

Crystallographic Characterisation of Organolithium and Organomagnesium Intermediates in Reactions of Aldehydes and Ketones

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Dedicated to the Memory of *Jack D. Dunitz*, a fellow Glaswegian and brilliant scientist

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We report reactions of LiNacNac and NacNacMg(TMP) with common organic substrates (TMP = 2,2,6,6-tetramethylpiperidide). Using bulky β -diketiminate compound NacNac (Me, Dipp), we have trapped metalated intermediates amenable to X-ray crystallographic study. LiNacNac and acetone produced the NacNac-free hexameric diacetone alkoxide $[\{LiO(MeC(=O)CH_2C(Me)_2\}_6]$; whereas pinacolone gave the simple monomeric donor–acceptor complex $[Li\{(MeCN-2,6\text{-}i\text{-}Pr_2C_6H_3)_2CH\}\{O=C(Me)^tBu\}]$. Benzaldehyde produced dimeric $[Li\{(MeCN-2,6\text{-}i\text{-}Pr_2C_6H_3)_2CC(=O)Ph\}\{O=C(Ph)OCH_2Ph\}]_2$, where one benzaldehyde molecule has inserted in to the γ -carbon position of the NacNac ligand, with a molecule of benzyl benzoate derived from a *Tishchenko* reaction of the aldehyde acting as a terminal donor to lithium. Tetranuclear, mixed dimer $[\{LiO(MeCN-2,6\text{-}i\text{-}Pr_2C_6H_3)_2CH-CH(Ph)\}_2\{LiO(PhC(=O))\}]$ containing the same modified NacNac ligand was the fortuitous product from repeating the reaction of LiNacNac and benzaldehyde in a solution presumably contaminated with benzoic acid. Combining NacNacMg(TMP) with pinacolone affords monomeric heteroleptic $[Mg\{(MeCN-2,6\text{-}i\text{-}Pr_2C_6H_3)_2CH\}\{OC(^tBu)(Me)CH_2C(=O)^tBu\}]$ with an aldolate constituting the second anion. Completing the set is dimeric $[Mg\{(MeCN-2,6\text{-}i\text{-}Pr_2C_6H_3)_2CH\}\{O(C=CH_2)Ph\}]_2$, where the enolate derived from acetophenone bridges the magnesium centres.

Keywords: aldehydes, β -diketimimates, ketones, lithium, magnesium, metalation, structure elucidation.

Introduction

Organolithium (RLi) and organomagnesium (R_2Mg , $RMgX$) reagents play pivotal roles in shaping the modern chemical landscape, as throughout the past century they have performed one or more steps in a vast number of syntheses carried out in both academia and industry.^[1–10] Despite their many decades as established workhorses in both organic and inorganic fields, these organometallic reagents can still provide new structural and mechanistic insights into their

activities. *Wilhelm Schlenk* may have defined the *Schlenk* equilibrium as long ago as 1929, but efforts are still ongoing to fully understand this process and characterise the various intermediates in modern organomagnesium *Grignard* reagents.^[11–17] In more recent years, seminal research by *Knochel* has provided the community with a new class of reactivity enhanced reagents, so called *turbo-Grignard* reagents, expanding considerably the range of applications possible for these organomagnesium-based compounds.^[18,19] As beautifully highlighted by *Williard* in 1993, the range of intermediate structures which may be obtained from similarly long established organolithium reactions is significant, presenting a far more complex picture of organolithium reactions than is typically

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given in organic textbooks.^[20] Exciting steps forward have been trodden in the development of new mechanistic insights and enhanced stability of commonly used organometallic reagents by the *Capriati*, *Garcia-Alvarez* and *Hevia* groups, primarily in the deployment of such reagents in air, potentially revolutionising the safety and accessibility of such reactions.^[21–29] These ongoing developments clearly show that we have not yet had the final word on the mechanisms, structures and behaviours of organolithium and organomagnesium reagents, and that this field remains a thriving and heavily utilised area of research.

The recent widespread use of β -diketimines (commonly abbreviated as NacNacs or BDIs) within the realm of main group metal chemistry, as bulky and adaptable ligands, enables us to explore a wide range of reactivities and provides such a degree of stabilisation that they have become key to characterising previously unknown main group metal bonding as well as novel catalytic applications.^[30–39] Initially considered to be innocent ligands, an increasing number of examples of non-innocent behaviour by NacNac ligands have been reported, leading to unexpected, and often undesired, side reactivity of NacNac supported complexes.^[40–47] Whilst most non-innocent behaviour generally does not find any useful purpose, some studies have begun to deliberately characterise insertions at the γ -carbon position on the NacNac backbone.^[48–53] This is because in anionic NacNac the negative charge is delocalised over the NCCCN framework, so that the HOMO and HOMO-1 are located at the α -nitrogen and γ -carbon, respectively, which charges them with nucleophilic character. Such studies show that a range of small molecules can be used either to block off this position to prevent non-innocent behaviour, in particular through the work of the *Jones* group, or simply to generate novel new structures.^[54] Our group has previously presented a selection of examples of such γ -carbon-inserted NacNac species in recent publications.^[45,46]

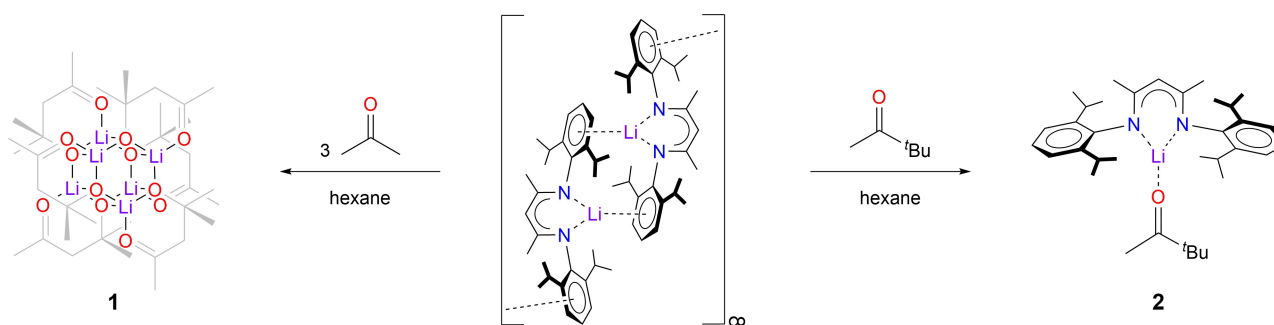
In addition to reporting γ -inserted NacNac species, we have recently presented some examples of model intermediate donor–acceptor complexes, involving lithium NacNac, which provided crystallographic confirmation for previously proposed intermediates from a range of reactions.^[46] Here, NacNac refers to the aminoimine, 2,6-diisopropylphenyl- β -methylidketimine (NacNacH (Me, Dipp), labelled for brevity throughout this text as NacNacH) when its N–H bond has been deprotonated. A simple procedure for the high yielding synthesis of this parent amine was developed

in 2001 by *Power* and co-workers, who also synthesised and characterised the deprotonated lithium salts, helping to popularise the use of NacNac ligands, to the extent that it is still the most widely used β -diketiminates today and the focus of this study.^[55] As NacNac is an anionic ligand, balancing lithium's monocationic charge, a key feature of lithium NacNac intermediates is detail of how any organic substrate engages with the cation-anion unit either through dative complex formation and/or mixed-ligand aggregation, features which are commonly found in organolithium chemistry.^[56–59] Magnesium NacNac complexes can provide even more bonding insight since another anion is required for charge balance due to the metal's divalent nature and often the second anion can be that of the substrate or substrate derivative under investigation. This feature of organometallic NacNac moieties presents an opportunity to characterise, by crystallographic and spectroscopic methods, species that could be viewed as model intermediates for reactions involving small molecules. Primarily due to its direct bearing to homogeneous catalysis, small molecule activation is an intensely studied subarea of organometallic chemistry, with emerging focus on using cheap, abundant, and environmentally benign resources (here, organometallic compounds of non-precious metals rather than precious metals) and eliminating waste, in alignment with United Nations (UN) Sustainable Development Goals.^[60] The fact that small molecule activation is expected to play a key role in the future of green energy, providing a way to store energy in chemical bonds, plays into this rise in research interest.^[61–71] If lithium and magnesium NacNac species can be used to trap the intermediates of small molecules, it may provide us with fresh insight, helping in elucidating the pathways of long-established organometallic reactions, or assisting in the understanding of some of the vast array of new small molecule transformations being developed. Towards that aim, a selection of such newly crystallographically characterised intermediates, isolated from solutions containing lithium NacNac or magnesium NacNac species, are reported herein.

Results and Discussion

Isolation and Crystallographic Characterisation of Organolithium Intermediates

In light of our group's previous success of inserting CO₂ and a range of isocyanates into the γ -carbon position on the backbone of lithium NacNac and



Scheme 1. Products **1** and **2** formed from the reaction of LiNaCNac with acetone and pinacolone, respectively.

isolating and characterising the resultant complexes, we decided to turn attention to simple ketone compounds as the small molecule substrate. Ketones with H-atoms in the α -position would typically be expected to be deprotonated in the presence of LiNaCNac leading to enolate derivatives and so an excess of ketone was used in an attempt to improve the opportunities of any alternative, γ -carbon centred, reactivity being observed on the NaCNac NCCCN framework. The results of these reactions of LiNaCNac and small ketone species are depicted in *Scheme 1*. Note that the primary objective of this work was to try and coax crystals of any intermediates from these reactions suitable for X-ray crystallographic determination rather than to refine the processes to give high yields of pure products.

The first ketone reacted with LiNaCNac was the smallest and simplest, namely acetone, $\text{Me}_2\text{C}=\text{O}$. An example of acetone insertion into the γ -C position of NaCNac has been reported before, as a feature of intermediates isolated from a study of Phospha-Wittig reactions using a TiNaCNac derivative.^[72] In our case, no nucleophilic attack by the γ -carbon took place, neither was the acetone simply converted to the lithium enolate of acetone $\text{Me}(\text{H}_2\text{C}=\text{O})\text{C}-\text{OLi}$, but due to the excess ketone instead formed the lithium derivative of diacetone alcohol (4-hydroxy-4-methyl-2-pentanone), complex **1**, $[\{\text{LiO}(\text{MeC}(\text{=O})\text{CH}_2\text{C}(\text{Me})_2)\}_6]$ (*Figure 1*).^[73–77] This reaction was carried out in a 1:3 stoichiometric ratio of LiNaCNac to acetone in hexane solution. It was found that the addition of PMDETA (*N,N,N',N'',N'''*-pentamethyldiethylenetriamine) donor solvent to this reaction is required to stimulate crystal growth when performed on scales smaller than 0.5 mmol. Examples of PMDETA aiding crystal formation have been previously observed by us though reasons for this aiding are still not clear.^[46] Surprisingly despite being known for decades, neither of these lithium enolate or aldolate structures have been

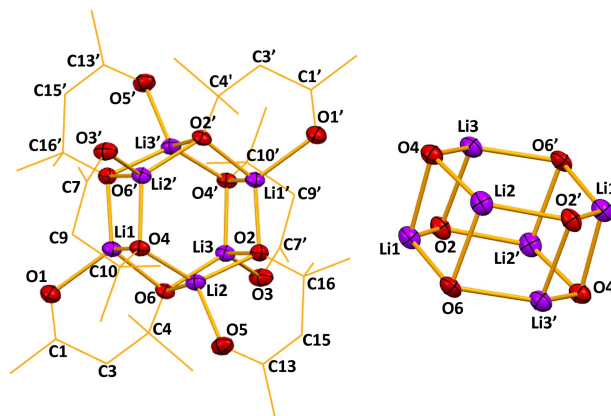


Figure 1. Left-hand side: Molecular structure of **1**, with H-atoms omitted and organic groups shown as wire frame for clarity; right-hand side: its double $(\text{LiO})_3$ stacked ring core. Thermal ellipsoids are displayed at 40% probability level, symmetry transformations used to generate equivalent atoms: $1-x$, $1-y$, $1-z$.

crystallographically characterised, despite the pioneering work of the Seebach group and others on structures of this type, so the crystal structure of **1** is unique.^[20,77,78] It forms a hexameric cage-like structure with an alternating lithium and oxygen motif. This structure could also be described as a double stack of $(\text{LiO})_3$ rings based on the ring-stacking and laddering principles in organolithium chemistry conceived by *Snaith*.^[79] In compound **1**, the anion acts in an unsymmetrical bidentate manner, with one bridging anionic oxygen (O2, O4, O6) in the cage and one terminal neutral oxygen (O1, O3, O5) acting as an external donor outside of the cage.

The hexameric structure of **1** has each 4-coordinate Li-atom occupying a *pseudo* tetrahedral geometry, with a four-coordinate geometry index in a range of $\tau_4 = 0.81-0.83$ over each of the three distinct Li-atoms (where 1 is a perfectly tetrahedral geometry and 0 is perfectly square planar).^[80] The nature of the double

C=O and single C–O bonds is confirmed in their mean lengths of 1.220 Å and 1.392 Å respectively. Structures resembling **1**, $[\{^t\text{BuC}(\text{=CH}_2)\text{OLi}\}_6]$, $[\{^t\text{BuC}(\text{=C})\text{OLi}\cdot\text{THF}\}_4]$ and $[\{(\text{CH}_3)_2\text{C}=\text{C}(\text{Ph})\text{OLi}\}_6]$, have been reported previously by groups studying the mechanisms of the aldol reaction, with some sharing the hexagonal prismatic arrangement of **1**, but no examples with a diacetone alkoxide unit as reported here.^[81–83] Many such enolate aggregate intermediates have been found to preferentially adopt smaller tetrameric structures in the presence of coordinating solvents, as shown by the representative examples in *Figure 2*.^[84,85] Unfortunately, we were unable to grow crystals of a THF-solvate of **1**.

Complex **1** will likely have formed from a straightforward aldol reaction, whereby an initial acetone unit was deprotonated by LiNaCNac, generating NaCNac(H) as a co-product, traces of which can be observed in the ¹H-NMR spectrum of product **1** (proposed pathway shown in *Scheme 2*). This step is followed by attack of the electrophilic C=O carbon atom of a second acetone molecule by a $\text{CH}_3\text{C}(\text{=O})\text{CH}_2^{\delta-}\text{Li}^{\delta+}$ intermediate. This intermediate may or may not have the neutral

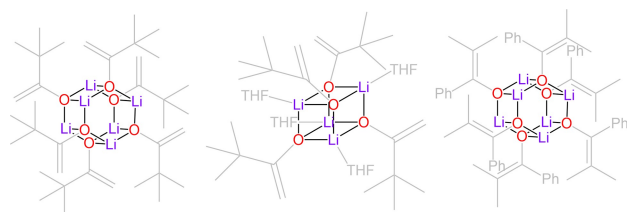
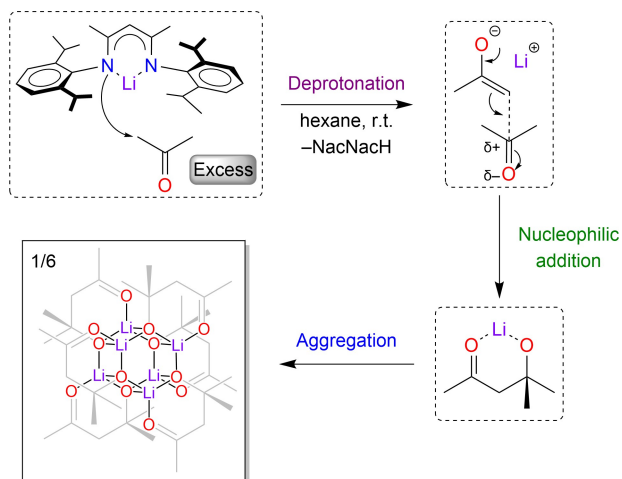


Figure 2. Representative literature hexameric and tetrameric (centre) lithium enolate structures $[\{^t\text{BuC}(\text{=CH}_2)\text{OLi}\}_6]$, $[\{^t\text{BuC}(\text{=C})\text{OLi}\cdot\text{THF}\}_4]$ and $[\{(\text{CH}_3)_2\text{C}=\text{C}(\text{Ph})\text{OLi}\}_6]$.



Scheme 2. Probable pathway for the formation of **1**.

NaCNacH ligand still bonded transiently to the lithium centre, but the formation of the aldolate **1** with its strong Li–O bonding implies that aggregation of six lithiated diacetone alcohol units is strongly favoured over any solvated variant with concomitant release of the bulky NaCNacH molecule.^[75]

Complex **1** represents the simplest ketone-ketone aldolate to be crystallographically characterised so far, certainly lending it novelty as a newly characterised intermediate in the formation of diacetone alcohol. However, there are other examples of lithium aldolate-type species that form complicated cage structures. Prior to their aforementioned seminal work on mapping the aldol reaction in terms of lithiated aggregates, the *Willard* group characterised the original lithiated aldolate structure in 1985, when reaction between the lithium enolate of pinacolone and trimethylacetaldehyde yielded tetrameric $[\{^t\text{BuC}(\text{=O})\text{CH}_2\text{CH}(\text{tBu})\text{OLi}\}_4]$ (*Figure 3*).^[86] The group followed this work with the first crystallographic characterisation of a dilithiated aldolate in 2011, $[\{^t\text{BuC}(\text{=O})\text{CH}_2\text{C}(\text{tBu})\text{MeOLi}\}\cdot\{^t\text{BuC}(\text{OLi})\text{CHC}(\text{tBu})\text{MeOLi}\}_3\cdot\{^t\text{BuC}(\text{=O})\text{Me}\}]$ (*Figure 3*), from the reaction of LDA and pinacolone that produced a complex cage structure.^[87] Containing six 4-membered $(\text{LiO})_2$ rings and devoid of a cube-shaped motif, this structure is different to that of the typical tetramers that enolates and aldolates are known to form which stems from the fact that a remarkable three distinct anions are incorporated within it.

There have been several examples of diacetone alcohol structures reported, observed in simpler, single metal centre monomers or dimers, where the parent diacetone alcohol species acts as a neutral donor solvent.^[88–92] Despite this, there appear to be no other crystallographic examples of such β -hydroxy ketone

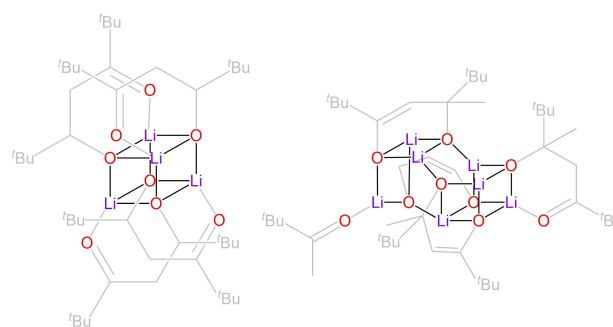


Figure 3. Known literature lithiated aldolates $[\{^t\text{BuC}(\text{=O})\text{CH}_2\text{CH}(\text{tBu})\text{OLi}\}_4]$ (left-hand side) and $[\{^t\text{BuC}(\text{=O})\text{CH}_2\text{C}(\text{tBu})\text{MeOLi}\}\cdot\{^t\text{BuC}(\text{OLi})\text{CHC}(\text{tBu})\text{MeOLi}\}_3\cdot\{^t\text{BuC}(\text{=O})\text{Me}\}]$ (right-hand side); for reasons of clarity, parts of the ligands have been omitted in this compound.

intermediates isolated from diacetone alcohol formation reactions. The key to the formation of **1** appears to be both the use of a bulky lithium source in LiNacNac, as well as the 1:3, LiNacNac/acetone stoichiometry used, since excess acetone appears essential to the isolation of this intermediate aggregate, with reproducible crystalline samples only being generated at this stoichiometry. When a significant deficit or a significantly greater excess of acetone is used, no crystals could be obtained from the solutions.

Following the result obtained from acetone, we turned our attention to the related enolisable ketone, pinacolone, ^tBuC(=O)Me. There was thought to be potential to either reproduce the known lithium pinacolone enolate hexamer [^tBuC(=CH₂)OLi]₆ (Figure 2), capture of an aldol condensation type intermediate analogous to **1** or forming a donor–acceptor type complex.^[46] Pleasingly, we had success in growing yellow crystals of [Li{(MeCN-2,6-ⁱPr₂C₆H₃)₂CH}{O=C(Me)^tBu}] (**2**; 63% yield), a presumed donor–acceptor intermediate in the formation of the lithium pinacolone enolate (Figure 4). This was produced from a 1:3, LiNacNac/pinacolone reaction stoichiometry, though other stoichiometries were attempted.

From the ORTEP diagram of **2** (Figure 4), the planarity of the NCCCN ring in **2** remains intact, with bond lengths around the backbone of the NacNac unit suggesting a degree of π bond delocalisation (Li1–N1, 1.893(13) Å; N1–C1, 1.306(8) Å; C1–C3, 1.408(9) Å;

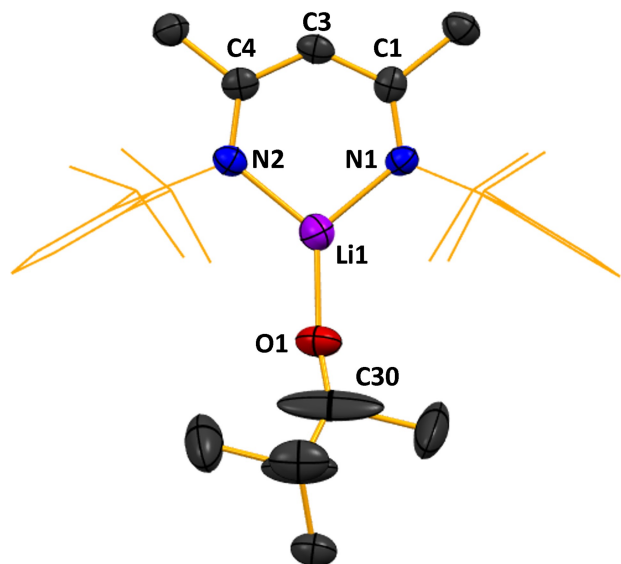


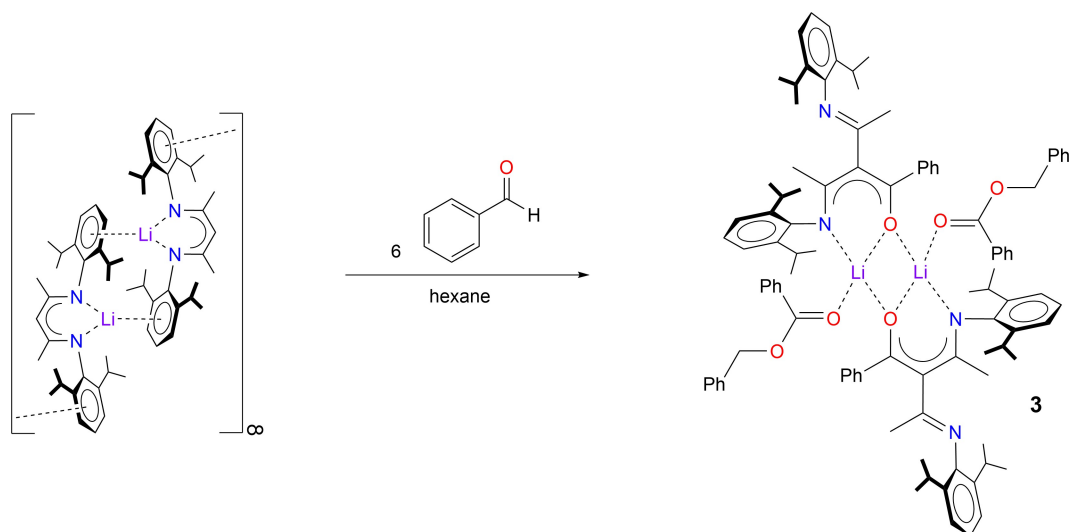
Figure 4. Molecular structure of **2**, H-atoms and second unit of **2** are omitted and the NacNac Dipp groups are shown as wire frame for clarity. Thermal ellipsoids are displayed at 40% probability level.

C3–C4, 1.417(10) Å; Li1–N2, 1.906(13) Å). The lithium atom sits in an approximately trigonal planar environment, with bond angles ranging from 100.60(6)° (bite angle: N1–Li1–N2) to 130.30(7)° (O1–Li1–N2) with the Li atom equidistant between the nitrogen atoms. ¹H- and ¹³C-NMR spectroscopic data on **2** showed agreement between the assignments of the observed resonances and the composition of the determined crystal structure. This is supported by the ⁷Li-NMR spectrum, which shows a significant change in the lithium environment, a shift of 2.37 ppm, from the starting material.

The first crystallographically verified example of bonding between R₂C=O and Li involving the extensively studied NacNac (Me, Dipp) scaffold was published by our group in 2021, in the benzophenone complex [Li{(MeCN-2,6-ⁱPr₂C₆H₃)₂CH}{O=C(Ph)₂}]}. Prior to this, there were no previous examples of an aldehyde/ketone C=O unit coordinating to either Li, Na or K within the NacNac (Me, Dipp) scaffold in this way.^[46] Such intermediates have previously been implicated in catalytic hydroboration of aldehydes and ketones using pinacolborane by *Sen* in 2018 on the basis of DFT studies.^[93] In an earlier paper, *Mair* predicted an analogous intermediate containing the R₂C=O→LiNacNac unit from NMR evidence in a study of reversible C–C bond formation in an aldol-like reaction.^[94] Complex **2** provides further evidence that such structures can be generated and isolated in the solid state, in addition to being observed by NMR spectroscopy in the solution state.

Next, our study was extended to the simplest aryl aldehyde, benzaldehyde. The reaction of LiNacNac with a three-fold excess of benzaldehyde in hexane solution led to the formation and subsequent isolation of colourless crystalline [Li{(MeCN-2,6-ⁱPr₂C₆H₃)₂CC(=O)Ph}{O=C=O>C(Ph)OCH₂Ph}]₂ (**3**; Scheme 3, Figure 5).

An X-ray crystallographic study determined the centrosymmetric structure of **3** (Figure 5). Its crystallographically equivalent lithium atoms have a *pseudo*-tetrahedral geometry ($\tau_4=0.87$) comprising three O-atoms (one from each of the two NacNac inserted groups and one from the benzoate ligand) and one N-atom from the NacNac unit. Dimerization results in a planar four-membered (Li–O)₂ ring, a motif common in organolithium chemistry.^[6,79,95–98] Here, dimerization gives rise to a fused, tricyclic 6–4–6 ring system. The backbone of the NacNac-derived NCCCO unit remains highly delocalised, as evidenced by the lack of a H-atom at the γ -C position and the bond lengths observed, (N1–C1, 1.295(3) Å; C1–C3, 1.473(3) Å;



Scheme 3. Product **3** formed from the reaction of LiNaCNac and benzaldehyde.

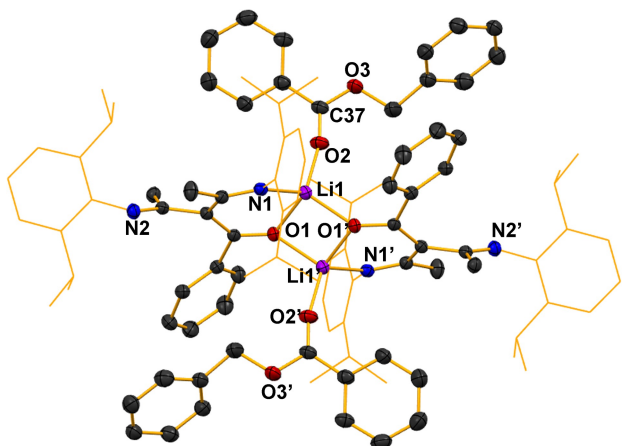


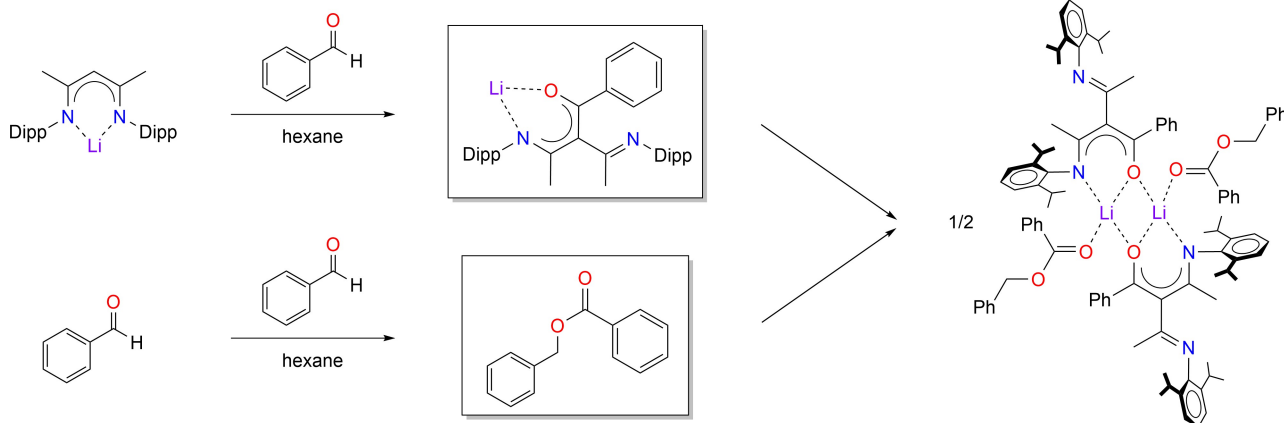
Figure 5. Molecular structure of **3**, H-atoms are omitted, and the organic groups are shown as wire frame for clarity. Thermal ellipsoids are displayed at 40% probability level, symmetry transformations used to generate equivalent atoms: 1–*x*, 1–*y*, 1–*z*.

C3–C6, 1.407(3) Å; C6–O1, 1.278(2) Å). By comparison, the benzyl benzoate unit shows more localised bonding, (O2–C37, 1.212(3) Å; C37–O3, 1.336(3) Å) as shown in Figure 5. The presence of independent resonances for each Dipp and Me group of the Nacnac unit in the ¹H-NMR spectrum also clearly indicate an inequivalence in these environments, as displayed within the crystal structure of **3**.

It is proposed that compound **3** is the product of two distinct reactions (see Scheme 4). One is the insertion of a single unit of benzaldehyde into the γ -carbon position of the Nacnac ligand, analogous to the insertion of other small unsaturated molecules at

this position seen previously by the *Mulvey* group and other groups involving, for example, alkenes, alkynes, isocyanates, isothiocyanates, carbodiimides, CO₂ or diphenylketene.^[4–54] The second is the initiation of a *Tishchenko* reaction, which describes the dimerization of aldehydes to the corresponding carboxylic ester, in this case two units of benzaldehyde converting to benzyl benzoate. In compound **3**, the neutral benzyl benzoate ligand acts as a *Lewis* base in coordinating to the lithium centre through its carbonyl O-atom (Figure 5). Note that compound **3** can be made reproducibly as the sole crystalline product, where the unit cell matches that of **3**, when the rational 1:3 stoichiometry is applied.

Known for about 130 years, the *Tishchenko* reaction has been viewed as a promising candidate for a universal, atom efficient method of preparing esters, though it has long been plagued with selectivity issues when combining two distinct aldehyde species, with four possible products from each two-aldehyde combination.^[99–101] Catalysis of this reaction by *Lewis* acids and transition metals has been well documented, and recently its scope has been expanded to include several *s*-block metal catalysts, which show that this method of ester formation can also be carried out by simple alkali metal *tert*-butoxides, hydrides or amides.^[102–104] Relevant to the research reported herein is that among these new main group *Tishchenko* catalysts is work by *Hill* showing alkaline earth metal pre-catalysts bearing Nacnac ligands.^[105] To the best of our knowledge, there is currently no literature proposing the use of alkali metal Nacnac catalysts for



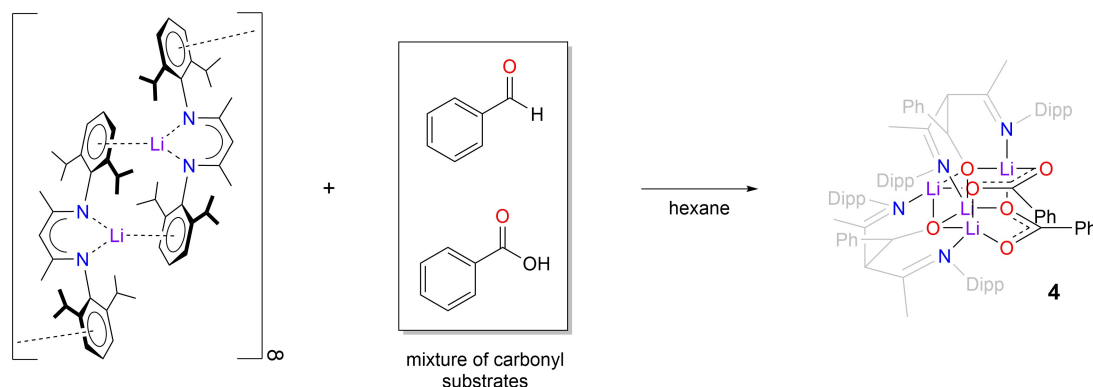
Scheme 4. Proposed reactions leading to the formation of **3**. Top: Insertion of benzaldehyde unit into the γ -C position of LiNaCNac. Bottom: *Tishchenko* reaction catalysed by benzaldehyde inserted LiNaCNac.

the *Tishchenko* reaction. Despite this fact, compound **3** may provide a caution that such catalysts would likely be highly susceptible to nucleophilic attack at the γ -position by the unsaturated aldehyde molecule. While there is discussion of the formation of an alkaline earth metal alkoxide as the active species for *Hill's* MNaCNac $\{N(SiMe_3)_2\}(THF)_2$ catalysts (where $M = Ca, Sr$ or Ba), in line with other proposed *Tishchenko* reaction mechanisms, they do not report crystallisation or observation by NMR spectroscopy of any γ -carbon inserted intermediates analogous to **3**.^[104–106] Thus, it could be speculated that in such reactions where alkali metal NaCNac catalysts are used, the active catalyst could potentially be a metal alkoxide of the *inserted* NaCNac species, such as the unit observed in **3**.

Following the characterisation of **3**, the reaction of LiNaCNac with benzaldehyde displayed further complexity when a further repeat attempt at a 1:3 stoichiometry was undertaken. Determined by X-ray

crystallography, the isolated product of this reaction was the tetranuclear, mixed dimer $\{[LiO(MeCN-2,6-Pr_2C_6H_3)_2CH-CH(Ph)]_2[LiO(PhC(=O))]_2\}$ (**4**; *Scheme 5*, *Figure 6*). We assume that the dimeric lithium benzoate unit $\{LiO(PhC(=O))\}_2$ in **4** comes from the presence of benzoic acid in the contaminated solution as benzaldehyde is known to oxidise slowly in air.^[100,101] The other dimeric fragment in **4** incorporates both units of LiNaCNac where benzaldehyde has been inserted at the γ -C position. These benzoates and inserted NaCNac units co-complex, the former through the Li–O edges of its 8-membered $(LiOCO)_2$ ring and the latter through its 4-membered $(LiO)_2$ ring.

As seen in *Figure 6*, there is an open cube fragment containing four lithium centres and six oxygen centres, with an average Li–O bond length of 1.922 Å. As shown by the structure from the *Henderson* and *Williard* groups in *Figure 3*, distorted cubic arrangements such as that of **4** are not unheard of in lithium



Scheme 5. Alternative product **4**, formed from the reaction of LiNaCNac and benzaldehyde.

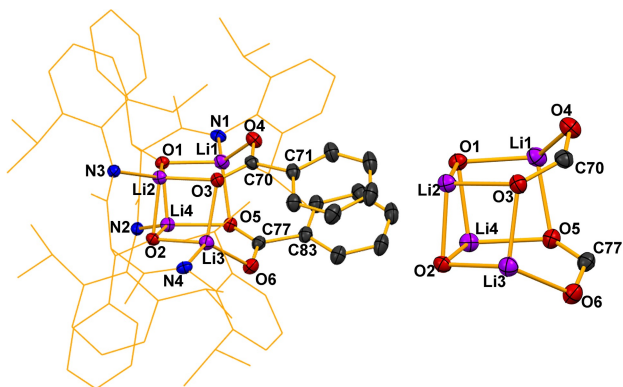


Figure 6. Left-hand side: Molecular structure of **4**, H-atoms and solvent molecules are omitted, and the organic groups are shown as wire frame for clarity. Right-hand side: Open cube-shaped core. Thermal ellipsoids are displayed at 40% probability level.

chemistry, though they appear to be less common than cubic and hexameric arrangements.^[59,84,87,98,107,108] There are also relatively few crystallographically characterised examples of structures containing simple lithium benzoate units, such as seen in **4**, currently on the CCDC.^[109,110] Attempts to reproduce **4** rationally through deliberate introduction of benzaldehyde and benzoic acid mixtures is ongoing.

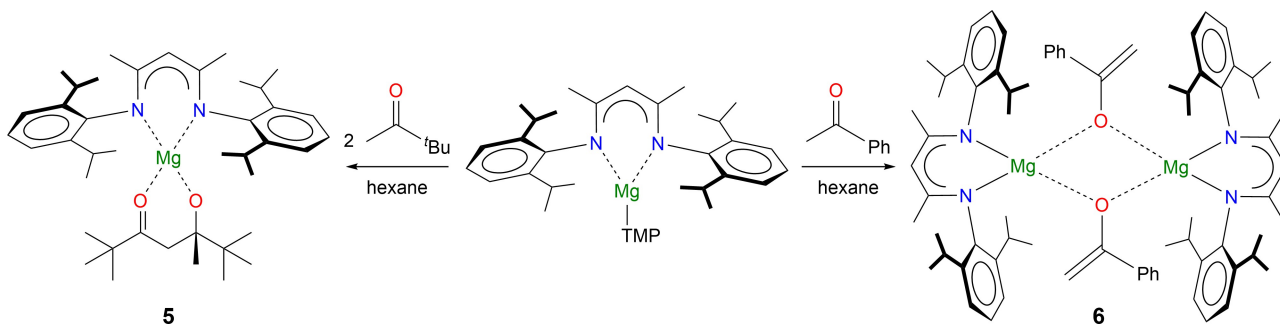
Isolation and Crystallographic Characterisation of Organomagnesium Intermediates

In previous publications by the *Mulvey, Ma* and *Hill* groups, a range of heteroleptic NaCNacMg(R) species have shown interesting dual insertion patterns when reacted with unsaturated small molecules, where R = TMP^[46], ⁿBu^[50] or SiMe₂Ph.^[52] In light of this previous work, we have reacted the heteroleptic magnesium species NaCNacMg(TMP), first synthesised by the *Hevia*

group, with a range of small aldehydes and ketones.^[111] Of these reactions, only those with the ketones pinacolone and acetophenone gave products that we could crystallise and isolate from solution, the primary objective of our study (*Scheme 6*).

Upon reaction of NaCNacMg(TMP) and pinacolone in hexane, an aldol-type reaction pathway was initiated in a manner akin to that proposed for **1** (*Figure 1*). However, the resultant product, [Mg{(MeCN-2,6-ⁱPr₂C₆H₃)₂CH}{OC(^tBu)(Me)CH₂C(=O)^tBu}] (**5**; 41% yield; *Figure 7*), formed neither an aggregate as in the case of **1**, nor a simple donor–acceptor complex as in the case of **2**, instead, the β-diketiminato ligand remained chelated to the magnesium centre in a monomeric arrangement. The other anionic ligand present is an aldolate, arising from a deprotonated pinacolone molecule attacking a second pinacolone molecule through addition to its electropositive carbonyl carbon atom to generate a magnesiated β-hydroxy ketone.

Product **5** can be considered as forming through a similar pathway to product **1** (*Scheme 2*) regarding its alkoxy-ketone unit, in this instance TMP(H) is eliminated as a by-product instead of NaCNac(H) which can be rationalised by the relative pK_a values, with TMP[−] being a stronger *Brønsted* base than the NaCNac[−] anion. The four-coordinate metal centre in **5** sits in a *pseudo*-tetrahedral geometry, with a four-coordinate geometry index of τ₄ = 0.82 (similar to that of **1**).^[80] Bonding in the magnesium aldolate is highly localised as evidenced by the significantly different O–C bond lengths (O1–C37, 1.226(2) Å and O2–C35, 1.374(3) Å), representing the C–O[−] and C=O bonds, respectively. Bonding across the NaCNac backbone remains delocalised, mimicking that observed in its parent compound NaCNacMg(TMP), (N1–C2, 1.331(2) Å and N2–C4, 1.320(2) Å). This intermediate in the conversion of pinacolone to a beta-hydroxy ketone has been shown



Scheme 6. Products obtained from the reaction of NaCNacMg(TMP) with pinacolone **5** and acetophenone **6**.

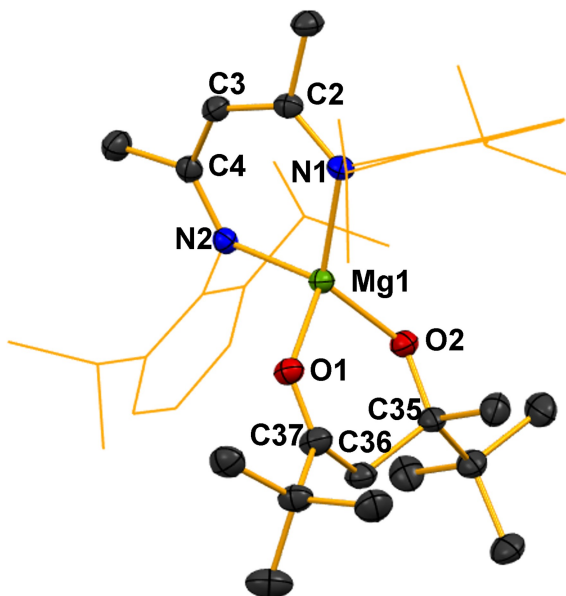


Figure 7. Molecular structure of **5**, H-atoms and disordered components are omitted and the NacNac Dipp groups are shown as wire frame for clarity. Thermal ellipsoids are displayed at 40% probability level.

to be highly reproducible across a range of pinacolone stoichiometries (0.5 to three equivalents).

A related titanium structure to that of **5**, $[\text{Ti}(\text{Cl})\{\text{(MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{OC}^i\text{Pr}\}(\text{CH}_3)\text{CH}_2\text{C}(\text{O})^i\text{Pr}]$, was reported in 2019, in which the titanium(III) centre carries an additional chloride anion. This product was unintended as it was a side-product from a study of Phospha-Wittig intermediates, which also reported that the analogous acetone product, $[\text{Ti}(\text{Cl})\{\text{(MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{OC}(\text{Me}_2)\text{CH}_2(\text{C}=\text{O})\text{Me}\}]$ had been observed by elemental analysis, though it could not be confirmed crystallographically.^[72] In 1999, Henderson characterised the first amidomagnesium aldolate intermediate in $[\{(\text{Me}_3\text{Si})_2\text{NMg}[\mu\text{-OC}(\text{Me})^t\text{BuCH}_2\text{C}(\text{Bu}=\text{O})]\}_2]$ (Figure 8), to which compounds **1** and **5** bear some structural resemblances. This magnesium structure

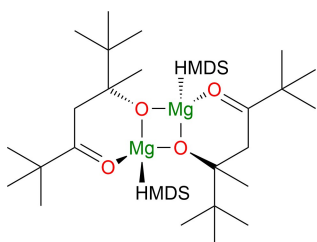


Figure 8. Structure of $[\{(\text{Me}_3\text{Si})_2\text{NMg}[\mu\text{-OC}(\text{Me})^t\text{BuCH}_2\text{C}(\text{Bu}=\text{O})]\}_2]$ synthesised by Henderson *et al.* in 1999.

exists as a dimer in the crystal due to the presence of the monodentate HMDS ligand which is less sterically bulky than NacNac. Therefore, heteroleptic **5** could be seen as a dual bidentate-ligated alternative to this intermediate, further opening up the potential for exploration of s-block metal β -diketiminates as mediators in aldol reactions.^[112]

Following on from the interesting structure provided by **5**, the only other ketone in our substrate scope found to produce an isolable product upon reaction with NacNacMg(TMP) was acetophenone, where an electron-withdrawing phenyl group has replaced the electron-donating ^tBu group present in pinacolone. This reaction was carried out in hexane at a 1:1 stoichiometry and afforded transparent, colourless crystals of $[\text{Mg}\{\text{(MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{O}(\text{C}=\text{CH}_2)\text{Ph}\}_2]$ (**6**), which X-ray crystallography revealed to be a heteroleptic centrosymmetric dimer with a planar $(\text{MgO})_2$ core (Figure 9). The symmetry equivalent magnesium centres sit in a distorted tetrahedral geometry, with a four-coordinate geometry index of $\tau_4 = 0.77$. Bonding in the phenylethenolate units is highly localised; while the bonding in the NacNac backbone remains delocalised as anticipated with N–C and C–C existing as intermediate between single and double bonds. The bond length of C30–C31 in the enolate moiety confirms the presence of a double bond (1.326(19) Å), supported by the trigonal planar

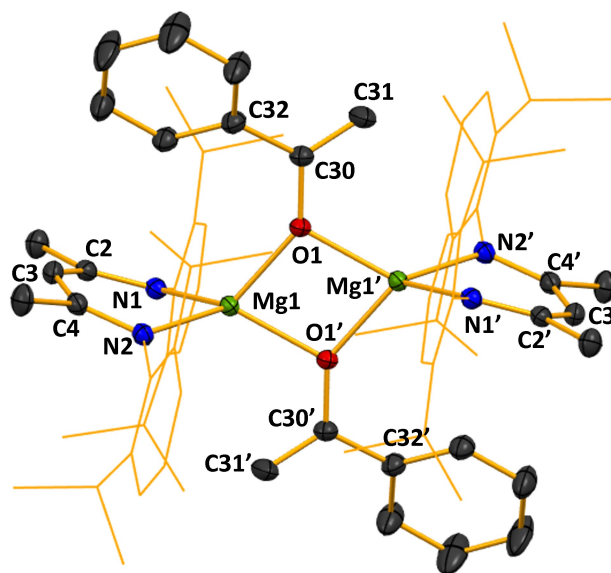


Figure 9. Molecular structure of **6**, H-atoms are omitted and the NacNac Dipp groups are shown as wire frame for clarity. Thermal ellipsoids are displayed at 40% probability level, symmetry transformations used to generate equivalent atoms: 1–x, 1–y, 1–z.

geometry of C30 (mean bond angle, 120.0°), with the C30–O1 length of 1.360(14) Å confirming its single bond status.

Searching the literature revealed that a close relative of structure **6** was implicated on the basis of ¹H-NMR spectroscopic studies by the Hill group in 2012 as an intermediate in the magnesium-catalysed hydroboration of aldehydes and ketones using pinacolborane. They propose their heteroleptic NaCNacMg(OCHPh₂) intermediate as the product of the insertion of benzophenone into the magnesium hydride bond of their dimeric magnesium hydride starting material (Figure 10). While they were unable to crystallographically verify this particular proposed intermediate, they were able to isolate and crystallographically characterise the next species in their proposed catalytic cycle, a bis(diphenylmethoxy)borato magnesium complex, lending further credence to their proposed diphenylmethoxy intermediate from the previous step.^[113]

In 2015, Hill also proposed the structure shown in Figure 10 when investigating the reactivity of magnesium dihydropyridines with organoisoocyanates.^[114] While not crystallographically confirmed by the Hill group, several closely related structures have been confirmed over the years, with ketone units bridging across NaCNacMg dimers, most notably by the Jones and Gibson groups.^[115,116] In light of the structure of **6**, we see that the ketone has undergone a deprotonation step and thus can be interpreted as a potential model intermediate of an early stage aldol type condensation reaction. The work of the Hill group suggests that **6** could also be viewed as a likely intermediate in the reduction of aldehydes and ketones prior to hydroboration using new magnesium NaCNac catalysts. From the dimeric structure of heteroleptic **6**, it would be anticipated that the presence of an ethereal solvent would breakdown the

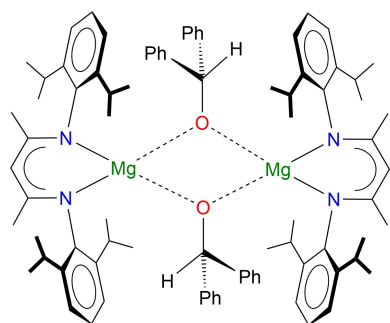
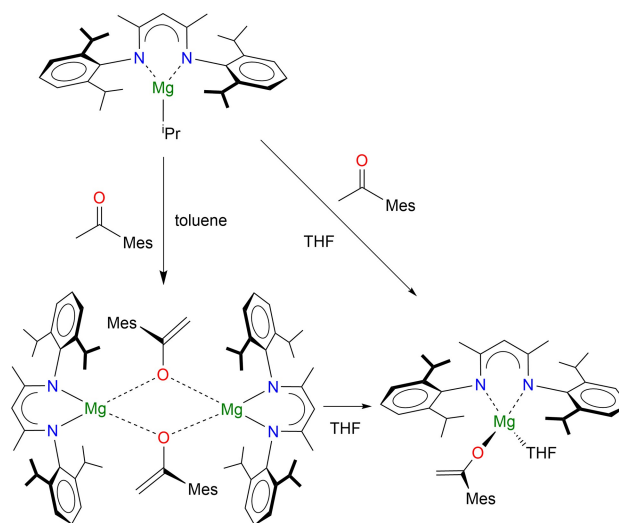


Figure 10. Structure of the NaCNacMg[{O=CH(Ph)₂}] intermediate proposed by Hill.

dimeric species into solvated monomeric units. This was confirmed when (ⁿBu)₂Mg in a hexane solution containing THF was used to prepare the NaCNacMg(TMP) starting material. The THF solvated monomer, [Mg{(MeCN-2,6-ⁱPr₂C₆H₃)₂CH}{O(C=CH₂)Ph}·THF] (**7**; 30% yield), was produced as a small batch of rapidly forming, colourless crystals. Monomer **7** was found to be reproducible when THF was added to hexane solutions of compound **6**. Though the crystallographic data for **7** was of insufficient quality for publication, clean NMR spectra was obtained to support its formation (see Supporting Information).

This deaggregation to a monomer by the addition of THF is comparable to the 2002 system published by Gibson (Scheme 7), whose use of NaCNacMg(ⁱPr) starting material to produce analogous structures to species **6** and **7** of this work, suggesting that species **6** and **7** would likely also be formed using this alternative precursor. It was subsequently found that compounds analogous to **5**, **6** and **7** could be generated when the R group of the magnesium starting material was varied, with the reactions of the starting materials NaCNacMg(ⁿBu) and NaCNacMg(ⁱPr) with pinacolone and acetophenone each generating crystals whose unit cell matched those of **5** and **6**, respectively. Interestingly, while compounds **6** and **7** have been generated in this work mainly for structural analysis, the Hill group considered the dimeric analogue of **6** as their species of interest as an intermediate in catalysed hydroboration reactions, while the Gibson group synthesised the monomeric magnesium enolate analogue of **7** as an initiator for



Scheme 7. Formation of dimeric and monomeric magnesium enolates of 1-mesitylethanone by Gibson *et al.*

highly syndioselective polymerisation of methylmethacrylate (*s*-poly(MMA)), a process which they later patented.^[116]

Conclusions

The philosophy behind this study was to show that the bulky β -diketiminato NacNac (Me, Dipp) ligand could be used to trap, stabilise and lead to the crystallographic characterisation of novel intermediates in common organic reactions mediated either by organolithium or organomagnesium reagents. For lithium, pinacolone gave a predictable intermediate in the donor-acceptor complex $[\text{Li}\{\text{MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{O}=\text{C}(\text{Me})^t\text{Bu}\}]$, while acetone gave the hexameric diacetone alkoxide $[\{\text{LiO}(\text{MeC}(=\text{O})\text{CH}_2\text{C}(\text{Me})_2)\}_6]$ in which NacNac does not appear, driven by the thermodynamic stability of Li–O aggregate formation. Benzaldehyde gave a more complicated outcome where NacNac reveals its non-innocence with a benzaldehyde molecule inserting into its γ -carbon site in $[\text{Li}\{\text{MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CC}(=\text{O})\text{Ph}\}\{\text{O}=\text{C}(\text{Ph})\text{OCH}_2\text{Ph}\}]_2$ with benzyl benzoate formed from a *Tishchenko* aldehyde reaction acting as a *Lewis* donor to lithium. The same benzaldehyde reaction afforded tetranuclear, heteroleptic $[\{\text{LiO}(\text{MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}-\text{CH}(\text{Ph})\}_2\{\text{LiO}(\text{PhC}(=\text{O}))_2\}]$ presumably due to benzoic acid contamination. For reactions with the magnesium reagent NacNacMg(TMP), the NacNac ligand remains intact on the divalent metal centre. Pinacolone gave monomeric heteroleptic $[\text{Mg}\{\text{MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{OC}(^t\text{Bu})(\text{Me})\text{CH}_2\text{C}(=\text{O})^t\text{Bu}\}]$ containing an aldolate anion, while with acetophenone an enolate bridges the two Mg centres in dimeric $[\text{Mg}\{\text{MeCN-2,6-}^i\text{Pr}_2\text{C}_6\text{H}_3)_2\text{CH}\}\{\text{O}(\text{C}=\text{CH}_2)\text{Ph}\}]_2$. Information of this type could help shed light on mechanisms in other stoichiometric and catalytic reactions, especially in cases of low yield/efficiency where the structure of the NacNac ligand has been compromised. Such structural elucidation could be of increasing importance since *s*-block organometallic compounds are now being widely studied in homogeneous catalysis as can be evidenced by a recent book on the subject.^[117]

Experimental Section

Synthetic protocols and characterization of the new compounds are reported in the electronic supporting information. CCDC deposition numbers 2182653 to

2182658, contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint *Cambridge Crystallographic Data Centre* and *Fachinformationszentrum Karlsruhe Access Structures* service www.ccdc.cam.ac.uk/structures. A dataset underlying this research can be located at [10.15129/a79e0465-457a-40cd-81f6-fd2b90df2a3d](https://doi.org/10.15129/a79e0465-457a-40cd-81f6-fd2b90df2a3d).

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Data Availability Statement

The data that support the findings of this study are openly available in PURE at <https://doi.org/10.15129/80fafec7-7a78-46c3-8bf6-1660d835f21c>, reference number 137601244.

Author Contribution Statement

J. R. L. carried out the experiments and synthesis and characterisations of all materials. *A. R. K.* and *J. R. L.* performed the X-ray diffraction studies. *R. E. M.* supervised the work, while *R. E. M.* and *J. R. L.* produced the manuscript. *J. B.* and *J. R.* were involved in project conception and manuscript review.

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