direct alumination of the substrates has occurred. Since the homometallic lithium or aluminum reagents are unable to effect such deprotonations these reactions are synergic in nature and can be considered examples of AMM*Al*. Drawing together previously published work in the field of AMM*Al*, together with other pertinent experimental observations and new density functional theory (DFT) computational studies, we propose a potential rationale for the "unusual" reactivity patterns witnessed in this branch of heterometallic synthetic chemistry with respect to other Alkali Metal Mediated Metalations which appear to behave in a more conventional manner.



INTRODUCTION

Deprotonative metalation, the breaking of a relatively inert carbon−hydrogen bond by a metal-based reagent followed by the making of a more reactive (and thus more chemically useful) carbon−metal bond, is a classical reaction which is practiced in all disciplines of synthetic chemistry.[1] Typically achieved by utilizing polar organo alkali-metal reagents such as amido [R_2N-Li, e.g. $(Me_3Si)_2NLi$] or alkyl [R-Li, e.g. ^nBuLi] lithium reagents or, when the hydrogen to be abstracted is not sufficiently acidic, LiCKOR superbases.[2] However, these reagents, which exist only under inert atmospheres, can suffer from a variety of significant limitations, for example, an intolerance of certain functional groups is often encountered, while subambient temperatures are routinely required to suppress the highly reactive alkali-metal reagents. The metalated products themselves are often too reactive to be useful, displaying poor kinetic stability.

Overcoming such drawbacks in organolithium/alkali-metal chemistry, an aspiration shared by many research groups worldwide, would be of enormous benefit to both fundamental chemical synthesis and process chemistry.[3] Substantial progress toward this goal has recently been made through the design and application of "ate" modifications of organo alkali-metal bases. Superficially simple,[4] this improved approach capitalizes on the juxtaposition of an alkali-metal with another softer metal (e.g., Mg^{II},[5] Mn^{II},[6] Zn^{II}[7]) within a basic ligand environment. Combining them either within a single molecular framework or a charge-separated variant can export the reactivity of the alkali-metal base to the softer metal which, though reactivity enhanced, retains the superior selectivity and functional group tolerance of a softer metal compound. By definition alkali-metal ate compounds (e.g., $Li^+ MR_3^-$, where M is a divalent metal or $Na^+ MR_4^-$ where M is a trivalent metal) have their negative charge located on the molecular fragment containing the softer, less electropositive metal M, but while this is clearly a contributory factor for the observed reactivity transfer (historically Wittig[8] noted this as "anionic activation") the full explanation must be significantly more complicated as many formulations labeled as ates do not exhibit reactivity enhancement. As most chemists would associate ate formulations with solvent separated ion pairs, we suggest it is more fitting to discuss this chemistry in terms of heterobimetallics or mixed-metal systems as the structures involved can

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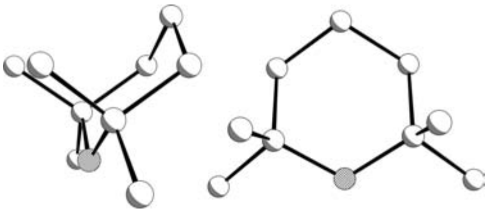


Figure 1. Side on (left) and front on (right) representation of the chair-shaped TMP anion showing how its anionic nitrogen (shaded) is sterically protected.

often be molecular and charge neutral contact ion pairs, though the bonding within them is usually highly polarized.[9]

At the vanguard of these heterometallic advances in deprotonative metalation lies two distinct approaches: the metal halide salt supported method (type **A**), elaborated by Knochel and co-workers; and the mixed organic anion strategy (type **B**), popularized by Kondo, Uchiyama and co-workers,[10] Mongin and co-workers,[11] Hevia and co-workers,[7,12] and our own group. The beating heart of all these approaches is the anion of 2,2,6,6-tetramethylpiperidine, TMP (Figure 1), and the veins through which it communicates are the bonds it forms with the different metal centers.

Four flanking methyl groups provide steric protection for its N reactive center, which, since it bonds only to saturated sp^3-C atoms, retains most of the negative charge associated with its anionic status. This combination of steric and electronic features gives TMP its key synthetically exploitable qualities of low reluctant nucleophilicity and high enthusiastic Brønsted basicity. In the vast majority of its synthetic applications, TMP has been used in the form of its lithium derivative LiTMP.[13,14] What is evident, especially from the rapidly accumulating pages of literature on heterometallic systems, is that the reactivity profile of TMP is profoundly sensitive to the form in which it is dispensed. Multicomponent systems containing TMP as in the two distinct heterometallic approaches **A** and **B** introduced above can have markedly different reactivity profiles. Each component in the system (e.g., alkali-metal, softer metal, supporting anions, neutral solvent ligands) to a smaller or larger extent, can influence reactivity and selectivity and therefore must be taken explicitly into consideration along with the usual discriminatory experimental factors (such as stoichiometry, solubility, bulk solvent, concentration, and temperature) when rationalizing a TMP reaction. Fleming and O'Shea recently provided a pertinent example[15] observing that the Schlosser-Lochmann superbase ^{n}BuLi-KO^{t}Bu executed *ortho*-metalation of OMOM-substituted/activated toluenes but switched to selective benzylic metalation on the addition of stoichiometric or catalytic quantitities of TMP(H) (implying a metal or more likely a mixed-metal TMP species, not identified, is essential for the selectivity switch).

The background and development of the mixed organic anion strategy for deprotonative metalation has been detailed in some recent reviews.[4,9] For brevity this is not repeated here, instead this article focuses on material not covered previously in these reviews as well as on new unpublished results in the area of lithium-mediated *ortho* alumination which stimulates new thoughts on the structural and mechanistic roots of this synergic chemistry. The article begins with a brief summary of the alternative metal halide salt supported deprotonative metalation.

Turbo-Grignard and Related Reagents. Originally proficient in halogen-metal exchange, the halide salt supported mixed metal reagent mixtures (type **A**, for a typical example see Figure 2) are now at the cutting edge of deprotonative metalation.[16] The seminal research of Knochel and co-workers has yielded a prodigious amount of examples whereby such reagents directly metalate substituted aromatics in an efficient manner according to the well established principles of directed *ortho*-metalation (D*o*M).[17] Generally utilized in polar (tetrahydrofuran, THF) solvent, the introduction of LiCl (or $MgCl_2$[18] or $ZnCl_2$[19]) to the amido metal chloride or bis(amido) metal reagent is credited with boosting reactivity at least in part by increasing solubility. What makes these mixed metal reagent mixtures particularly attractive is their excellent tolerance of sensitive functional groups, as well as their improved kinetic basicity, regioselectivity, and chemoselectivity with respect to the parent softer metal homometallic reagent. While the most common subordinate metals are magnesium and zinc in the form of (TMP)MCl·LiCl (M = Mg,[20] Zn[21]), $(TMP)_2Mg\cdot 2LiCl$[22] or $(TMP)_2Zn\cdot 2MgCl_2\cdot 2LiCl$,[23] Knochel and co-workers have recently and expeditiously extended this concept further to successfully initiate direct manganation,[24] alumination,[25] ferration,[26] lanthanation,[27] and even zirconation[28] of functionalized aromatic molecules, while incorporation of Lewis acidic BF_3 into a halide salt supported mixed metal magnesiate was shown to activate previously unreactive C−H bonds in polyfunctional pyridines and related heterocycles.[29] The versatility of this class of reagent has been elaborated further by a recent report of the selective metalation of alkenes.[30] This is ongoing work which will undoubtedly produce other major advances in due course.

While the ability of these reagent mixtures to induce regioselective or chemoselective direct metalations is undoubted, the mechanisms by which these reactions occur remain ambiguous since no metalated intermediates are isolated or otherwise characterized. Typically, a bi- (or even tri- or tetra-) metallic melange is prepared in THF, reacted with a substrate, and subsequently quenched with an electrophile or is cross coupled. Recently, we unveiled the solid state structures of a classical Knochel magnesiate base, THF solvated (TMP)MgCl·LiCl (**1**),[31] and its (dimeric) diisopropylamide [$^{i}Pr_2N^-$, DA] congener (**2**)[32] (Figure 3), allowing the proposal of a structural rationale for the contrasting reactivities displayed by each.

NMR spectroscopic evidence, including DOSY experiments,[33] suggested these LiCl supported complexes do not retain their structural integrity in solution with the presence of solvent separated ion pairs a strong possibility. These "ates" are predisposed to metalating *ortho* to directing groups which in certain cases is in contrast to contacted-ion (type **B** − for a typical example see Figure 4a) structures which can anchor a substrate within a premetalation framework, opening up the possibility of less conventional metalation patterns occurring via a potentially intramolecular pathway.

Recent Developments in Alkali-Metal Mediated Metalation. Coupled with their ability to effect conventional *ortho* metalation of functionalized aromatic molecules containing a directing group, mixed organic anion (type **B**) heterometallic bases also have the capability of carrying out "unusual" deprotonations. This can take the form of metalation at nonactivated (less acidic) sites or through polymetalation of substrates which are not typically prone to experiencing more than a single deprotonation. A simple example of the former is the special *meta* deprotonation of toluene with the mixed alkyl-amido sodium magnesiate base TMEDA·Na(μ-TMP)(μ-Bu)Mg(TMP)[34] or the *meta* deprotonation of *N*,*N*-dimethylaniline with the related zincate base TMEDA·Na(μ-^{t}Bu)(μ-TMP)Zn(^{t}Bu),[35] while the latter is witnessed spectacularly via the regioselective 1,1′,3,3′

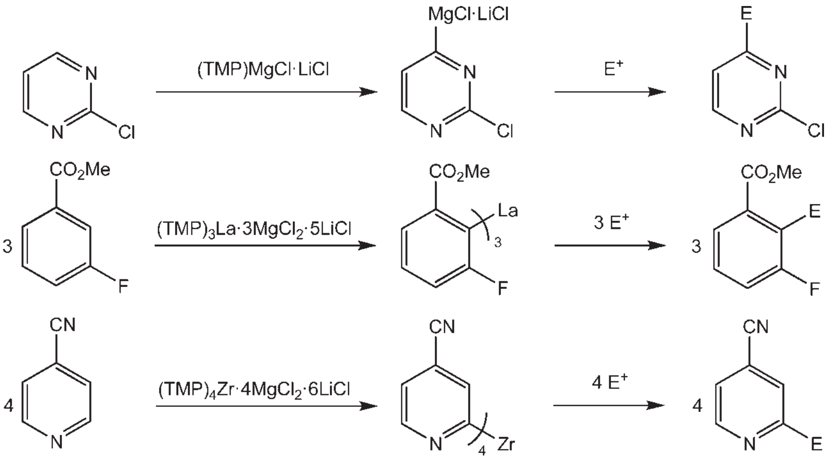


Figure 2. Some representative examples of metalation and electrophilic quenching of functionalized aromatics utilizing halide salt supported mixed-metal reagent (type **A**) mixtures showing magnesiation (top), lanthanation (middle), and zirconation (bottom).

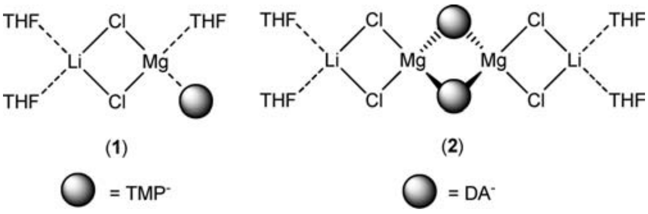


Figure 3. Representation of the experimentally determined crystal structures of the Turbo-Grignard reagents **1** and **2**.

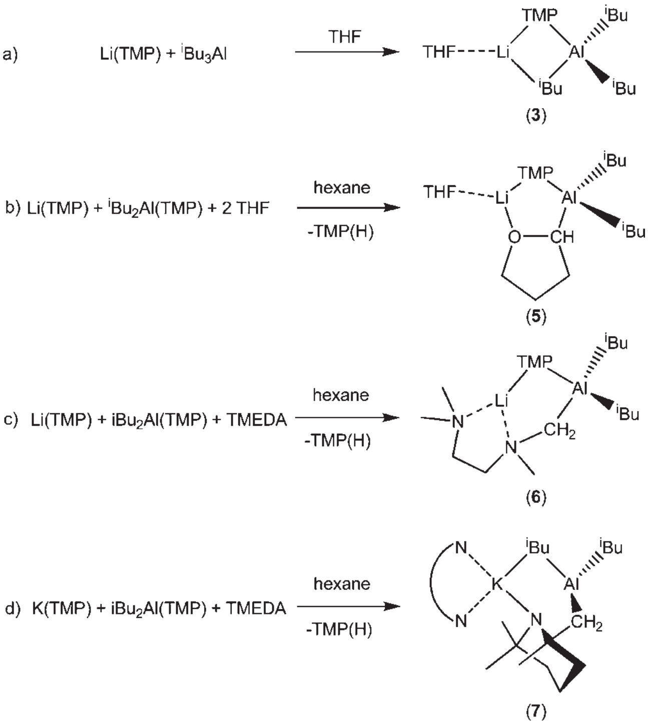
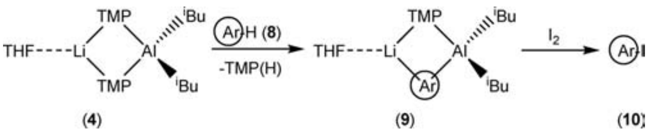


Figure 4. Some representative examples of the structural diversity available in alkali-metal mediated alumination (AMM*Al*).

Scheme 1



tetra-deprotonation of ferrocene,[36] ruthenocene,[37] and osmocene[37] with $NaMg(N^iPr_2)_3$. Novel host−guest ring compounds, labeled inverse crowns because of the antithetical location of the Lewis acidic/basic atoms with respect to a traditional crown ether complex, are often the result of such bimetallic-induced single or multiple deprotonations[38] although inverse crowns can also be prepared via co-complexation.[39] The contacted ion pair nature of these intermediate complexes plays a dominant role in their unconventional behavior, as mentioned above.

Judicious selection of the subordinate metal, the anions, and the donor are clearly paramount if the desired reactivity toward any given substrate is to be achieved. With regards to the metal, this is eloquently demonstrated by the deprotonation of THF—when the mixed metal sodium−zincate base $[TMEDA \cdot Na(\mu\text{-}TMP)(\mu\text{-}CH_2SiMe_3)Zn(CH_2SiMe_3)]$[40] is employed, the deprotonated highly sensitive cyclic ether molecule is captured with its OC_4 ring intact within the molecular framework, while changing to the magnesiate or manganate $[TMEDA \cdot Na(\mu\text{-}TMP)(\mu\text{-}CH_2SiMe_3)M(TMP)]$ (M = Mg, Mn)[41] results in cleavage of THF with the fragments being sequestered by residues of the base,[42] the oxygen containing fragment forming an oxo inverse crown.[43] The importance of anion selection is emphasized by two similar aluminate systems: $THF \cdot Li(\mu\text{-}TMP)(\mu\text{-}^iBu)Al(^iBu)_2$ (**3**) can be isolated in crystalline form and is stable in THF solution;[44] while its putative amide enriched counterpart $THF \cdot Li(\mu\text{-}TMP)_2Al(^iBu)_2$ (**4**) can be prepared in situ but not isolated, with deprotonation of a THF molecule to yield $THF \cdot Li(\mu\text{-}TMP)(\mu\text{-}C_4H_7O)Al(^iBu)_2$ (**5**) being favored (Figure 4).[45] Lewis donor identity is also important, as articulated by Stalke and co-workers, who demonstrated that the $MeLi/Me_2Zn$ combination yields a contact ion pair in the presence of PMDETA but a solvent separated ion pair in the presence of diglyme.[46] The reasons for the current prominence of aluminum chemistry are 2-fold; first aluminum metal is cheap, abundant, and relatively nontoxic—all important considerations for today's synthetic chemist;[47] and second preliminary work in the dominion of mixed metal aluminum chemistry has exposed several unusual metalation patterns including

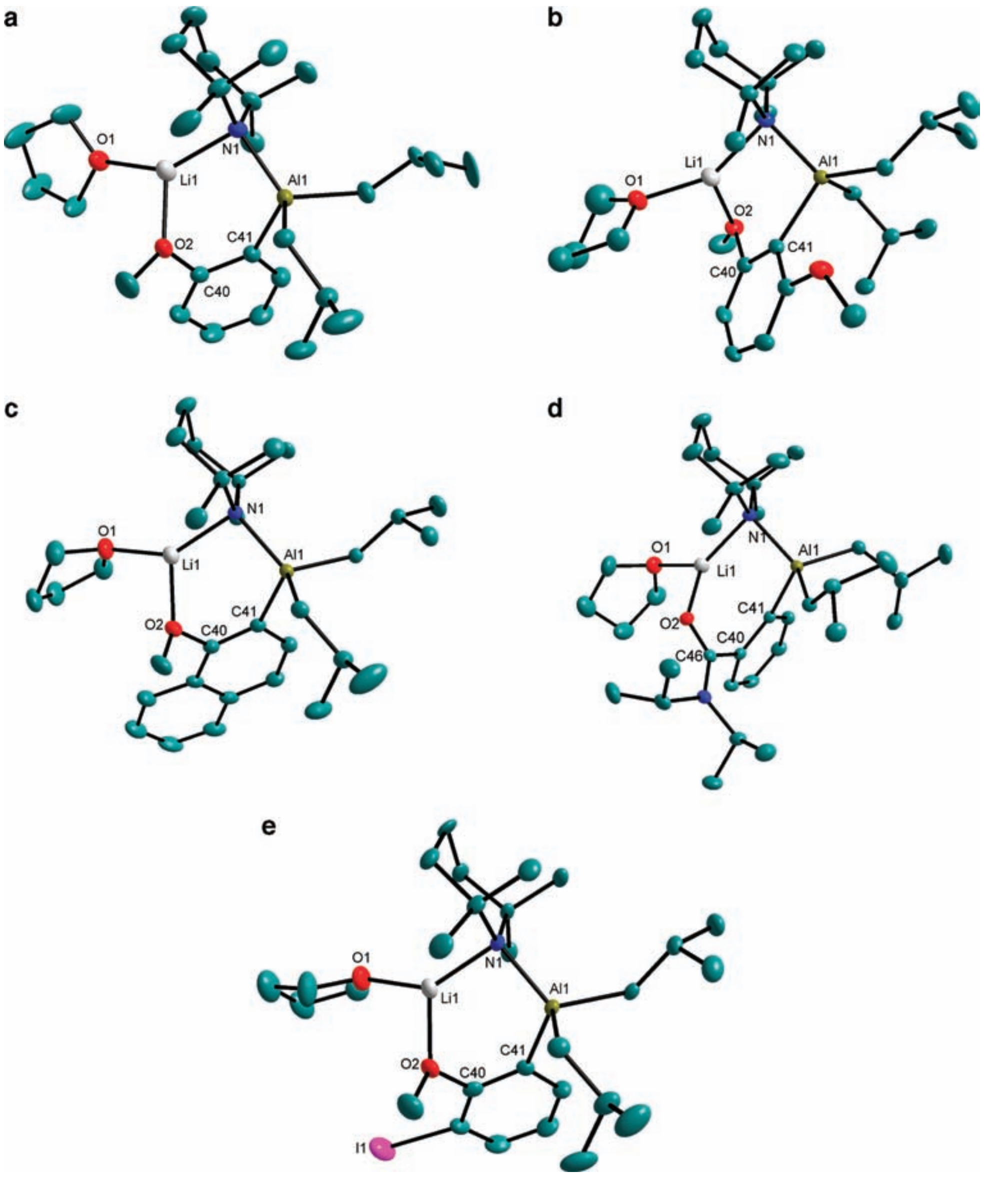


Figure 5. Molecular structures of complexes **9a**−**9e** with thermal ellipsoids displayed at the 50% probability level. Hydrogen atoms and any minor disorder components are omitted for clarity.

alumination[48] of α-C-H units of the polyamines TMEDA (**6**)[49] or PMDETA,[50] fragmentation of 1,4-dioxane,[51] or methyl deprotonation of the TMP anion to give **7**[52] (Figure 4).

Toward gaining a greater understanding of the bisamido/bisalkyl lithium aluminate **4**, and by implication of alkali-metal mediated metalation in general, the current paper documents a detailed investigation of the reactivity of this in situ generated base toward a variety of substituted aromatic substrates (**8a**−**8e**, Table 2) resulting in a series of extensively characterized mixed-metal complexes of general formula $^{i}Bu_2Al(\mu\text{-TMP})(\mu\text{-R})Li\cdot THF$ (**9a**−**9e**, where R is the deprotonated substrate) and the products of such metalated intermediates upon electrophilic quenching with elemental iodine (**10a**−**10e**). Adding to the knowledge already acquired on AMM*Al*, we then re-examine some of the more unusual results obtained thus far and provide theoretical and mechanistic insight into some of the potential reasons why ligand/metal choice is so fundamentally important in these intriguing heterometallic systems.

RESULTS AND DISCUSSION

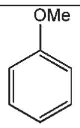
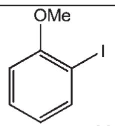
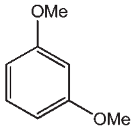
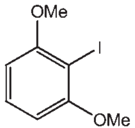
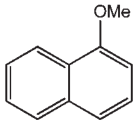
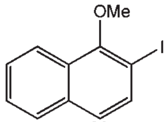
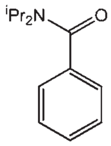
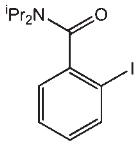
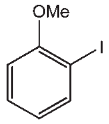
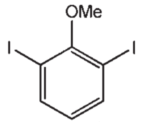
The ability of "$^{i}Bu_2Al(\mu\text{-TMP})_2Li\cdot THF$" (**4**) to effect the room temperature deprotonation of some representative functionalized aromatic molecules according to the reactions in Scheme 1 was studied. Specifically, anisole (**8a**), 1,3-dimethoxybenzene (**8b**), 1-methoxynaphthalene (**8c**), and *N*,*N*-diisopropylbenzamide (**8d**) were chosen as representative substituted aromatic substrates for this task.

Given that Uchiyama and co-workers[10f] and Knochel and co-workers[25] have previously observed that Al/Li bases favor deprotonative metalation over metal halogen exchange, 2-iodoanisole (**8e**) was also considered in the study. The outcomes of these reactions were monitored by both the identification of the crystalline intermediates (**9a**−**9e**) and also the identification of their subsequent metal-free organic products obtained via electrophilic quenching with iodine (**10a**−**10e**). For complete synthesis and characterization of **9a**−**9e** and **10a**−**10e** see Supporting

Table 1. Selected Bond Parameters of Complexes 9a–9e (in Å and deg)

	9a	9b	9c	9d	9e
Al1–N1	1.981(1)	1.985(1)	1.975(1)	1.985(1)	1.974(3)
N1–Li1	2.036(3)	2.032(3)	2.039(2)	2.064(2)	2.015(6)
Li1–O1	1.929(3)	1.940(2)	1.943(2)	1.941(2)	1.906(7)
Li1–O2	1.922(3)	1.991(4)	1.909(2)	1.905(2)	1.904(6)
O2–C40	1.415(2)	1.409(2)	1.422(1)		1.402(4)
O2–C46				1.250(1)	
C46–C40				1.500(1)	
C40–C41	1.391(2)	1.394(2)	1.367(2)	1.418(1)	1.384(4)
C41–Al1	2.049(1)	2.082(2)	2.057(1)	2.088(1)	2.047(3)
O1–Li1–O2	103.5(1)	102.5(1)	99.8(1)	102.8(1)	102.0(3)
O1–Li1–N1	142.7(1)	145.1(1)	142.5(1)	133.4(1)	140.2(3)
N1–Li1–O2	113.8(1)	112.3(1)	117.6(1)	121.4(1)	117.7(3)
Li1–N1–Al1	97.1(1)	88.9(1)	98.7(1)	87.7(1)	98.7(2)

Table 2. Substrates and Products upon Electrophilic Quenching of Aluminated Aromatic Intermediates with Iodine

Entry	Substrate	Product
1	 **8a**	 **10a**: 77 % [a]
2	 **8b**	 **10b**: 81 % [a]
3	 **8c**	 **10c**: 70 % [a]
4	 **8d**	 **10d**: 88 % [a]
5	 **8e**	 **10e**: 96 % [b]

[a] The identity of these iodated compounds was confirmed by comparison of their ^{1}H NMR spectra with those previously published by Kondo and Uchiyama; see ref 10e for full spectroscopic details. [b] See Supporting Information for complete characterization.

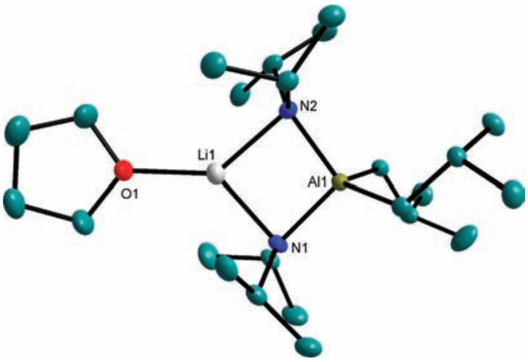


Figure 6. Molecular structure of complex **11** with thermal ellipsoids displayed at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond parameters (in Å and deg): Al1–N1 1.935(1), Al1–N2 1.936(1), Li1–N1 2.075(3), Li1–N2 2.086(3), Li1–O1 1.969(3); N1–Al1–N2 100.67(5), Al1–N1–Li1 84.10(8), Al1–N2–Li1 83.78(8), N1–Li1–N2 91.45(10), N1–Li1–O1 132.8(1), N2–Li1–O1 135.7(1).

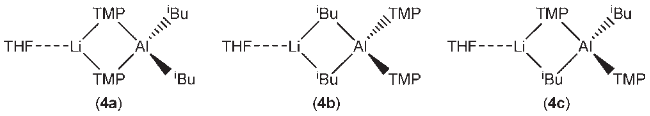


Figure 7. Potential structures of complex **4** studied via DFT calculations.

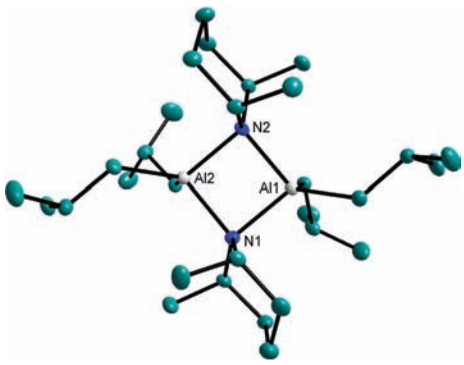


Figure 8. Molecular structure of complex **12a** with thermal ellipsoids displayed at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond parameters (in Å and deg): Al1–N1 2.009(2), Al1–N2 2.021(2), Al2–N1 2.020(2), Al2–N2 2.003(2); N1–Al1–N2 86.34(8), N1–Al2–N2 86.51(8), Al1–N1–Al2 87.76(8), Al1–N2–Al2 87.89(8).

Information. In each case, the site of alumination was shown to be *ortho* to the functional group (for **8b**, the metalation occurred at the site mutually *ortho* to both OMe groups). As anticipated, the base **4** tolerated the carboxamide functionality of **8d** and the iodo functionality of **8e**. Such *ortho* deprotonations have transpired via directed *ortho* metalation (DoM), that is the heteroatomic functional group can play a dual purpose by both acidifying the *ortho* proton inductively and providing a lone pair of electrons on which to anchor the incoming metal. Of principal importance in these reactions was that they were all achieved in nonpolar hexane solution at room temperature, obviating the need for more expensive polar solvents or nonambient temperature regimes which are generally required for homometallic, organolithium based DoM. The crystalline products could be isolated in decent yields (44–71%), but in fact the metalation was nearly quantitative as shown by electrophilic quenching (vide infra).

While mixed-metal bases have routinely been employed to deprotonate a plethora of organic substrates, the identity of the

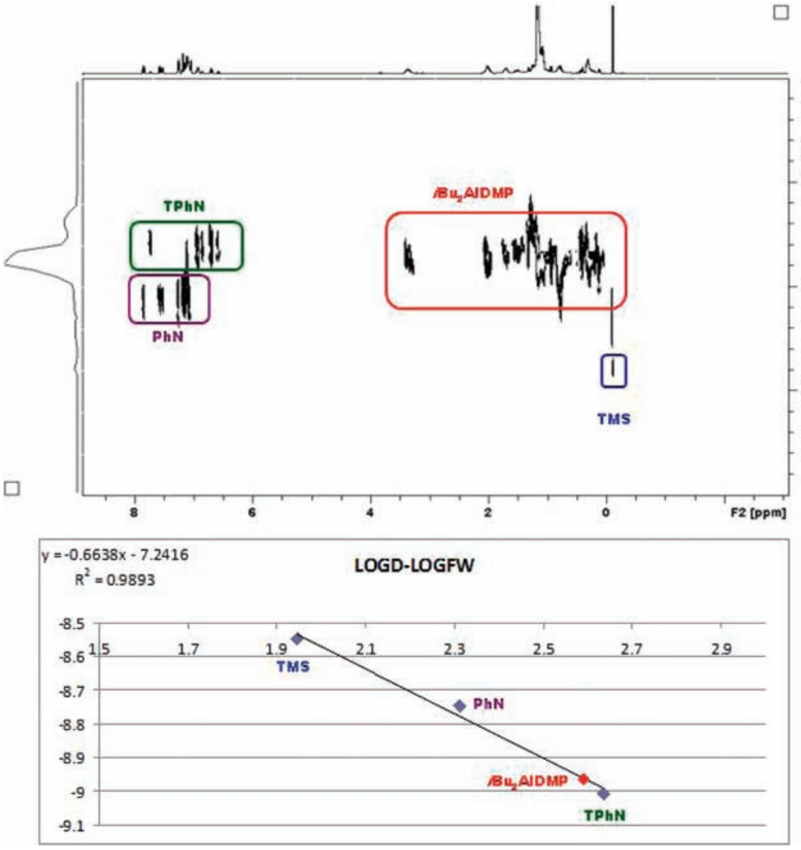


Figure 9. (top) ^{1}H DOSY NMR spectrum of ^{i}Bu$_2$Al(DMP) (**12a**), TPhN, PhN and TMS at 25 °C in C_6D_6 and (bottom) log D − log FW representation from the ^{1}H DOSY data obtained for the mixture of ^{i}Bu$_2$Al(DMP) (**12a**), TPhN, PhN and TMS at 25 °C in C_6D_6.

metal which actually displaces the proton is often assumed since the metalated intermediate is not in itself characterized but rather used in situ and quenched with an electrophile. Although this assumption is not necessarily incorrect, the solid state structures of complexes **9a**−**9e** (Figure 5) unambiguously confirm in these cases that it is *direct alumination* of the substrate that is occurring. The presence of lithium is however of paramount importance since the parent homometallic reagent, ^{i}Bu$_2$Al(TMP) does not deprotonate **8a**−**8e** by itself [in confirmation of this, samples of **8a**−**8e** with ^{i}Bu$_2$Al(TMP) in C_6D_{12} solution were found not to react by ^{1}H NMR spectroscopy after 2 h at room temperature followed by 1 h at 70 °C] and thus these alumination reactions can be considered synergic in origin, operating via Li···Al communication through a TMP linker.

The molecular structures of complexes **9a**−**9e** share many features: for example they are all bimetallic (Li/Al) molecular contacted ion pair arrangements incorporating two ^{i}Bu groups terminal on aluminum, a TMP ligand bridge (with the substituted piperidide ring leaning toward lithium in the chair formation), a bridging C−H deprotonated aromatic molecule, and a solitary molecule of THF solvating the lithium. This motif results in a distorted tetrahedral (C_3N) aluminum center, and a trigonal planar lithium atom. The substrate has clearly been aluminated *ortho* to the functional group, with the heteroatom donating via its lone pair of electrons to the electropositive lithium resulting in a six-membered LiNAlC$_2$O ring (or, in the case of carboxamide **9d**, a seven-membered LiNAlC$_3$O ring). That notwithstanding, the features of these structures are unspectacular and require no further discussion (see Table 1 for pertinent bond parameters). Multinuclear NMR data confirms that such structures maintain their integrity in the solution state (see Experimental Section for full details), while purity of the bulk sample was evidenced via satisfactory elemental analyses.

Of course, while a crystallographic determination gives a clear snapshot of the salient intermediates, it is perilous to assume this to be representative of the entire solution. Consequently, the reactions were repeated and the in situ generated intermediates **9a**−**9e** were subjected to electrophilic quenching using elemental iodine to give **10a**−**10e** in good to excellent (70−96%) yield. The iodated products were purified via column chromatography to give the final products whose identity was confirmed by ^{1}H NMR spectroscopy.[10e]

Meanwhile, the structure of the active base **4** remains elusive. However, its in situ generation and reaction with two molar equivalents of diisopropylamine [^{i}Pr$_2$NH, DA(H)] yielded its diisopropylamide derivative ^{i}Bu$_2$Al(μ-DA)$_2$Li·THF (**11**),[53] produced in a crystalline yield of 55%. The molecular structure of **11** (Figure 6) shows that the electron rich amide groups occupy the bridging positions between the two metals, with the alkyl groups residing in the terminal positions.

Theoretical and Mechanistic Examination of AMM*Al*. On considering the preceding results in the field of Alkali Metal Mediated Alumination (vide supra) we feel that two important questions are worth asking: (a) why can the THF solvated bis-DA bis-alkyl lithium aluminate complex **11** be isolated yet its TMP analogue complex **4** is only a putative intermediate?; and (b) why is Uchiyama's lithium aluminate THF·Li(μ-TMP)(μ-^{i}Bu)Al(^{i}Bu)$_2$ (**3**) stable indefinitely in THF solution yet a

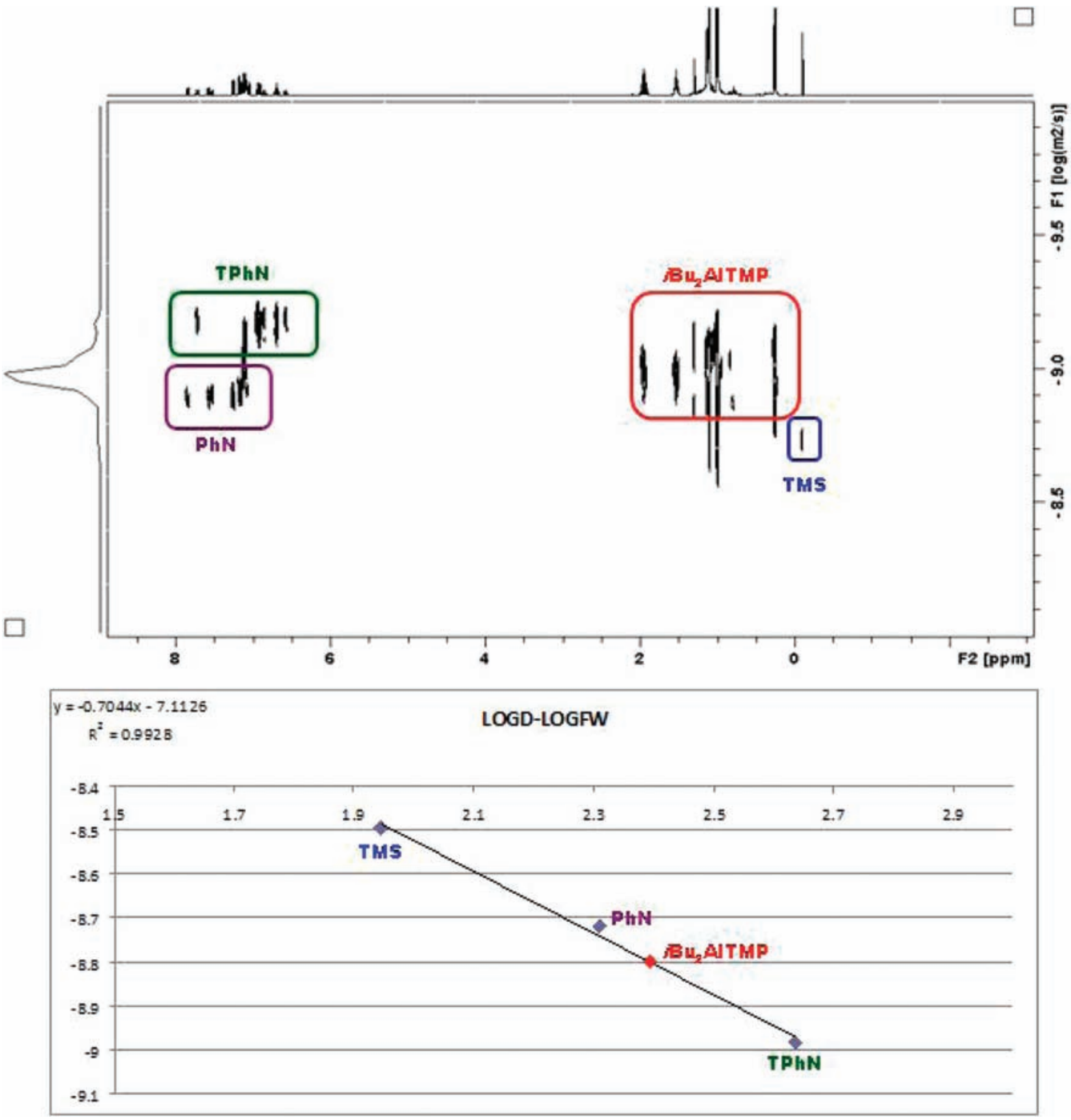


Figure 10. (top) ^{1}H DOSY NMR spectrum of ^{i}Bu$_2$Al(TMP) (**12b**), TPhN, PhN, and TMS at 25 °C in C_6D_6 and (bottom) log D − log FW representation from the ^{1}H DOSY data obtained for the mixture of ^{i}Bu$_2$Al(TMP) (**12b**), TPhN, PhN, and TMS at 25 °C in C_6D_6.

hexane solution of **4** will deprotonate a stoichiometric amount of THF to yield THF·Li(μ-TMP)(μ-OC$_4$H$_7$)Al(^{i}Bu)$_2$ (**5**)?

To try and elucidate possible answers we next carried out a series of density functional theory (DFT) calculations, which coupled with other experimental observations, allow us to propose a potential rationale for the witnessed reactivity described above.

DFT calculations were performed using the Gaussian 03 package[54] with geometry optimization using the B3LYP density functionals[55] and the 6-311(d,p) basis set[56] with a frequency analysis being performed after each geometry optimization. The energy values quoted include the zero point energy contribution.

We investigated the relative energies of three potential structural manifestations of **4**, that is, with the bridging positions occupied by either (a) both TMP anions; (b) both ^{i}Bu anions; or (c) a mixture of one TMP and one ^{i}Bu anion (**4a**-**4c**, Figure 7).

Hypothetical mixed bridge complex **4c** was also studied for two alternative conformations, namely, with the bridging TMP group having its γ-C apex pointing toward the Al (**4c′**) or toward the Li center (**4c″**). Unsurprisingly, given that complexes **9a**−**9e** all have terminal ^{i}Bu groups, complex **4a** is the most energetically

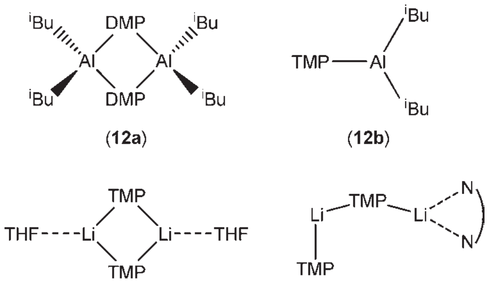


Figure 11. Known solid state structures of some pertinent DMP/TMP complexes (**12a**, **13a**, **13b**) and the proposed structure of **12b** as predicted on the basis of DOSY NMR spectroscopy.

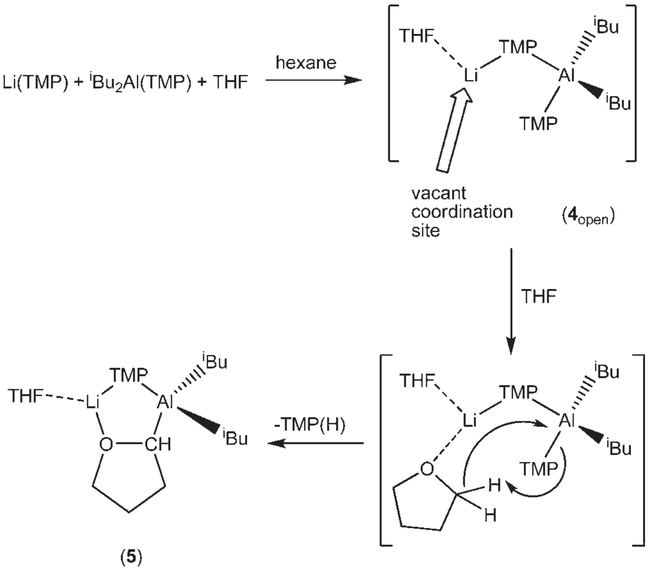


Figure 12. Proposed open structure of the putative bisamido bisalkyl lithium aluminate **4** with a possible mechanism giving complex **5**.

favorable by 14.75, 4.85, and 10.06 kcal mol^{-1} compared to **4b**, **4c**′, and **4c**″ respectively. However, perhaps surprisingly, this study also reveals that the product is energetically unfavorable with respect to the homometallic starting materials of which it is composed (a combination of THF solvated and unsolvated starting materials were computed, eqs 1a−1c).

$$\frac{1}{4}[\mathrm{Li(TMP)}]_4 + \mathrm{THF\cdot Al(TMP)^iBu_2} \rightarrow \mathrm{THF\cdot Li(\mu\text{-}TMP)_2Al^iBu_2} \quad \Delta E = +14.16\ \mathrm{kcal\ mol^{-1}} \tag{1a}$$

$$\frac{1}{2}[\mathrm{LiTMP\cdot THF}]_2 + \mathrm{Al(TMP)^iBu_2} \rightarrow \mathrm{THF\cdot Li(\mu\text{-}TMP)_2Al^iBu_2} \quad \Delta E = +14.19\ \mathrm{kcal\ mol^{-1}} \tag{1b}$$

$$\frac{1}{2}[\mathrm{LiTMP\cdot THF}]_2 + \mathrm{THF\cdot Al(TMP)^iBu_2} \rightarrow \mathrm{THF\cdot Li(\mu\text{-}TMP)_2Al^iBu_2} + \mathrm{THF} \quad \Delta E = +20.60\ \mathrm{kcal\ mol^{-1}} \tag{1c}$$

$$\frac{1}{2}[\mathrm{LiTMP\cdot THF}]_2 + \mathrm{THF\cdot Al(TMP)^iBu_2} \rightarrow \mathrm{THF\cdot Li(\mu\text{-}TMP)(\mu\text{-}C_4H_7O)Al^iBu_2(5)} + \mathrm{TMP(H)} \quad \Delta E = -5.30\ \mathrm{kcal\ mol^{-1}} \tag{1d}$$

Despite the preparation of **4** from its component homometallic parts being energetically unfavorable, a calculation of the same starting materials to give the THF deprotonated species **5** was also carried out (eq 1d). This confirms that the preparation of this complex is favorable and can perhaps be attributed to the formation of a five-membered LiNAlCO ring which would alleviate the ring strain felt in the four membered ring of the hypothetical species **4**. For full geometrical details of the calculated structures of **5** and the bisamido bisalkyl species **11** see Supporting Information.

The inability to isolate a stable derivative of composition **4** is perhaps attributable to the steric protection of the nitrogen in the TMP being too much to allow the necessary AlN$_{TMP}$LiN$_{TMP}$ closed ring to form since clearly, as the molecular structure of **11** shows, an AlNLiN ring can be obtained with a slightly less bulky secondary amide. This is further supported by our comparative study of homometallic ^{i}Bu$_2$AlNR$_2$ (NR$_2$ = DMP, *cis*-2,6-dimethylpiperidide, **12a**; TMP, **12b**) which were prepared by mixing an equimolar amount of ^{i}Bu$_2$AlCl with LiNR$_2$ in hexane. DMP has only 2 of TMP's 4 methyl substituents, so its anionic N center is marginally less sterically protected.[57] In these reactions after filtering the mixture to remove LiCl, the product was obtained in excellent yield as a crystalline solid (**12a**) or yellow oil (**12b**) respectively. Ascertained via a single crystal X-ray diffraction study, the molecular structure of **12a** (Figure 8) exists as a cyclodimer with the alkyl groups in the terminal positions and the DMP ligands bridging the two trivalent metal atoms.

Since the molecular structure of complex **12b** could not be determined, we turned to a DOSY NMR study in an attempt to harvest further information on the aggregation of these two species in solution. Here, different components present in solution can be separated according to their molecular weight. Such component(s) can then have their molecular weights estimated provided inert samples of known molecular weight are also present in the solution for calibration purposes since the log of molecular weight can be linearly correlated to log *D* (diffusion coefficient). The ^{1}H DOSY NMR spectra and plots of log *D* − log FW for **12a** and **12b** are shown in Figures 9 and 10 (see Supporting Information for full experimental details).

The results gave a predicted molecular weight (MW$_{DOSY}$) of 395 and 243 g mol^{-1} for **12a** and **12b**, respectively. Clearly, **12a** seems to have a higher solution molecular weight than **12b** despite having a smaller empirical molecular weight. The value of MW$_{DOSY}$ is intermediate between that of ^{i}Bu$_2$Al(DMP) and [^{i}Bu$_2$Al(DMP)]$_2$ [253 and 507 g mol^{-1} respectively and is consistent with a monomer−dimer equilibrium. The value for **12b** is within 13% error of the molecular weight for a monomeric species (MW = 281) and as it is on the lower side of the predicted value it is likely to in fact exist as a monomer in solution.

We thus appear to have discerned a point at which steric bulk around the anion will prevent dimerization from occurring. Indeed, the Al$_2$N$_2$ ring of **12a** is extremely strained, as evidenced by the movement of the ring away from planarity. For comparison, a search of the Cambridge Crystallographic database[58] for dialkylamidoaluminum structures which have dimerized through their amido ligands reveals 124 positive matches. While the N−Al−N angles [86.34(8) and 86.51(8)°] of **12a** are consistent with those previously reported [mean = 86.634°, median = 87.557°], the Al−N−Al angles [87.76(8) and 87.89(8)°] are considerably tighter than expected [mean = 91.908°, median = 91.820°], resulting in a butterfly motif [hinge angle = 36.23(6)°]. Likewise, the Al−N bond lengths are relatively long, falling in the range 2.003(2)−2.021(2)Å (average 2.013 Å) when compared with those reported in the literature [1.883−2.045 Å, with a mean value of 1.974 Å and a median value of 1.977 Å]. Clearly, the presence of simply two more methyl groups (that is substituting DMP by TMP) close to the bridging point is sufficient to inhibit dimerization. The inability of **12b** to dimerize is consistent with the accomplished work of Nöth who has crystallographically characterized a series of solvated and unsolvated TMP containing aluminum

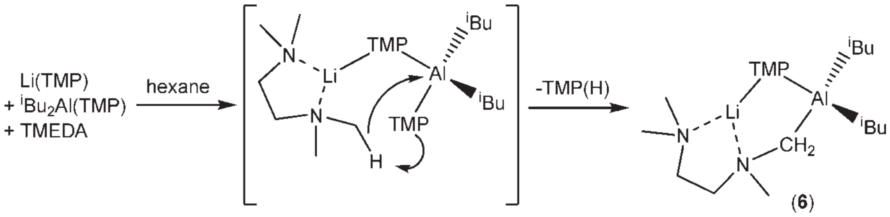


Figure 13. Proposed mechanism for deprotonation of coordinated TMEDA via an open structure to give complex **6**.

complexes of general formula $(TMP)_2AlX$ (X includes halides,[59] phosphides,[60] amides,[60a] alkoxides,[60a] thiolates,[60a] borazinyl[61]) which are primarily monomeric. Of the dimers known, such as $[(TMP)_2AlF]_2$ or $[(TMP)AlCl(OEt)]_2$,[59a] none dimerize through bridging TMP groups. Dimeric species with a dianionic $[(CH_2)^{2-}$ [62] or $(PPh)^{2-}$ [60b]] bridge or trimeric species with a N═N═N or C≡N bridge have also been divulged.[63] Nöth also reported previously that $[(TMP)AlH_2]_3$ is a trimer with hydride bridges while $[(DMP)AlH_2]_2$ is a dimer with DMP bridges.[64]

At this juncture, it is pertinent to note that thus far there have been no reported examples of a $LiN_{TMP}LiN_{TMP}$ closed ring in the literature containing a four coordinate lithium center. While such a ring can be formed, each lithium cation is only monosolvated (trigonal planar, **13a**),[14f] while an attempt to use a bidentate donor (namely TMEDA) resulted in an open, hemisolvated dinuclear structure (**13b**, Figure 11) with a mixture of two and three coordinate lithium centers.[14d] TMEDA solvated Li(DMP) forms a central four membered ring, but TMEDA binds in a unidentate fashion, bridging between adjacent Li_2N_2 rings to give a polymeric motif.[65]

Given that Al-bridging amide bonds are shorter than Li-bridging amide bonds (see Table 1), coupled with the fact that a $[LiN_{TMP}]_2$ ring cannot be formed with four-coordinate lithium for presumably steric reasons, it is unlikely that the $Li-N_{TMP}-Al-N_{TMP}$ ring is obtainable, and any species with the empirical formula of **4** should therefore exist in an open form. This suggestion is further supported by the change from dimeric (four-coordinate Al) to monomeric (three-coordinate Al) on slightly increasing the amide bulk from DMP to TMP in the homometallic complexes **12** (vide supra).

With this increasing body of indirect evidence supporting an open structure, we are now in a position to propose a hypothetical mechanism for the synthesis of **5**. If **4** prevails in an open form such as displayed in Figure 12, a vacant coordination site on lithium would exist on which a second molecule of THF could attach via its Lewis donating oxygen center. Consequently, the close proximity of this second THF molecule to the pseudoterminal TMP anion could result in attack at the α-C-H unit by the amido base, giving the energetically favorable complex **5** as the thermodynamic product with elimination of TMP(H).

The same principle can be applied to the deprotonation of the NCH_3 unit of TMEDA to yield complex **6** (Figure 13), again an open intermediate is proposed which brings the TMEDA molecule into partial proximity allowing one of its α-Me groups to be deprotonated by the reactive pseudoterminal TMP anion. In both cases, formation of a more stable five membered $[AlN_{TMP}LiXC]$ ring (X = O, **5**; N, **6**) would provide a driving force for the reaction.

This accumulated evidence allows us to propose a plausible hypothesis to answer questions a and b: the combined bulk of two TMP molecules with their tetrasubstituted α-carbon atoms is just sufficient to prevent the formation of a stable four-membered ring; whereas with less bulky ^{i}Bu or N^{i}Pr$_2$ groups such a ring is feasible in either **3** or **11**. It is this open structure, with a "pseudoterminal" TMP ligand, which may confer increased reactivity on heterometallic bases of this type, consequently leading to the deprotonation of a donor molecule at a relatively nonacidic site normally considered resistant toward metalation.

CONCLUSION

The synthetic utility of the lithium aluminate base "THF·Li(μ-TMP)$_2$Al(^{i}Bu)$_2$" has been extended toward *ortho* alumination of substituted aromatic molecules and shows excellent regio- and chemo-selectivity. Operating at room temperature, this bimetallic complex directly aluminates the substrate in an efficient manner and is tolerant of sensitive functionality on the aromatic substrate (e.g., carboxamide and halide functionalities), as proven by the isolation and identification of a series of aluminated aryl intermediates. The presence of a second TMP anion in this bis-alkyl bis-amido base with respect to its more alkyl rich counterpart THF·Li(μ-TMP)(μ-^{i}Bu)Al(^{i}Bu)$_2$ clearly plays an important role in reactivity since this seemingly innocent alteration to the composition of the base has previously induced less conventional metalation patterns. DFT calculations, in conjunction with some new observations in the domain of aluminum and lithium alkyl/amide chemistry, have allowed us to propose a potential hypothesis for this increased reactivity. The steric bulk of the TMP anion when considered against less bulky ^{i}Bu might inhibit formation of a stable four-membered ring, leaving an open intermediate structure with greater reactivity imparted via easier access of the organic substrate possibly involving a pseudoterminal TMP anion. As research into alkali-metal mediated alumination progresses, more examples of unorthodox metalation patterns should become apparent, which in time should lead to an even greater understanding of the cooperative (metal−ligand−metal′) effects which influence this intriguing topical branch of chemistry.

ASSOCIATED CONTENT

Ⓢ **Supporting Information.** Full experimental details, crystallographic details, and optimized structures of complexes **5** and **11** including calculated bond parameters. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: r.e.mulvey@strath.ac.uk.

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REFERENCES

(1) Schlosser, M. *Organometallics in Synthesis: A Manual*, 2nd ed.; Wiley: Chichester, 2002.

(2) For an outstanding historical review of alkyl and aryl derivatives of the alkali-metals through to superbases see: Seyferth, D. *Organometallics* **2009**, *28*, 2.

(3) Wunderlich, S. H.; Rohbogner, C. J.; Unsinn, A.; Knochel, P. *Org. Process Res. Dev.* **2010**, *14*, 339.

(4) For a review of AMMM see: Mulvey, R. E. *Acc. Chem. Res.* **2009**, *42*, 743.

(5) For a recent example of AMM*Mg* see: Blair, V. L.; Kennedy, A. R.; Mulvey, R. E.; O'Hara, C. T. *Chem.—Eur. J.* **2010**, 8600.

(6) For a recent example of AMM*Mn* see: Blair, V. L.; Clegg, W.; Mulvey, R. E.; Russo, L. *Inorg. Chem.* **2009**, *48*, 8863.

(7) For a recent example of AMM*Zn* see: Armstrong, D. R.; Blair, V. L.; Clegg, W.; Dale, S. H.; García-Álvarez, J.; Honeyman, G. W.; Hevia, E.; Mulvey, R. E.; Russo, L. *J. Am. Chem. Soc.* **2010**, *132*, 9480.

(8) Wittig, G. *Angew. Chem.* **1958**, *70*, 65.

(9) (a) Mulvey, R. E.; Mongin, F.; Uchiyama, M.; Kondo, Y. *Angew. Chem., Int. Ed.* **2007**, *46*, 3802. (b) Mulvey, R. E. *Organometallics* **2006**, *25*, 1060.

(10) (a) Kondo, Y.; Shilai, M.; Uchiyama, M.; Sakamoto, T. *J. Am. Chem. Soc.* **1999**, *121*, 3539. (b) Imahori, T.; Uchiyama, M.; Sakamoto, T.; Kondo, Y. *Chem. Commun.* **2001**, 2450. (c) Uchiyama, M.; Miyoshi, T.; Kajihara, Y.; Sakamoto, T.; Otani, Y.; Ohwada, T.; Kondo, Y. *J. Am. Chem. Soc.* **2002**, *124*, 8514. (d) Kondo, Y.; Morey, J. V.; Morgan, J. C.; Naka, H.; Nobuto, D.; Raithby, P. R.; Uchiyama, M.; Wheatley, A. E. H. *J. Am. Chem. Soc.* **2007**, *129*, 12734. (e) Naka, H.; Uchiyama, M.; Matsumoto, Y.; Wheatley, A. E. H.; McPartlin, M.; Morey, J. V.; Kondo, Y. *J. Am. Chem. Soc.* **2007**, *129*, 1921. (f) Naka, H.; Morey, J. V.; Haywood, J.; Eisler, D. J.; McPartlin, M.; García, F.; Kudo, H.; Kondo, Y.; Uchiyama, M.; Wheatley, A. E. H. *J. Am. Chem. Soc.* **2008**, *130*, 16193.

(11) (a) Seggio, A.; Lannou, M.-I.; Chevallier, F.; Nobuto, D.; Uchiyama, M.; Golhen, S.; Roisnel, T.; Mongin, F. *Chem.—Eur. J.* **2007**, *13*, 9982. (b) Seggio, A.; Chevallier, F.; Vaultier, M.; Mongin, F. *J. Org. Chem.* **2007**, *72*, 6602. (c) L'Helgoual'ch, J. M.; Bentabed-Ababsa, G.; Chevallier, F.; Yonehara, M.; Uchiyama, M.; Derdour, A.; Mongin, F. *Chem. Commun.* **2008**, 5375. (d) L'Helgoual'ch, J.-M.; Seggio, A.; Chevallier, F.; Yonehara, M.; Jeanneau, E.; Uchiyama, M.; Mongin, F. *J. Org. Chem.* **2008**, *73*, 177. (e) Snégaroff, K.; L'Helgoual'ch, J.-M.; Bentabed-Ababsa, G.; Nguyen, T. T.; Chevallier, F.; Yonehara, M.; Uchiyama, M.; Derdour, A.; Mongin, F. *Chem.—Eur. J.* **2009**, *15*, 10280. (f) Dayaker, G.; Chevallier, F.; Gros, P. C.; Mongin, F. *Tetrahedron* **2010**, *66*, 8904. The active heterometallic bases in these cases are formed via a salt metathesis route which produces LiCl as a by-product. Since the base is not isolated it cannot be completely ruled out that these systems operate as described for Type **A** bases.

(12) (a) Hevia, E.; Kennedy, A. R.; Klett, J.; McCall, M. D. *Chem. Commun.* **2009**, 3240. (b) Clegg, W.; Conway, B.; Hevia, E.; McCall, M. D.; Russo, L.; Mulvey, R. E. *J. Am. Chem. Soc.* **2009**, *131*, 2375.

(13) Clayden, J. *Organolithiums: Selectivity for Synthesis*; Pergamon, Elsevier Science Ltd.: Oxford, U.K., 2002.

(14) For NMR and crystallographic studies of LiTMP see: (a) Lappert, M. F.; Slade, M. J.; Singh, A.; Atwood, J. L.; Rogers, R. D.; Shakir, R. *J. Am. Chem. Soc.* **1983**, *105*, 302. (b) Renaud, P.; Fox, M. A. *J. Am. Chem. Soc.* **1988**, *110*, 5702. (c) Romesberg, F. E.; Collum, D. B. *J. Am. Chem. Soc.* **1992**, *114*, 2112. (d) Williard, P. G.; Liu, Q.-Y. *J. Am. Chem. Soc.* **1993**, *115*, 3380. (e) Lucht, B. L.; Collum, D. B. *J. Am. Chem. Soc.* **1994**, *116*, 7949. (f) Armstrong, D. R.; García-Álvarez, P.; Kennedy, A. R.; Mulvey, R. E.; Robertson, S. D. *Chem.—Eur. J.* **2011**, DOI: 10.1002/chem.201100523.

(15) Fleming, P.; O'Shea, D. F. *J. Am. Chem. Soc.* **2011**, *133*, 1698.

(16) LiCl has also been credited with accelerating the rate of reaction of lithium diisopropylamide and other organolithium reagents. For a leading reference to this homometallic chemistry see: Gupta, L.; Hoepker, A. C.; Singh, K. J.; Earnshaw, D. B. *J. Org. Chem.* **2009**, *74*, 2231 and references cited therein.

(17) (a) Gschwend, H. W.; Rodriguez, H. R. *Org. React.* **1979**, *26*, 1. (b) Snieckus, V. *Chem. Rev.* **1990**, *90*, 879. (c) Whisler, M. C.; MacNeil, S.; Snieckus, V.; Beak, P. *Angew. Chem., Int. Ed.* **2004**, *43*, 2206.

(18) Metzger, A.; Bernhardt, S.; Manolikakes, G.; Knochel, P. *Angew. Chem., Int. Ed.* **2010**, *49*, 4665.

(19) Dong, Z.; Clososki, G. C.; Wunderlich, S. H.; Unsinn, A.; Li, J.; Knochel, P. *Chem.—Eur. J.* **2009**, *15*, 457.

(20) (a) Krasovskiy, A.; Krasovskaya, V.; Knochel, P. *Angew. Chem., Int. Ed.* **2006**, 45. (b) Lin, W.; Baron, O.; Knochel, P. *Org. Lett.* **2006**, *8*, 5673. (c) Boudet, N.; Lachs, J. R.; Knochel, P. *Org. Lett.* **2007**, *9*, 5525. (d) Stoll, A. H.; Mayer, P.; Knochel, P. *Organometallics* **2007**, *26*, 6694. (e) Mosrin, M.; Knochel, P. *Org. Lett.* **2008**, *10*, 2497. (f) Mosrin, M.; Boudet, N.; Knochel, P. *Org. Biomol. Chem.* **2008**, *6*, 3237. (g) Mosrin, M.; Knochel, P. *Chem.—Eur. J.* **2009**, *15*, 1468. (h) Despotopoulou, C.; Klier, L.; Knochel, P. *Org. Lett.* **2009**, *11*, 3326.

(21) (a) Mosrin, M.; Knochel, P. *Org. Lett.* **2009**, *11*, 1837. (b) Mosrin, M.; Bresser, T.; Knochel, P. *Org. Lett.* **2009**, *11*, 3406. (c) Mosrin, M.; Monzon, G.; Bresser, T.; Knochel, P. *Chem. Commun.* **2009**, 5615. (d) Bresser, T.; Mosrin, M.; Monzon, G.; Knochel, P. *J. Org. Chem.* **2010**, *75*, 4686.

(22) (a) Clososki, G. C.; Rohbogner, C. J.; Knochel, P. *Angew. Chem., Int. Ed.* **2007**, *46*, 7681. (b) Rohbogner, C. J.; Clososki, G. C.; Knochel, P. *Angew. Chem., Int. Ed.* **2008**, *47*, 1503. (c) Rohbogner, C. J.; Wirth, S.; Knochel, P. *Org. Lett.* **2010**, *12*, 1984.

(23) (a) Wunderlich, S. H.; Knochel, P. *Angew. Chem., Int. Ed.* **2007**, *46*, 7685. (b) Wunderlich, S. H.; Knochel, P. *Org. Lett.* **2008**, *10*, 4705. (c) Wunderlich, S. H.; Knochel, P. *Chem. Commun.* **2008**, 6387.

(24) Wunderlich, S. H.; Kienle, M.; Knochel, P. *Angew. Chem., Int. Ed.* **2009**, *48*, 7256.

(25) Wunderlich, S. H.; Knochel, P. *Angew. Chem., Int. Ed.* **2009**, *48*, 1501.

(26) Wunderlich, S. H.; Knochel, P. *Angew. Chem., Int. Ed.* **2009**, *48*, 9717.

(27) Wunderlich, S. H.; Knochel, P. *Chem.—Eur. J.* **2010**, *16*, 3304.

(28) Jeganmohan, M.; Knochel, P. *Angew. Chem., Int. Ed.* **2010**, *49*, 8520.

(29) Jaric, M.; Haag, B. A.; Unsinn, A.; Karaghiosoff, K.; Knochel, P. *Angew. Chem., Int. Ed.* **2010**, *49*, 5451.

(30) Bresser, T.; Knochel, P. *Angew. Chem., Int. Ed.* **2011**, *50*, 1914.

(31) García-Álvarez, P.; Graham, D. V.; Hevia, E.; Kennedy, A. R.; Klett, J.; Mulvey, R. E.; O'Hara, C. T.; Weatherstone, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 8079.

(32) Armstrong, D. R.; García-Álvarez, P.; Kennedy, A. R.; Mulvey, R. E.; Parkinson, J. A. *Angew. Chem., Int. Ed.* **2010**, *49*, 3185.

(33) For leading reviews on DOSY NMR spectroscopy see: (a) Li, D.; Keresztes, I.; Hopson, R.; Williard, P. G. *Acc. Chem. Res.* **2009**, *42*, 270. (b) Macchioni, A.; Ciancaleoni, G.; Zuccaccia, C.; Zuccaccia, D. *Chem. Soc. Rev.* **2008**, *37*, 479. (c) Antalek, B. *Concepts Magn. Reson., Part A* **2007**, *30*, 219.

(34) Andrikopoulos, P. C.; Armstrong, D. R.; Graham, D. V.; Hevia, E.; Kennedy, A. R.; Mulvey, R. E.; O'Hara, C. T.; Talmard, C. *Angew. Chem., Int. Ed.* **2005**, *44*, 3459.

(35) Armstrong, D. R.; Clegg, W.; Dale, S. H.; Hevia, E.; Hogg, L. M.; Honeyman, G. W.; Mulvey, R. E. *Angew. Chem., Int. Ed.* **2006**, *45*, 3775.

(36) Clegg, W.; Henderson, K. W.; Kennedy, A. R.; Mulvey, R. E.; O'Hara, C. T.; Rowlings, R. B.; Tooke, D. M. *Angew. Chem., Int. Ed.* **2001**, *40*, 3902.

(37) Andrikopoulos, P. C.; Armstrong, D. R.; Clegg, W.; Gilfillan, C. J.; Hevia, E.; Kennedy, A. R.; Mulvey, R. E.; O'Hara, C. T.; Parkinson, J. A.; Tooke, D. M. *J. Am. Chem. Soc.* **2004**, *126*, 11612.

(38) (a) Kennedy, A. R.; Mulvey, R. E.; Raston, C. L.; Roberts, B. A.; Rowlings, R. B. *Chem. Commun.* **1999**, 353. (b) Andrews, P. C.; Kennedy, A. R.; Mulvey, R. E.; Raston, C. L.; Roberts, B. A.; Rowlings, R. B.

Angew. Chem., Int. Ed. **2000**, *39*, 1960. (c) Gallagher, D. J.; Henderson, K. W.; Kennedy, A. R.; O'Hara, C. T.; Mulvey, R. E.; Rowlings, R. B. *Chem. Commun.* **2002**, 376.

(39) Bomparola, R.; Davies, R. P.; Hornauer, S.; White, A. J. P. *Angew. Chem., Int. Ed.* **2008**, *47*, 5812.

(40) Kennedy, A. R.; Klett, J.; Mulvey, R. E.; Wright, D. S. *Science* **2009**, *326*, 706.

(41) Mulvey, R. E.; Blair, V. L.; Clegg, W.; Kennedy, A. R.; Klett, J.; Russo, L. *Nat. Chem.* **2010**, *2*, 588.

(42) Deprotonation of THF at the α-position usually results in decomposition [(a) Bates, R. B.; Kroposki, L. M.; Potter, D. E. *J. Org. Chem.* **1972**, *37*, 560] although the ring opened C_4O fragment can also be trapped in a cyclic [(b) Corrente, A. M.; Chivers, T. *Dalton Trans.* **2008**, 4840] or acyclic framework [(c) Geier, S. J.; Stephan, D. W. *J. Am. Chem. Soc.* **2009**, *131*, 3476]. ^{t}BuLi has cleaved THF and captured the resulting CH_2-CH_2 fragment resulting in the formation of a THF solvated Li-^{n}hexyl tetramer [(d) Kottke, T.; Lagow, R. J.; Hoffman, D.; Thomas, R. D. *Organometallics* **1997**, *16*, 789]. The enolate anion has been trapped by $[Li_3(N^tBu)^3S]^+$ in both a high and low temperature polymorph upon ^{t}BuLi induced cleavage of THF via an α-deprotonation followed by a $[\pi 4s + \pi 2s]$-cycloreversion [(e) Walfort, B.; Pandey, S. K.; Stalke, D. *Chem. Commun.* **2001**, 1640].

(43) (a) Westerhausen, M. *Dalton Trans.* **2006**, 4755. (b) Clark, N. M.; García-Álvarez, P.; Kennedy, A. R.; O'Hara, C. T.; Robertson, G. M. *Chem. Commun.* **2009**, 5835. (c) Vélez, E.; Alberola, A.; Polo, V. *J. Phys. Chem. A* **2009**, *113*, 14008. (d) Lu, X.-H.; Ma, M.-T.; Yao, Y.-M.; Zhang, Y.; Shen, Q. *Inorg. Chem. Commun.* **2010**, *13*, 1566. (e) Wu, J.; Pan, X.; Tang, N.; Lin, C.-C. *Inorg. Chem.* **2010**, *49*, 5362. (f) Cárdenas, C. V.; Hernández, M. A. M.; Grévy, J.-M. *Dalton Trans.* **2010**, *39*, 6441.

(44) Uchiyama, M.; Naka, H.; Matsumoto, Y.; Ohwada, T. *J. Am. Chem. Soc.* **2004**, *126*, 10526.

(45) Crosbie, E.; García-Álvarez, P.; Kennedy, A. R.; Klett, J.; Mulvey, R. E.; Robertson, S. D. *Angew. Chem., Int. Ed.* **2010**, *49*, 9388.

(46) Merkel, S.; Stern, D.; Henn, J.; Stalke, D. *Angew. Chem., Int. Ed.* **2009**, *48*, 6350.

(47) Greenwood, N. N.; Earnshaw, A. *Chemistry of the Elements*, 2nd ed.; Elsevier: Oxford, 1997.

(48) For a review on α-deprotonation of tertiary amines via a Lewis-acid complexation strategy see: Kessar, S. V.; Singh, P. *Chem. Rev.* **1997**, *97*, 721.

(49) García-Álvarez, J.; Graham, D. V.; Kennedy, A. R.; Mulvey, R. E.; Weatherstone, S. *Chem. Commun.* **2006**, 3208.

(50) Conway, B.; García-Álvarez, J.; Hevia, E.; Kennedy, A. R.; Mulvey, R. E.; Robertson, S. D. *Organometallics* **2009**, *28*, 6462.

(51) García-Álvarez, J.; Hevia, E.; Kennedy, A. R.; Klett, J.; Mulvey, R. E. *Chem. Commun.* **2007**, 2402.

(52) Conway, B.; Kennedy, A. R.; Mulvey, R. E.; Robertson, S. D.; García-Álvarez, J. *Angew. Chem., Int. Ed.* **2010**, *49*, 3182.

(53) A DFT calculation for the reaction of **4** with two molar equivalents of $^iPr_2NH$ to give **11** has a ΔE value of -23.88 kcal mol^{-1}.

(54) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. *Gaussian 03*, revision B.05; Gaussian, Inc.: Pittsburgh, PA, 2004.

(55) (a) Kohn, W.; Becke, A. D.; Parr, R. G. *J. Phys. Chem.* **1996**, *100*, 12974. (b) Becke, A. D. *Phys. Rev. A.* **1988**, *38*, 3098. (c) Lee, C. T.; Yang, W.; Parr, R. G. *Phys. Rev. B.* **1988**, 37, 785.

(56) (a) McLean, A. D.; Chandler, G. S. *J. Chem. Phys.* **1980**, 5639. (b) Krishnan, R.; Binkley, J. S.; Seeger, R.; Pople, J. A. *J. Chem. Phys.* **1980**, *72*, 650.

(57) Campbell, R.; Conway, B.; Fairweather, G. S.; García-Álvarez, P.; Kennedy, A. R.; Klett, J.; Mulvey, R. E.; O'Hara, C. T.; Robertson, G. M. *Dalton Trans.* **2010**, *39*, 511.

(58) Allen, F. H. *Acta Crystallogr.* **2002**, *B58*, 380.

(59) (a) Krossing, I.; Nöth, H.; Tacke, C.; Schmidt, M.; Schwenk, H. *Chem. Ber.* **1997**, *130*, 1047. (b) Krossing, I.; Nöth, H.; Schwenk-Kircher, H. *Eur. J. Inorg. Chem.* **1998**, 927.

(60) (a) Knabel, K.; Krossing, I.; Nöth, H.; Schwenk-Kircher, H.; Schmidt-Amelunxen, M.; Siefert, T. *Eur. J. Inorg. Chem.* **1998**, 1095. (b) Habereder, T.; Nöth, H.; Paine, R. T. *Eur. J. Inorg. Chem.* **2007**, 4298.

(61) Gemünd, B.; Günther, B.; Knizek, J.; Nöth, H. *Z. Naturforsch., B: Chem. Sci.* **2008**, *63*, 23.

(62) Knabel, K.; Nöth, H.; Seifert, T. *Z. Naturforsch., B: Chem. Sci.* **2002**, *57*, 830.

(63) Knabel, K.; Nöth, H. *Z. Naturforsch., B: Chem. Sci.* **2005**, *60*, 155.

(64) Klein, C.; Nöth, H.; Tacke, M.; Thomann, M. *Angew. Chem., Int. Ed.* **1993**, *32*, 886.

(65) Clegg, W.; Horsburgh, L.; Couper, S. A.; Mulvey, R. E. *Acta Crystallogr.* **1999**, *C55*, 867.