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Alkali-Metal-Mediated Magnesiations of an N-Heterocyclic Carbene: Normal, Abnormal, and "Paranormal" Reactivity in a Single Tritopic Molecule

Antonio J. Martínez-Martínez, M. Ángeles Fuentes, Alberto Hernán-Gómez, Eva Hevia, Alan R. Kennedy, Robert E. Mulvey, and Charles T. O'Hara*

Abstract: *Herein the sodium alkylmagnesium amide [$Na_4Mg_2(TMP)_6(nBu)_2$] (TMP = 2,2,6,6-tetramethylpiperidide), a template base as its deprotonating action is dictated primarily by its 12 atom ring structure, is studied with the common N-heterocyclic carbene (NHC) IPr [1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene]. Remarkably, magnesiation of IPr occurs at the para-position of an aryl substituent, sodiation occurs at the abnormal C4 position, and a dative bond occurs between normal C2 and sodium, all within a 20 atom ring structure accommodating two IPr^{2-}. Studies with different K/Mg and Na/Mg bimetallic bases led to two other magnesiated NHC structures containing two or three IPr^{-} monoanions bound to Mg through abnormal C4 sites. Synergistic in that magnesiation can only work through alkali-metal mediation, these reactions add magnesium to the small cartel of metals capable of directly metalating a NHC.*

Chemists often find fascination in synergistic systems, especially if the cooperativity can be usefully exploited in a practical application. Such effects are prominent in synthetic organometallic chemistry where two metals are involved.[1] For example, elegant studies by Xi[2] show that close proximity of two Li centers in 1,4-dilithio-1,3-butadienes can promote intra- and intermolecular reactions beyond the scope of monolithio systems. As a core tool in synthesis, metalation has advanced greatly in recent times through cooperative effects delivered, not by dimetallo dianions, but by combinations of different metal monoanion components.[3] Knochel's salt boosted organometallic reagents,[4] typified by TMPMgCl·LiCl (TMP = 2,2,6,6-tetramethylpiperidide), the use of which has recently been extended to continuous flow reactors,[5] are exemplars of these multicomponent metalators. LiTMP lithiations can also be rendered synergistic by premixing the aromatic substrate with a salt (e.g., $MgCl_2$) so that sensitive lithiated substrates can be transmetalated rapidly (in situ trapping) to a more stable, more synthetically pliable form.[6] Trans-metal-trapping with [$iBu_2Al(TMP)$] not only stabilizes LiTMP lithiated substrates but can shift equilibrium reactions towards the wanted product.[7] Of special relevance in this work are pre-inverse-crowns,[8] which are two-metal macrocyclic complexes whose deprotonating action is governed more by their template structures than by the substituents on the aromatic substrates. Thus the pre-inverse-crown [$Na_4Mg_2(TMP)_6(nBu)_2$] can doubly deprotonate N,N-dialkylanilines and *tert*-butylbenzene selectively at the *meta*,*meta*' positions,[9] and is in violation of directed *ortho*-metalation (D*o*M) principles.[10] Here, in reporting the first metalation study between pre-inverse-crowns and N-heterocyclic carbenes (NHCs), we describe the first directly magnesiated NHCs at positions both expected and wholly unexpected.

NHC metalation (C–H to C–metal exchange) is a relatively recent development within the fast-growing NHC literature.[11] Robinson and co-workers made a seminal breakthrough in 2010 by deprotonating IPr [1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene] at C4 (alkenic backbone) with *n*BuLi[12] to open up an abnormal construction point for functionalization. Waters and Goicoechea subsequently synthesized the potassium congener of this lithium carbanionic NHC by metathesis with *t*BuOK to use in ligand-transfer applications.[13] Bertrand and co-workers achieved C4-functionalization by a different approach, that is, by making imidazolium IPr cations with the C2-position blocked by E substituents [E = e.g., PhC(O), PPh_2], which intramolecularly rearrange to a C4–E species upon deprotonation by KHMDS.[14] Both indirect (by Robinson's lithiated NHC and Et_2Zn)[15] and direct (by Hevia's sodium TMP-zincate reagent)[16] methods of zincating IPr at C4 have also been reported. An unusual amido-directed lateral lithiation of a $CH(Me)_2$ wingtip on a Dipp (diisopropylphenyl) group in a 4-amido NHC has recently been described by Braunstein and co-workers.[17]

In this work, IPr was directly magnesiated by the pre-inverse-crown [$\{KMg(TMP)_2(nBu)\}_6$] (**1**) in methylcyclohexane/THF to afford the bis(carbene) magnesiate [$\{KMg(IPr^-)_2(nBu)(THF)\}_\infty$] (**2**; Scheme 1, where IPr^- is [$:C\{[N(2,6\text{-}iPr_2C_6H_3)]_2CHC^-\}$]). Interestingly this reaction is not a template metalation. When **1** acts as a template base, for example towards naphthalene, its six *n*Bu ligands are substituted by six 2-naphthalenide anions (*n*-butane is expelled) with retention of its 24-atom $(KNMgN)_6$ ring architecture.[8] In contrast, in making **2**, **1** acts formally as an amido dibase while retaining an *n*Bu group. The dibasicity of **1** can be inferred but the moderate yield of **2** (absolute 20%; with respect to IPr, 40%) and the failure to increase the yield on

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[*] Dr. A. J. Martínez-Martínez, Dr. M. Á. Fuentes, Dr. A. Hernán-Gómez, Prof. E. Hevia, Dr. A. R. Kennedy, Prof. R. E. Mulvey, Dr. C. T. O'Hara
WestCHEM, Department of Pure and Applied Chemistry
University of Strathclyde
295 Cathedral Street, Glasgow, G1 1XL (UK)
E-mail: r.e.mulvey@strath.ac.uk

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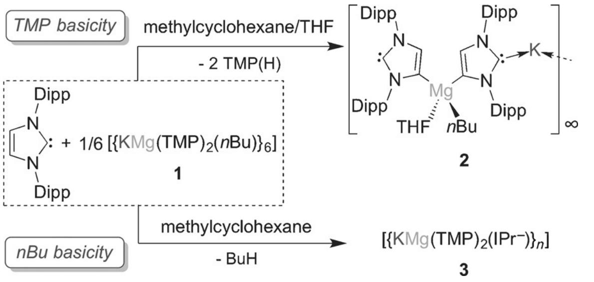


Scheme 1. Solvent-dependent reactions of IPr with **1**. Synthesis of $[\{KMg(IPr^-)_2(nBu)(THF)\}_\infty]$ (**2**) and $[\{KMg(TMP)_2(IPr^-)\}_n]$ (**3**). THF = tetrahydrofuran.

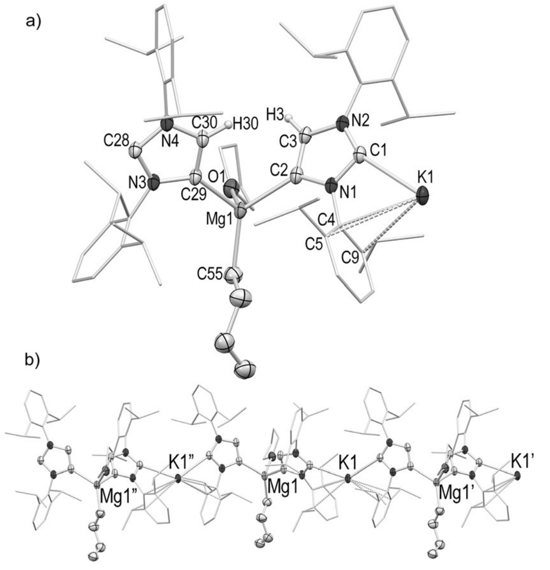


Figure 1. a) Molecular structure of $[\{KMg(IPr^-)_2(nBu)(THF)\}_\infty]$ (**2**),[23] showing the contents of the asymmetric unit, which corresponds to a single turn of the zig-zag chain. Displacement ellipsoids are displayed at 35% probability. Hydrogen atoms (except H3 and H30) and disordered components for *n*Bu and *i*Pr groups are omitted for clarity. Dipp and THF groups are pictured as capped sticks for clarity. The dashed lines illustrate K⋯C(aryl) contacts. b) Section of the extended framework structure showing atom connectivity between normal C2 (C1 and C28) sites and K, and both abnormal C4 (C2 and C29) and *n*Bu ligand to Mg.

adding more IPr suggests a redistribution process is more likely starting from the putative $[KMg(IPr^-)(TMP)(nBu)]$, though the key point is, irrespective of **1** being a mono- or diamido base, *n*Bu is retained. The groups of Robinson and Goicoechea have reported related redistribution processes with anionic NHCs of Zn[15] and Mn,[18] respectively. The crystalline **2** was also fully characterized by NMR spectroscopy in $[D_8]$THF solution.[19] A 2:1 ratio for IPr^- and *n*Bu ligands is observed in the ^1H NMR spectrum and is in agreement with the formulation of **2**. The $CH(CH_3)_2$ fragments of the Dipp groups resonate as two distinct sets of signals in the ^1H and ^{13}C NMR spectra as a result of the symmetry loss in IPr^-. The symmetry loss, as a result of the metalation in the backbone of the imidazole ring, is also mirrored by a large downfield resonance at $\delta = 156.4$ ppm in the ^{13}C NMR spectrum for the Mg–C4 fragment ($\delta = 122.5$ ppm in the free IPr). In addition, the resonance assigned to the carbonic C2 is shifted upfield ($\delta = 214.1$ ppm) compared to that observed in free IPr ($\delta = 221.1$ ppm), thus reflecting the formation of an NHC complex with potassium. A fluxional process at room temperature makes equivalent the dative C2→K interaction on both IPr^- fragments, hence explaining the single resonance for C2. More significantly, a unique broad singlet is observed for the two imidazole CH moieties at $\delta = 4.96$ ppm, and is dramatically upfield to that in free IPr ($\delta = 7.20$ ppm) and previous C4-metalated examples (range: $\delta = 6.07$–6.66 ppm).[12–13,16] This unexpected shielding of the imidazole CH in **2** correlates with the upfield resonances for the *para* and *meta* CH groups (at $\delta = 6.43$ and 6.86 ppm, respectively) of one of two inequivalent Dipp groups. This effect can be explained by a close intramolecular spatial proximity between the imidazole CH of one IPr^- and a Dipp ring from the second IPr^- moiety (and vice versa), and results in an overall mutual shielding by anisotropic effects. THF could be a factor in the lack of a template effect in the metalation as this lone-pair donor can compete for metal coordination sites and deaggregate the $(KNMgN)_6$ 24 atom ring structure. Significantly donor-solvated potassium magnesiate $[(PMDETA)KMg(TMP)_2(CH_2SiMe_3)]$ is known to deprotonate aromatic substrates kinetically through TMP.[20] The crystalline **2** exhibits an infinite, zig-zag chain structure (Figure 1). Mg occupies a distorted tetrahedral (C_3O) anionic site comprising two distinct C4-deprotonated IPr^- groups, one *n*Bu, and one THF ligand. Alternating with anionic moieties along the chain, K^+ bridges two normal IPr^- sites (C1 and C28′: mean bond length, 2.87 Å) and engages in longer K-η^3C_6 π-arene interactions with one Dipp substituent on each IPr^- at *ipso*, *ortho*, and *meta* sites [length range: 3.029(2)–3.406(3) Å]. Repeating the reaction without THF (Scheme 1) gave only an oily mixture from which a brown solid was extracted. Though this product could not be obtained as single crystals, NMR characterization in $[D_8]$THF solution[19] is consistent with a single compound of empirical formula $[\{KMg(TMP)_2(IPr^-)\}_n]$ (**3**), where IPr is deprotonated at C4.[21] Most compelling is that the ^1H DOSY NMR[22] data of **3** in $[D_8]$THF confirm a single monomeric version of **3** $[([D_8]THF)_3KMg(IPr^-)(TMP)_2]$.[19] Significantly, this formulation is consistent with a template metalation through *n*Bu basicity (butane loss), thus matching other reactions of **1** in non-donor media. This implies that here IPr acts as a C–H substrate as opposed to a donor, since donor IPr synergic metalations usually show TMP basicity [TMP(H) loss] as evidenced by the TMP zincate study by Hevia and co-workers.[16]

The sodium magnesiate $[(TMEDA)NaMg(TMP)_2(nBu)]$[24] (**4**) reacted with IPr in a 1:1 stoichiometry in *n*-hexane and after a crystallization process in *n*-hexane/THF, the tris(monoanionic) carbene $[(THF)_3Na(\mu\text{-}IPr^-)Mg(THF)(IPr^-)_2]$ was isolated (**5**; Figure 2). Our NMR studies point to a complicated ligand redistribution process in forming **5** (Scheme 2) when THF is present in the reaction media.[19] When **4** was subjected to IPr in a 1:3 molar ratio in *n*-hexane a similar compound to **2**, of empirical formula $[(THF)NaMg(IPr^-)_2(nBu)]$ (**6**; Scheme 2), was isolated and characterized

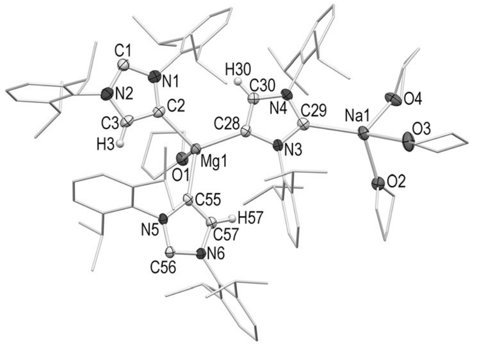
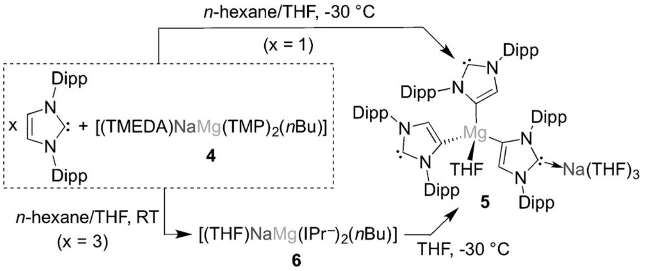


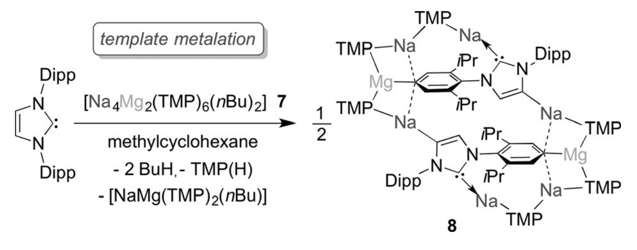
Figure 2. Molecular structure of $[(THF)_3Na(\mu\text{-}IPr^-)Mg(THF)(IPr^-)_2]$ (**5**).[23] Displacement ellipsoids are displayed at 35 % probability. Hydrogen atoms (except H3, H30, and H57) and disordered components for one THF molecule and one *i*Pr group are omitted for clarity. Dipp and THF groups are pictured as capped sticks for clarity.



Scheme 2. Synthesis of $[(THF)_3Na(\mu\text{-}IPr^-)Mg(THF)(IPr^-)_2]$ (**5**) and $[(THF)NaMg(IPr^-)_2(nBu)]$ (**6**).

by NMR spectroscopy. ^{1}H NMR data of **6** in [D$_8$]THF solution show a singlet for the imidazole CH at $\delta = 6.30$ ppm, two discrete resonance sets for the Dipp groups, and a characteristic MgCH_2 signal at $\delta = -1.25$ ppm for the *n*Bu group. Abnormal C4 exhibits a resonance at $\delta = 161.0$ ppm in the ^{13}C NMR spectrum, and is in agreement with that seen in **2**. Similarly, the formation of the crystalline **5** was observed when **6** was dissolved in *n*-hexane/THF, thus reinforcing the idea of a ligand-induced redistribution phenomena in forming **5**. The discrete contacted ion pair structure of **5** has a distorted tetrahedral tris(THF)-solvated Na^+ bound to a carbenic C2 [Na1-C29, 2.492(4) Å], as previously seen in the zincate $(THF)_3Na[:C\{[N(2,6\text{-}iPr_2C_6H_3)]_2CHCZn(tBu)_2\}]$.[16] However, the counter anion is unique, thus exhibiting a distorted tetrahedral Mg, bound to one THF molecule and the C4-positions of three IPr^- ligands and, two terminal and one bridging to Na. Homoleptic metal complexes containing three anionic NHC ligands are extremely rare.[25]

The most extraordinary result came upon subjecting IPr to the pre-inverse-crown $[Na_4Mg_2(TMP)_6(nBu)_2]$ (**7**) in hydrocarbon media. An equimolar reaction (Scheme 3) produced the remarkable inverse crown $[\{Na_3Mg(TMP)_3(IPr^{2-})\}_2]$ (**8**; IPr^{2-}: $[:C\{[N(2,6\text{-}iPr_2C_6H_2^-\text{-}4)N(2,6\text{-}iPr_2C_6H_3)]CHC^-\}]$), which was isolated in a high (crystalline) yield of 72 % (with respect to IPr, quantitative conversion determined by NMR spectroscopy). The formation of an inverse crown, the



Scheme 3. Template metalation of IPr with $[Na_4Mg_2(TMP)_6(nBu)_2]$ (**7**), and formation of the inverse crown $[\{Na_3Mg(TMP)_3(IPr^{2-})\}_2]$ (**8**).

absence of *n*Bu in its formula, and the fact that the bulk solvent was donor-free, collectively signal a template, or at least partial template metalation. Byproducts of butane, TMP(H), and $[NaMg(TMP)_2(nBu)]$ would balance the reaction equation.

Figure 3 shows the discrete structure of one of two crystallographically unique molecules of **8**. Inverse crowns

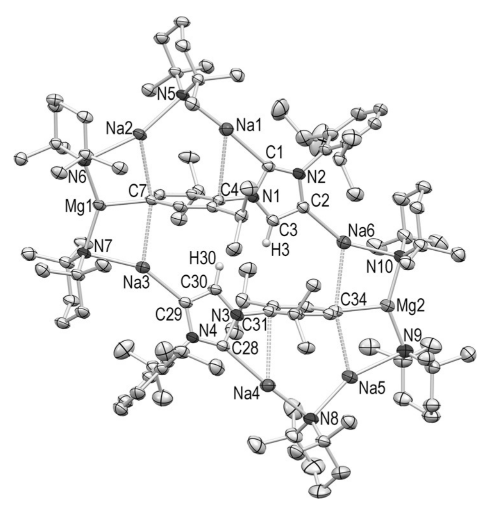
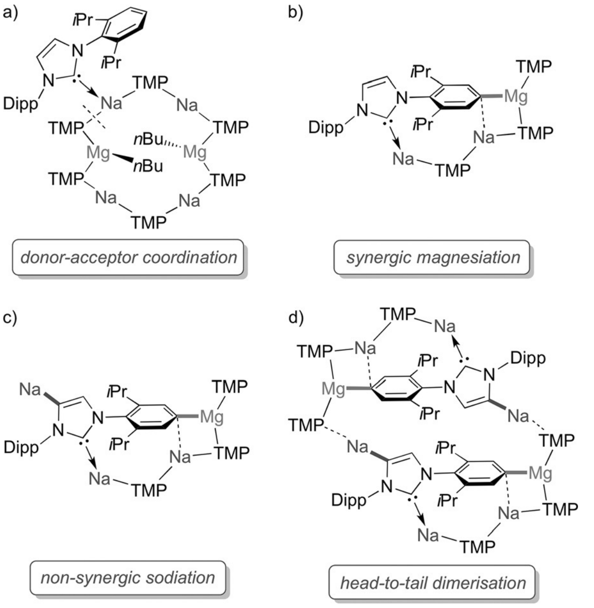


Figure 3. Molecular structure of the inverse crown $[\{Na_3Mg(TMP)_3(IPr^{2-})\}_2]$ (**8**),[23] showing one of the two crystallographically independent molecules. Displacement ellipsoids are displayed at 35 % probability. Hydrogen atoms (except H3 and H30) and methylcyclohexane molecules of crystallization are omitted for clarity. The dashed lines illustrate Na⋯C(aryl) contacts.

are defined by an outer polymetallic cationic ring charge balanced by an inner anionic moiety.[26] Each dimer of **8** displays a 20 atom $[(NaNMgNNaCNCNaN)_2]^{2+}$ ring, which encapsulates two IPr^{2-} dianions, but since one each of their negatively charged atoms (C2 and C29) lies within the ring wall the inner cavity carries only a 2− charge through C7 and C34 of the Dipp substituents. Thus the number of inner carbanion sites matches the number of outer-ring Mg atoms (through C7−Mg1; C34−Mg2), and is a signature feature of inverse crowns.[26] From an NHC perspective, IPr datively binds to Na through its normal C2 position (C1−Na1, C28−Na4), and is metalated by a second Na at its abnormal C4 (C2−Na6, C29−Na3), the ones nearest the intact Dipp groups, and by Mg at the *para* (paranormal) position of the other Dipp groups (C7−Mg1, C34−Mg2). Among many unique features, **8** represents the first crystallographically characterized sodium anionic carbene, whereas the simple C4-sodiated $\mathrm{Na^{+}IPr^{-}}$ exists as an insoluble, presumably polymeric solid.[19] Based on well-established metalation patterns a pathway of intermediates leading to **8** can be proposed (Scheme 4). Being an excellent σ-donor, IPr would initially coordinate to the more exposed acceptor Na in the pre-inverse-crown leading to template cleavage. Complexes of type $[\mathrm{(donor)NaMg(TMP)_2}(n\mathrm{Bu})]$ are common.[24] Pre-inverse-crowns invariably magnesiate through *n*Bu basicity so part of the template attached to C2, through Na, could execute the *para*-aryl magnesiation.[27] However, given the extended length of emergent $\mathrm{IPr^{-}}$ with respect to substituted benzene substrates, this magnesiation is likely to be accompanied by template fragmentation as its 12 atom ring would be too small to circumnavigate $\mathrm{IPr^{-}}$. The hemi-inverse-crown $[\mathrm{Na_2Mg(TMP)_3(IPr^{-})}]$ could result, hence stabilizing the anionic carbene by both a *para*-aryl C−Mg and normal C2→Na bond. A test reaction between **7** and IPr in a 1:2 stoichiometry showed that the metalation could not be stopped at the $[\mathrm{Na_2Mg(TMP)_3(IPr^{-})}]$ but proceeded to form **8**, as observed by NMR spectroscopy, thus implying that a cascade reaction is operative.[19] Related motifs are known when sodium TMP magnesiates deprotonate heterocyclic substrates such as tetrahydrothiophene, thus leading to C−Mg and heteroatom–metal dative bonds (e.g., S→Na).[28] In theory, the byproducts could be $[\mathrm{NaMg(TMP)_2}(n\mathrm{Bu})]$ and NaTMP, or alternatively, $[\mathrm{NaMg(TMP)_3}]$ and *n*BuNa, or a mixture of both pairs. Conventional Group 1 bases target abnormal C4 sites (recall Robinson's *n*BuLi reaction) so either NaTMP or *n*BuNa could effect a second deprotonation at C4 (i.e., C2 and C29 in **7**) to generate dianionic $\mathrm{IPr^{2-}}$. Since *n*Bu is attached to Mg in the template, NaTMP seems the more logical candidate for this sodiation, a choice reinforced by a control reaction between NaTMP and IPr, which upon $\mathrm{Me_3SiCl}$ quenching gave near-quantitative $\mathrm{Me_3Si}$ incorporation at C4.[19] Head-to-tail dimerization through N10−Na6 and N7−Na3 bonds involving TMP would complete the structure of **8**. A notable metric feature of **8** is that the N5-Na1-C1 and N8-Na4-C28 bond angles involving normal C2 atoms (mean, 174.4°) approach linearity, whereas N10-Na6-C2 and N7-Na3-C29 involving abnormal C4 are distinctly bent (mean, 154.3°). Aside from bridging two TMP N atoms, Na2, Na3, Na5, and Na6 interact with paranormal magnesiated C7 and C34 (mean length 2.74 Å), while bridging TMP N and carbene C2 atoms, Na1, and Na4 engage in longer contacts with Dipp *ipso* C4/C31 atoms (mean length, 2.92 Å). Mg atoms have distorted trigonal-planar ($\mathrm{N_2C}$) coordination. NMR characterization of **8** in $[\mathrm{D_{12}}]$cyclohexane solution[19] revealed a singlet at $\delta = 6.41$ ppm in the ^{1}H spectrum for the remaining imidazole CH, which is slightly upfield to that of free IPr ($\delta = 6.87$ ppm), and an extraordinary downfield resonance for sodiated C4 in the ^{13}C spectrum ($\delta = 170.4$ ppm in **8**; reference $\delta = 121.6$ ppm in free IPr). A resonance for the carbenic C2 at $\delta = 200.2$ ppm in the ^{13}C spectrum confirms the dative C2→Na bond in **8**. Reflecting not only the loss of symmetry in the $\mathrm{IPr^{2-}}$ moiety but also the metalation in the *para* position of one Dipp group, two distinct sets of resonances are present for the Dipp groups in the ^{1}H and ^{13}C spectra. Two different signals are seen at $\delta =$ 2.79 and 2.91 ppm for the CH of the *i*Pr groups in the ^{1}H NMR spectrum, and more informative, is that a unique downfield singlet at $\delta = 7.67$ ppm appears for the two equivalent *meta*-CH moieties of the metalated Dipp aromatic ring (nonmetalated aromatic CH of the Dipp group, $\delta = 7.00$–7.12 ppm). Also, the paranormal magnesiated Dipp C exhibits an extreme downfield resonance in the ^{13}C NMR spectrum ($\delta = 167.3$ ppm in **8** relative to the typical Dipp resonances of 122.8–146.7 ppm).



Scheme 4. Proposed four key stages (a–d) in the formation of the new inverse crown **8**, starting from IPr and **7**.

In summary, while this study set out to introduce Mg to the cartel of metals which can directly metalate a NHC, an aim duly realized in both predictable and unpredictable ways, it has taken on greater significance with recognition that pre-inverse-crown template bases can undergo remarkable reactions with mismatched substrates, which are sterically incompatible with the ring template.

Experimental Section

Full experimental details and copies of ^{1}H and ^{13}C NMR spectra are included in the Supporting Information. CCDC 1417920 (**2**), 1417921 (**5**), and 1417922 (**8**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

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[27] Note that DOSY and EXSY NMR studies show that [$Na_4Mg_2(TMP)_6(n\text{Bu})_2$] is in equilibrium with a monomeric variant, [$Na_2Mg(TMP)_3(n\text{Bu})$], in [$D_{12}$]cyclohexane, though all evidence to date suggests it is the dimeric form which reacts with C−H substrates. See the Supporting Information in Ref. [9]. Note also that if [$Na_2Mg(TMP)_3(n\text{Bu})$] was the synergic magnesiating reagent in forming the hemi-inverse-crown, there would not be another sodium source available to sodiate C4.
[28] V. L. Blair, A. R. Kennedy, R. E. Mulvey, C. T. O'Hara, *Chem. Eur. J.* **2010**, *16*, 8600–8604.

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