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Pre-inverse-crowns: synthetic, structural and reactivity studies of alkali metal magnesiates primed for inverse crown formation†

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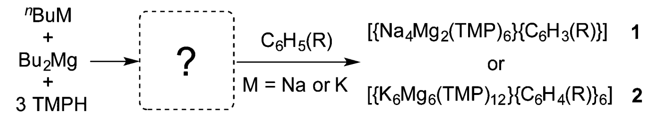
Two new alkali metal monoalkyl-bisamido magnesiates, the potassium compound $[KMg(TMP)_2{}^nBu]$ and its sodium congener $[NaMg(TMP)_2{}^nBu]$ have been synthesised in crystalline form (TMP = 2,2,6,6-tetramethylpiperidide). Devoid of solvating ligands and possessing excellent solubility in hydrocarbon solvents, these compounds open up a new gateway for the synthesis of inverse crowns. X-ray crystallography established that $[KMg(TMP)_2{}^nBu]$ exists in three polymorphic forms, namely a helical polymer with an infinite KNMgN chain, a hexamer with a 24-atom $(KNMgN)_6$ ring having *endo*-disposed alkyl substituents, and a tetramer with a 16-atom $(KNMgN)_4$ ring also having *endo*-disposed alkyl substituents. Proving their validity as pre-inverse-crowns, both magnesiates react with benzene and toluene to generate known inverse crowns in syntheses much improved from the original, supporting the idea that the metallations take place *via* a template effect. $[KMg(TMP)_2{}^nBu]$ reacts with naphthalene to generate the new inverse crown $[KMg(TMP)_2(2\text{–}C_{10}H_7)]_6$, the molecular structure of which shows a 24-atom $(KNMgN)_6$ host ring with six naphthalene guest anions regioselectively magnesiated at the 2-position. An alternative unprecedented 1,4-dimagnesiation of naphthalene was accomplished *via* $[NaMg(TMP)_2{}^nBu]$ and its NaTMP co-complex "$[NaMg(TMP)_2{}^nBu]\cdot NaTMP$", manifested in $[\{Na_4Mg_2(TMP)_4(2,2,6\text{-trimethyl-}1,2,3,4\text{-tetrahydropyridide})_2\}(1,4\text{-}C_{10}H_6)]$. Adding to its novelty, this 12-atom $(NaNNaNMgN)_2$ inverse crown structure contains two demethylated TMP ligands as well as four intact ones. Reactivity studies show that the naphthalen-ide and -*di*-ide inverse crowns can be regioselectively iodinated to 2-iodo and 1,4-diiodonaphthalene respectively.

Introduction

Alkali metal magnesiates have recently seen increasing utilisation in key organic transformations such as metal–hydrogen exchange, metal–halogen exchange and nucleophilic addition reactions.[1–20] Compared to the organolithium reagents commonly employed in these reactions, magnesiates (as well as other types of ate, most importantly zincates[1,21–45]) can show advantages of superior functional group tolerance and application at ambient temperature and in ethereal solvents. Highlighting the synergistic reactivity inherent to these bimetallics, conspicuously homometallic magnesium compounds [dialkyls, R_2Mg; Grignard (RMgX) or Hauser (R_2NMgX) reagents] are often inert in these same reactions, especially in aromatic functionalisations. Through an inspiring series of papers Knochel has shown that adding stoichiometric lithium chloride creates synergistic-operative "turbo-charged" organomagnesium reagents ($RMgX\cdot LiCl$ or $R_2NMgX\cdot LiCl$) that can exhibit excellent reactivity and regio-control across a range of deprotonation and addition applications.[6,46–84] Though deprotonation reactions of magnesiates can be viewed superficially as simple C–H to C–Mg(R) exchanges, the structural manoeuvrings to arrive there can be extraordinarily complex. A good early exemplar of this complexity was our report that an *in situ* 1 : 1 : 3 mixture of *n*-butylsodium, *n*,*s*-dibutylmagnesium and 2,2,6,6-tetramethylpiperidine [TMP(H)] in *n*-hexane deprotonates benzene or toluene, but that the C–H to C-*metal* exchanges are manifested in 12-atom macrocyclic ring complexes $[Na_4Mg_2(TMP)_6(\text{arenediide})]$ (**1a** or **1b**, Scheme 1). This structural novelty was accompanied by novel reactivity as in each example the arene has been



Scheme 1 Synthesis of inverse crown complexes **1a/b** and **2a/b** (for **a** R = H; for **b** R = Me).

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regiospecifically doubly deprotonated on its ring [1,4- for benzene leading to $(C_6H_4)^{2-}$ in **1a** or 2,5- for toluene leading to $(C_6H_3CH_3)^{2-}$ in **1b**] and remarkably the most thermodynamically acidic CH_3 hydrogen atoms of toluene in the latter complex are left untouched.[85] Perhaps counter-intuitively, only monodeprotonation of the arenes is achieved when switching to "more reactive" potassium, manifested in larger 24-atom polymetallic host rings $[K_6Mg_6(TMP)_{12}(\text{arene-ide})_6]$, **2a** and **2b**.[86] These macrocyclic compounds have been coined *inverse crowns*, due to their inverse topological relationship to conventional crown ethers.[87–90] However the downsides of these reactions are that the arene has to be used in vast excess, the yields of the products are only modest at best, and as the reactions could only be performed *in situ* the active intermediates to the bimetallic macrocycles could not be identified nor structurally characterised meaning that inverse crown preparations could only be optimised by trial and error rather than by tailoring *a posteriori*.

Here, for the first time, we report crystalline "pre-inverse-crowns", that is pure, well-defined unsolvated forms of the ate (alkali metal, magnesium, base ligand) mixtures, and provide evidence that inverse crown formation may occur *via* a template mechanism. As these multicomponent compounds possess excellent solubility in hydrocarbon solvents, a new gateway to inverse crowns is established. Using the fused ring aromatic hydrocarbon naphthalene as a case study we demonstrate that new inverse crowns can be rationally designed *via* these pre-inverse-crowns. The resulting new naphthalene-ide and -*di*-ide inverse crowns have subsequently been utilised in iodination reactions to produce iodo-substituted naphthalenes, which are potentially of use as building blocks in medicinal chemistry.[91]

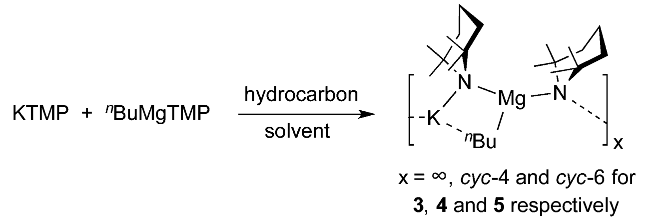
Results and discussion

Synthesis and characterisation of potassium pre-inverse-crowns

Focusing initially on potassium systems, we decided to study the equimolar reaction between freshly prepared KTMP and ^{n}BuMgTMP in a variety of hydrocarbon solvents (Scheme 2).

Pleasingly these reactions resulted in the isolation of several different oligomeric compounds. NMR spectroscopic studies of *in situ* mixtures of KTMP and ^{n}BuMgTMP in deuterated cyclohexane, *cyc*-C_6D_{12}, show a set of resonances that were not consistent with either starting material on their own (or potential monometallic metathesis products), indicating that co-complexation had occurred (see ESI)†. From a solid-state perspective, our first attempt to isolate a latent potassium-based pre-inverse-crown involved trying to grow crystals from a *cyc*-C_6D_{12} solution of an equimolar mixture of KTMP and ^{n}BuMgTMP at room temperature. Crystallization occurred and the isolated product was a solvate of the polymer $[KMg(TMP)_2{}^nBu]_\infty$ **3** (Fig. 1). Structural determination by X-ray crystallography revealed an unusual helical potassium magnesiate. The backbone of the structure (Fig. 1b) can be considered to be the repeating KNMgN unit. The one dimensional helical polymers so formed lie parallel to the crystallographic *a* direction and have approximate (*i.e.* non-crystallographic) 3_1 screw symmetry. Each $[KNMgN]_\infty$ chain is supported by K···C···K cross-links (where C is from ^{n}Bu) that thus form a series of four-atom, four-element (K–N–Mg–C) rings, fused together along the Mg–C edge to another ring of identical composition. Each potassium atom occupies a shared vertex that links neighbouring pairs of doubly-fused tetranuclear ring systems (Fig. 1). A total of twelve atoms within a K–N–Mg–C chain define both a single turn of the helix and the crystallographically unique segment of the polymer. The Mg centre forms short, strong bonds to the N atoms of both bridging TMP units [*e.g.*, Mg2–N21, 2.102(4); Mg2–N31, 2.045(4) Å], and the C atom of the *n*-butyl anion [Mg2–C2A, 2.169(5) Å], thus placing Mg in a distorted trigonal planar environment [N21–Mg2–N31, 134.44(17); N21–Mg2–C2A, 111.97(17); and N31–Mg2–C2A, 113.45(18)°]. Each K atom's coordination environment formally consists of a N_2C_2 ligand set. The K–N distances are approximately equal [K2–N31, 2.968(4); K2–N41, 2.943(4) Å], short in comparison to the more distended K···C contacts [K2–C2A 3.287(5) Å; K2–C3A 3.145(5) Å], which are primarily weak electrostatic interactions rather than formal covalent bonds. Interestingly, looking directly down the centre of the helix, the TMP ligands are arranged *exo*- whilst the *n*-butyl groups are arranged *endo*- with respect to the helical framework (Fig. 1c). Disordered solvent molecules occupy the gaps between polymeric chains – and thus the material is a channel solvate. This arrangement of a poly-amido outer scaffold with an inner alkyl unit follows the orientational pattern seen in the hexameric arene-encapsulated inverse crown species **2a/b**.[85]

When the same reaction mixture is allowed to crystallise from methylcyclohexane at ambient temperature, the tetrameric oligomer $[KMg(TMP)_2{}^nBu]_4$ **4** is produced. High quality single crystals could not be formed – with all datasets examined showing multiple diffraction patterns. However, the X-ray crystallographic study does allow the atomic connectivity of **4** to be established (Fig. 2). The structure consists of a 16-atom polymetallic ring, of composition $[K–N–Mg–N]_4$. Similarly to **3** above, the repeating KNMgN unit is supported by K···C···K cross links involving the *n*-butyl anion. Each K centre is thus four coordinate and the Mg atoms are three coordinate. As in the case of **3**, the *n*-butyl groups all orientate towards the centre of the molecule. They have an *anti* arrangement as they alternately point above and below the plane of the $[K–N–Mg–N]_4$ ring. Complex **4** exhibits similar structural features to the aforementioned inverse crowns **1** and **2** though its metal–nitrogen ring size (16-atom) differs (*versus* 12- and 24-atom, respectively[85,86]); but the salient feature is that instead of having



Scheme 2 Synthesis of potassium pre-inverse crowns.

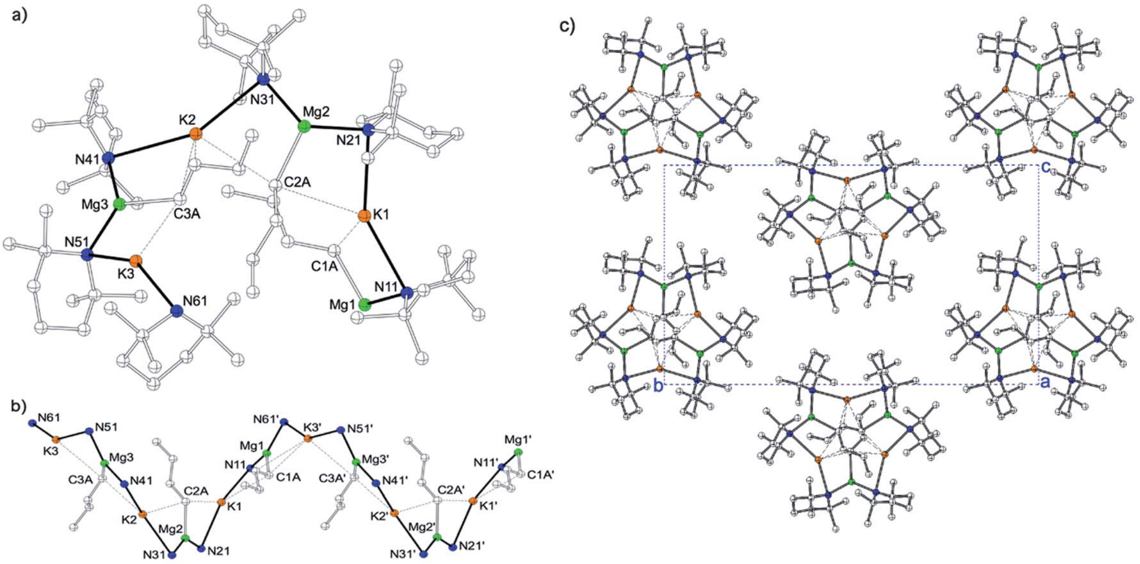


Fig. 1 (a) Molecular structure of $[\mathrm{KMg(TMP)_2}{}^n\mathrm{Bu}]_\infty$ **3**, showing the contents of the asymmetric unit, which corresponds to a single turn of the helical chain. Hydrogen atoms are omitted for clarity. (b) Section of the extended framework structure showing atom connectivity between the metals, the *n*-butyl and connecting N atom of the TMP ligands. (c) Packing diagram of $[\mathrm{KMg(TMP)_2}{}^n\mathrm{Bu}]_\infty$ **3** (viewed along a-axis). The dashed lines illustrate K⋯C contacts. Selected bond distances (Å) and angles (°): Mg1–C1A, 2.161(4); Mg1–N11, 2.033(4); Mg1–N61′, 2.069(4); K1–N11, 3.006(4); K1–N21, 2.939(4); K1–C1A, 3.321(5); K1–C2A, 3.142(5); Mg2–C2A, 2.169(5); Mg2–N21, 2.102(4), Mg2–N31, 2.045(4); 2.102(4); K2–N31, 2.968(4); K2–N41, 2.943(4); K2–C2A, 3.287(5); K2–C3A, 3.145(5); Mg3–N41, 2.098(4); Mg3–N51, 2.043(4); Mg3–C3A, 2.172(4); K3–N51, 2.985(4); K3–N61, 2.956(4); K3–C1A″, 3.129(5); K3–C3A, 3.295(5); N11–Mg1–N61′, 132.76(16); N11–Mg1–C1A, 114.90(18); N61′–Mg1–C1A, 112.17(17); N21–K1–N11, 150.25(11); N21–K1–C2A, 71.13(11); N11–K1–C2A, 138.22(12); N21–K1–C1A, 127.55(11); N11–K1–C1A, 67.75(10); C2A–K1–C1A, 90.58(11); N31–Mg2–N21, 134.44(17); N31–Mg2–C2A, 113.45(18); N21–Mg2–C2A, 111.97(17); N41–K2–N31, 149.85(10); N41–K2–C3A, 71.13(10); N31–K2–C3A, 138.46(11); N41–K2–C2A, 127.06(11); N31–K2–C2A, 68.36(10); C3A-K2-C2A, 91.47(12); N51–Mg3–N41, 133.88(17); N51–Mg3–C3A, 13.74(17); N41–Mg3–C3A, 112.23(17); N61–K3–N51, 150.05(11); N61–K3–C1A″, 70.41(10); N51–K3–C1A″, 139.03(11); N61–K3–C3A, 127.50(11); N51–K3–C3A, 68.20(10); C1A″–K3–C3A, 91.20(12). The symmetry operation used to generate the equivalent atoms labelled with ′ is $x - 1, y, z$; and ″ is $x + 1, y, z$.

a deprotonated aromatic solvent derived entity [*e.g.*, $(C_6H_4)^{2-}$ or $(C_6H_3CH_3)^{2-}$] as its third ligand component, **4** has strongly Brønsted basic *n*-butyl anions seemingly primed for executing deprotonation reactions. It is this latter feature that drew our attention to **4** as a potential pre-inverse-crown.

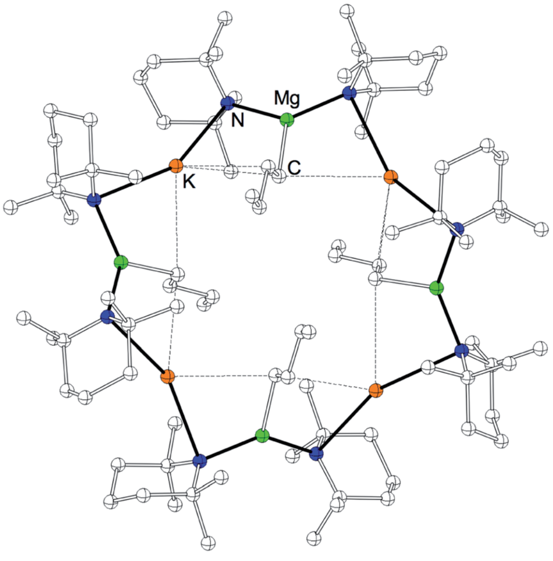


Fig. 2 Atomic connectivity of $[\mathrm{KMg(TMP)_2}{}^n\mathrm{Bu}]_4$ **4**. The dashed lines illustrate K⋯C interactions.

By altering the solvent of crystallization from methylcyclohexane to cyclohexane solution and by cooling the solution to 8 °C, a third oligomeric form, a hexameric variant of the magnesiate $[\mathrm{KMg(TMP)_2}{}^n\mathrm{Bu}]_6$ **5**, was obtained (Fig. 3). Hexamer **5** features a 24-atom $(\mathrm{KNMgN})_6$ centrosymmetric ring, with two and three coordinate K and Mg centres respectively, although the K is positioned in relatively close proximity to one of the *α*-carbon atoms of the neighbouring *n*-butyl groups [K1–C20, 3.143(5); K1–C20′, 3.243(5) Å]. The K atoms bridge between two TMP units, forming strong K–N contacts [K1–N1, 3.052(2); K1–N2, 3.053(2) Å], with a bridging N1–K1–N2 angle of 146.72(6)°. Mg occupies a distorted trigonal planar site [N1–Mg1–N2″, 133.63(9); N1–Mg1–C20, 115.57(14); N2″-Mg1–C20, 110.28(14)], and the inner *n*-butyl appendages point alternately above and below the ring plane, in a similar fashion to that observed in the tetrameric polymorph **4**. Interestingly, continuing the pre-inverse-crown notion (*i.e.*, **5** contains basic, reactive *n*-butyl ligands which are capable of inducing arene deprotonation), hexameric **5** appears to represent the perfect template to produce the arene-ide inverse crowns **2a** and **2b**, as it is directly comparable in terms of aggregation state and conformation with all its *n*-butyl appendages still intact to deprotonate benzene or toluene.[86] When isolated crystals of both oligomeric forms (**4** and **5**) or polymeric **3** were dissolved in *cyc*-C_6D_{12}, their ^1H NMR spectra were essentially identical to that obtained from a 1 : 1 mixture of KTMP and ^{n}BuMgTMP. This perhaps indicates that the energy difference between the

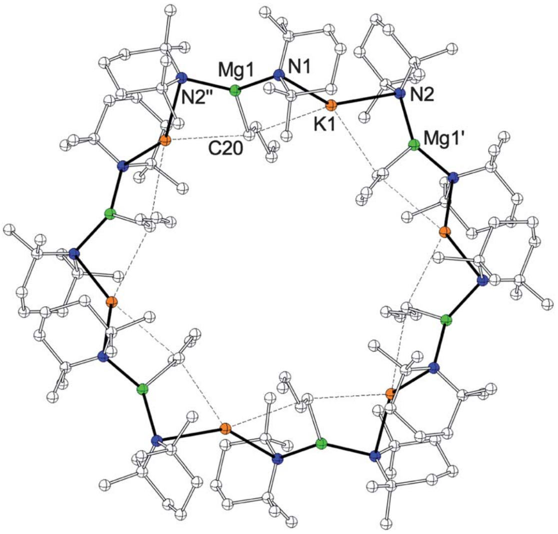


Fig. 3 Molecular structure of $[KMg(TMP)_2{}^nBu]_6$ **5**. Hydrogen atoms, solvent molecules of crystallization and one disordered component of the *n*-butyl ligand have been omitted for clarity. The dashed lines illustrate K⋯C contacts. Selected bond distances (Å) and angles (°): K1–N1, 3.052(2); K1–N2, 3.053(2); K1–C20, 3.143(5); K1–C20′, 3.243(5); Mg1–N1, 2.036(2); Mg1–N2″, 2.043(2); Mg1–C20, 2.192(4); N1–K1–N2, 146.72(6); N1–K1–C20, 70.55(9); N2–K1–C20, 130.39(9); N1–K1–C20′, 140.65(8); N2–K1–C20′, 66.95(8); C20–K1–C20′, 103.28(18); N1–Mg1–N2″, 133.63(9); N1–Mg1–C20, 115.57(14); N2″–Mg1–C20, 110.28(14); Mg1–N1–K1, 89.43(7); Mg1′–N2–K1, 92.03(7); Mg1–C20–K1, 84.37(14); Mg1–C20–K1″, 84.41(14); K1–C20–K1″, 163.21(18). The symmetry operation used to generate the equivalent atoms labelled with ′ is $y + 1, -x + y + 1, -z$; and ″ is $x - y, x - 1, -z$.

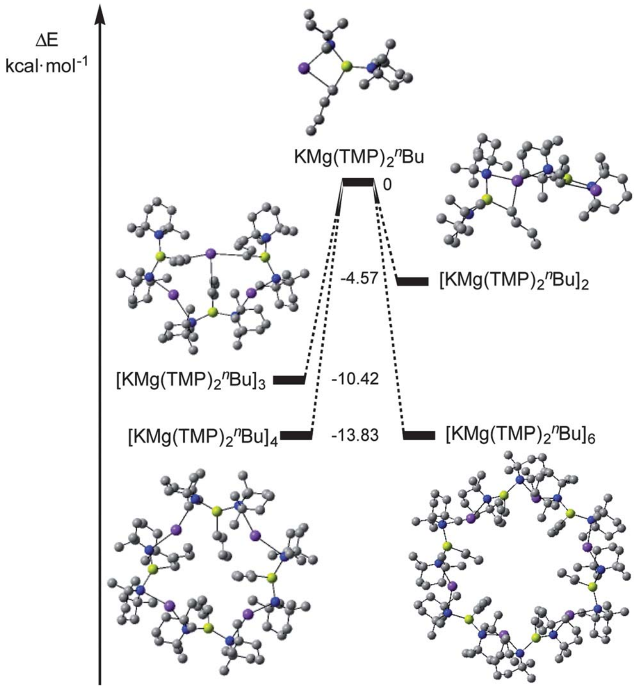


Fig. 4 Computed relative electronic energies of association for $KMg(TMP)_2{}^nBu$. Hydrogen atoms omitted for clarity.

different oligomers for this particular potassium magnesiate complex is small. DOSY (Diffusion-Ordered SpectroscopY) NMR studies[92–112] of a 1 : 1 mixture of KTMP and ^{n}BuMgTMP in *cyc*-C_6D_{12} was attempted but due to the highly reactive nature of the solution towards the employed standards, it was impossible to quantify the spectra.[113] However, by performing DOSY with external calibration (see, ESI† for full details) we could study the oligomeric make up of the solution. Rather surprisingly, only a single oligomer could be observed in solution under these conditions (400 MHz, 27 °C in *cyc*-C_6D_{12}). The data suggest that this oligomer has an approximate molecular weight (M_w) of 2478.7 g mol^{-1}, which is close to the predicted MW of hexameric **5** (M_w, 2406.1 g mol^{-1}; −3.0% difference in MW). Therefore, our data suggest that no deaggregation equilibria exist for this species.

Next we decided to employ Density Functional Theory (DFT) calculations[114] to estimate the relative gas-phase energy differences between the hypothetical monomeric, and dimeric oligomers of "$KMg(TMP)_2{}^nBu$" as well as the experimentally observed tetrameric and hexameric oligomers. By studying the association energies of each oligomer (Scheme 3) it was determined that the tetrameric and hexameric oligomers were equally as stable (ΔE, $= -13.83$ kcal mol^{-1} for each system, Fig. 4), thus mirroring the results of the solid-state data. As the oligomerisation state decreased from $n = 3$ to 1, the relative stabilities decreased (ΔE, $= -10.42$, -4.57 and 0 kcal mol^{-1} for trimer, dimer and monomer respectively).

$$KMg(TMP)_2{}^nBu \xrightarrow{\Delta E} 1/n\ [KMg(TMP)_2{}^nBu]_n$$

$$(n = 2, 3, 4, 6)$$

Scheme 3 Modelled energy of oligomerisation reactions for $KMg(TMP)_2{}^nBu$.

Application of potassium pre-inverse-crowns in the synthesis of inverse crowns

As already mentioned the original synthesis of the inverse crowns **1a/b** and **2a/b** relied on the employment of vast excesses of arene.[85,86] In order to assess the reactivity of **3** as a potential pre-inverse-crown, we decided to investigate its reaction with equimolar quantities of benzene and toluene and to study both the solution and solid-state products. Could **3** (in the form of an *in situ* mixture of KTMP and ^{n}BuMgTMP) replicate or even outperform the originally used *in situ* (^{n}BuK, $^{n,s}Bu_2Mg$, 3 TMPH) mixtures? In answer, we found that at ambient temperature, the previously prepared inverse crown molecules could be isolated in good to excellent isolated yields (44% and 93% for **2a** and **2b**, respectively). The aforementioned DOSY NMR spectroscopy study appears to rule out equilibria allowing the deaggregation of the large cyclic oligomers to smaller dimers/trimers *etc.* (and hence creating different deprotonating species). There are also two other pieces of evidence which provide support that the larger oligomers are involved in the deprotonative chemistry: (i) the aforementioned gas phase experiments (Fig. 4) show that the tetramer and hexamer are considerably more stable than their smaller aggregates, and as the deprotonative reactions are performed in the absence of donor media, there is no driving force to induce deaggregation; and (ii) the solid-state structure of previously reported inverse crowns (having similar macrocyclic structures to **5**) have been shown to be retained in hydrocarbon solution by a series of spectroscopic analyses.[115,116] Therefore it appears that the *in situ* mixture of **3** in hydrocarbon solution is an excellent forerunner for the rational synthesis of these inverse crown macrocyclic complexes. This led on to another question, "could we utilise this *in situ* mixture to synthesise new inverse crown molecules with other "guest" anions encapsulated within the cationic ring?"

To answer this question, we turned our attention to the fused ring aromatic hydrocarbon system, naphthalene, as a case study. Naphthalene has been studied previously in metallation chemistry, both in terms of its reactivity with traditional alkyllithium reagents[117,118] and more complex synergic bimetallic metallators.[119–121] However to the best of our knowledge it has never been magnesiated directly. The naphthalene skeleton represents a popular unit in chemical and pharmaceutical industries with interesting optical, electronic and biological properties.[122–131] In recent years, the development of new and efficient methodologies for the synthesis of substituted naphthalene derivatives has attracted attention in organic synthesis. Directed metallation of activated naphthalene derivatives with alkyllithium reagents akin to the Directed *ortho* Metallation (D*o*M)[118,132–146] of activated benzene derivatives has been shown to provide access to functionalized naphthalene compounds.[147,148] The more challenging metallation of non-substituted naphthalene has also been accomplished by the Lochmann–Schlosser superbase (^{n}BuLi·KO^{t}Bu, LICKOR) which can di-deprotonate naphthalene at cryogenic temperatures, but not in a regioselective manner as twelve different mono/di-substituted isomers are formed in a collectively poor yield.[121] Synergically-operative metallators such as sodium zincate (TMEDA)·Na(μ-TMP)(μ-^{t}Bu)Zn(^{t}Bu)[149–155] or sodium manganate (TMEDA)·Na(μ-TMP)(μ-CH_2SiMe_3)Mn(TMP)[119,156–159] offer an enhanced regioselectivity. Metallation (zincation[120] or manganation[119]) at the 2-position of naphthalene occurs at room temperature *via* these respective reagents. Also a 2,6-di-zincated naphthalene derivative can be isolated upon heating a 2 : 1 mixture of the sodium zincate and naphthalene.[120] However, although these last metallations have been carried out *via* alkali-metal-mediated metallations, none of them have produced an inverse crown product.

On reacting naphthalene with our new metallating agent **3** in methylcyclohexane/heptane solution we produced the first naphthalene-based inverse crown $[KMg(TMP)_2(2\text{-}C_{10}H_7)]_6$ **6** following recrystallization from toluene. The yield of the isolated crystalline solid was 41%; but ^{1}H NMR analysis of the crude reaction mixture showed that the reaction was essentially quantitative. The metallation of naphthalene was found to be highly regioselective at the 2-position, both in the isolated crystals and the crude reaction mixture. X-ray crystallographic analysis reveals that as with **5**, **6** crystallises as a hexamer with $\bar{3}$

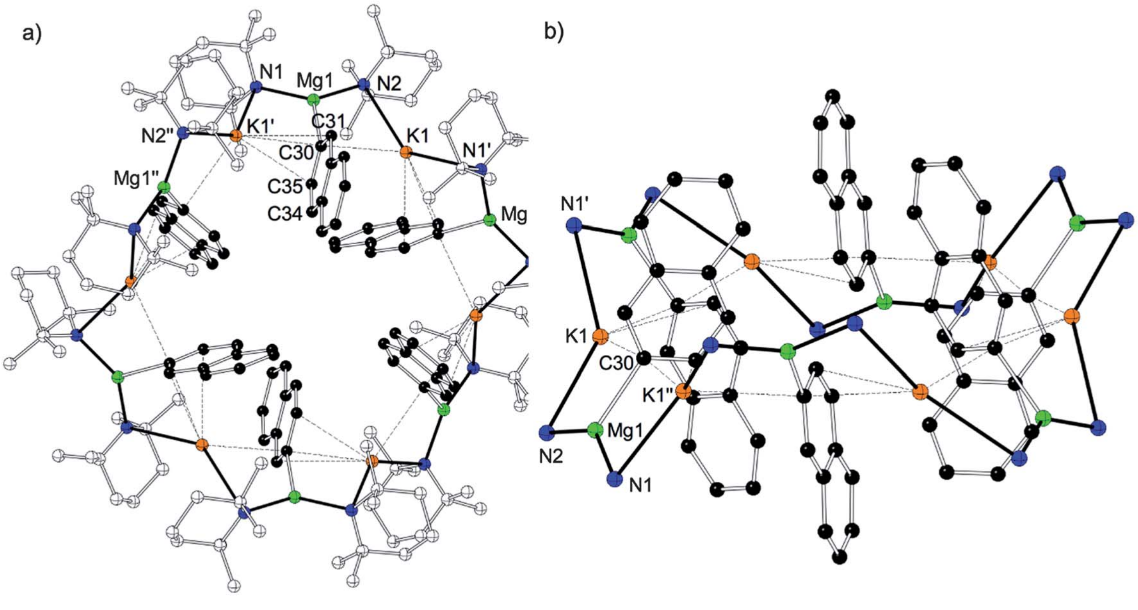
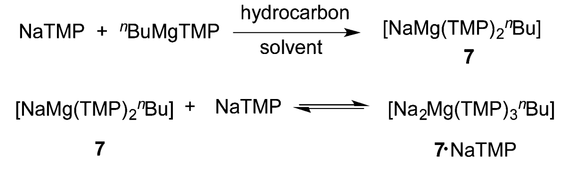


Fig. 5 (a) Molecular structure of $[KMg(TMP)_2(2\text{-}C_{10}H_7)]_6$ **6** (naphthalenide moiety in black), with hydrogen atoms, solvent molecule of crystallization and one disordered component of the naphthalenide ligand omitted for clarity; (b) core view (TMP C atoms and K–C interactions omitted for simplicity). The dashed lines illustrate K⋯C contacts. Key bond distances (Å) and angles (°): K1–C30, 3.128(4); K1–C31, 3.568(4); K1–C35, 3.525(5); K1–N2, 3.072(3); K1–C30′, 3.064(4); K1–N1′, 3.174(3); K1–C31′, 3.318(12); Mg1–N1, 2.028(3); Mg1–N2, 2.029(3); Mg1–C30, 2.248(2); N1–K1″, 3.174(3); C30–K1″, 3.064(4); C31–K1″, 3.318(4); C35–K1″, 3.282(4); C30′–K1–N2, 141.24(7); C30′-K1-C30, 117.75(11); N2–K1–C30, 70.50(7); C30′–K1–N1′, 68.49(7); N2–K1–N1′, 140.92(8); C30–K1–N1′, 125.30(7); N2–K1–C35′, 138.89(18); N1′-K1-C35′, 79.53(18); N2–K1–C31′, 117.52(17); N1′–K1–C31′, 84.4(2); N2–K1–C35, 84.54(7); N1′–K1–C35, 124.33(7); N1–Mg1–N2, 136.08(12); N1–Mg1–C30, 110.30(14); N2–Mg1–C30, 113.46(14); N1–Mg1–K1, 163.39(9); N2–Mg1–K1, 56.44(8); C30–Mg1–K1, 57.68(11); N1–Mg1–K1″, 57.09(8); N2–Mg1–K1″, 166.22(9); C30–Mg1–K1″, 54.13(11); K1–Mg1–K1″, 111.79(3); Mg1–N1–K1″, 90.48(10); Mg1–N2–K1, 90.17(9); Mg1–C30–K1″, 89.38(12); Mg1–C30–K1, 84.91(10). The symmetry operation used to generate the equivalent atoms labelled with ′ is $y, -x + y, -z + 1$; and ″ is $x - y, x, -z + 1$.

symmetry (Fig. 5). Its cationic ring is essentially isostructural to those of **2a**/**b**,[85,86] but its core contains six monodeprotonated naphthalenide ligands. This macrocycle features a 24-atom $(KNMgN)_6$ ring, with significant interactions between K and the π-system of the naphthalenide ring resulting in a series of smaller doubly fused four-atom ring appendages, mirroring the situation witnessed in the polymer **3** and hexamer **5**. The faces of each naphthalenide unit are orientated to maximize the number of contributing π interactions with the nearest K atom but the naphthalenide ring inclines slightly to favour one face. As a consequence, the equivalent K atoms engage in two distinct π-interactions, firstly binding to a naphthalenide anion in a classical η^3 mode *via* the 1, 2, and 3-positions. The second interaction is to a second naphthalenide anion; however, this is considerably weaker and is tending towards η^1 hapticity [for η^3, K1‴–C30, 3.064(4); K1‴–C31, 3.318(4); K1″–C35, 3.282(4); for η^1, K1–C30, 3.128(4); K1⋯C31, 3.568(4); K1⋯C35, 3.525(5) Å]. These K–C (naphthalenide) interactions also describe two elegant internal structures, a 12-atom hexagonal arrangement propagating through the 2-position of the naphthalenide, and a complementary 12-atom, six-pointed star structure consisting exclusively of K π-interactions[160–162] to C3-position of the naphthalenide group. The significant K-(naphthalenide) π-interactions make these smaller secondary rings essentially planar, revealing a doubly sided "paddle wheel" motif. When viewed side on, the $(KNMgN)_6$ ring is extremely puckered, in an identical fashion found for hexamer **5** (Fig. 5b). The Mg centres are trigonal planar as in all previous inverse crown complexes, and are σ-bound to the 2-position of the naphthalenide ring system and also to two bridging TMP N atoms [N1–Mg1–N2, 136.08(12), N1–Mg1–C30, 110.30(14); N2–Mg1–C30, 113.46(14)°]. The short Mg–C [Mg1–C30, 2.248(2) Å], and Mg–N bonds [Mg1–N1, 2.028(3); Mg1–N2, 2.029(3) Å], reveal that the metal is strongly bound to the naphthalenide and TMP ligands. Within the host metal-amido ring system, each metal points inwards towards the centre of the molecule, exhibiting obtuse exocyclic bridging angles [N1–Mg1–N2, 136.08(12); N2–K1–N1′, 140.92(8)°], with concomitant projection of the N atoms outwards away from the centre, with these endocyclic bond angles being nearly acute (mean angle = 90.33°).

The poly-naphthalene-ide inverse crown **6** exhibits low solubility in common non-polar deuterated hydrocarbon solvents; so NMR spectroscopic characterisation in the more polar (coordinating) d_8-THF has been used at the potential cost of changing the nature of the structure by deaggregating the hexamer. Consistent with the 2-magnesiation seen in the solid-state structure, the ^{1}H NMR spectrum for **6** shows seven spectroscopically unique and inequivalent aromatic resonances. The downfield singlet and doublet at 8.37 ppm and 8.20 ppm, respectively, are attributed to C31–H and C35–H, adjacent to the Mg–C bond. The doublet at 7.31 ppm is attributed to C34–H and the non-deprotonated second ring of the naphthalenide ligand gives rise to four distinct resonances between 7.01 and 7.57 ppm. The ^{13}C NMR spectrum mirrors that observed above, with seven distinct resonances in the aromatic region representative of the seven unique C–H environments.



Scheme 4 Synthesis of sodium pre-inverse crowns.

Previous examples of potassium-mediated magnesiations[163] with dinuclear Lewis base stabilized potassium alkyl-amido-magnesiates reveal that they react kinetically with arenes *via* their TMP anion [to afford a new organometallic as well as TMP(H)]. Ultimately, in turn these two compounds react together to produce the thermodynamic organometallic amide product and alkane co-product. This two-step mechanism has only been demonstrated with relatively simple dinuclear Lewis base stabilized motifs such as $(PMDETA).K(TMP)(CH_2SiMe_3)Mg(TMP)$ (PMDETA is *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine) which critically do not generate inverse crowns but retain their dinuclearity post metallation of the arene. In contrast the systems herein are Lewis base free having high polynuclear structures that appear set up to be able to deprotonate arenes thermodynamically in a single step through alkyl basicity.

Extension to sodium

Next it was decided to investigate a sodium base system with naphthalene. Following the precedent set by the potassium pre-inverse-crown system, by treating equimolar quantities of freshly prepared NaTMP, and ^{n}BuMgTMP in hydrocarbon solvents it was envisaged that these reagents could co-complex resulting in a potential precursor to **1a**/**b**.[85] This strategy was successfully employed in methylcyclohexane solution to generate "NaMg(TMP)$_2$^{n}Bu" **7** (Scheme 4). Sodium magnesiate **7** could be crystallised and isolated in a 61% yield from a methylcyclohexane solution at 8 °C. Unfortunately, attempts to obtain high quality crystallographic data for crystalline **7** were unsuccessful due to the high disorder found in both TMP and *n*-butyl ligands present within the structure. However, ^{1}H NMR spectroscopic data (obtained from a *cyc*-C_6D_{12} solution) are consistent with the 2 : 1 TMP:^{n}Bu composition expected for **7**. When an equimolar mixture of NaTMP and ^{n}BuMgTMP is dissolved in *cyc*-C_6D_{12}, its ^{1}H NMR spectrum is identical to that obtained from a solution of isolated crystals of **7** in the same solvent.

It is immediately apparent that the composition of the sodium magnesiate **7** (Na:Mg ratio, 1 : 1) is different from the polyamide ring required to form inverse crowns **1a**/**b** (Na:Mg ratio, 2 : 1).[85] Therefore it was decided to assess whether a hydrocarbon solution of **7** could be a precursor to **1a**/**b** or whether a different species was active in the preparation of the known inverse crown complexes.[85] Thus it was discovered that on treating **7** with an equimolar quantity of benzene or toluene, the respective inverse crowns **1a**/**b** could be isolated from the reaction solutions albeit in moderate yields (63% and 48%, for C_6H_6 and $C_6H_5CH_3$, respectively). Significantly, however, when **7** is pre-treated with an additional equivalent of NaTMP (to match the observed 2 : 1

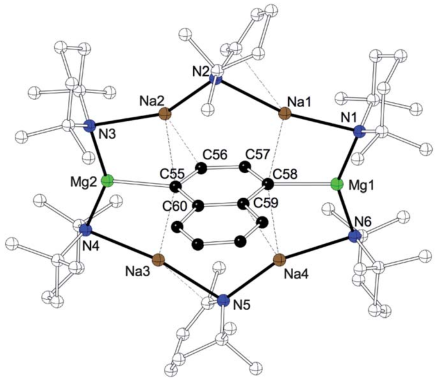
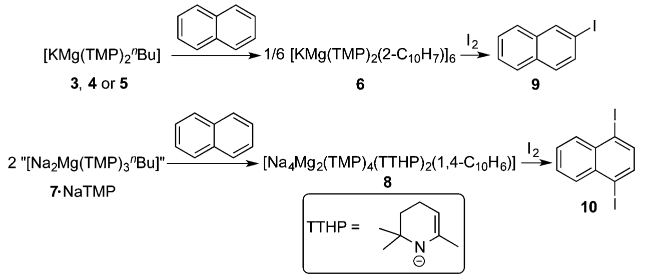


Fig. 6 Molecular structure of [{$Na_4Mg_2(TMP)_4$(2,2,6-trimethyl-1,2,3,4-tetrahydropyridide)$_2$}(1,4-$C_{10}H_6$)] **8**. Hydrogen atoms and one disordered component of the TTHP ligand omitted for clarity. The dashed lines illustrate Na⋯C interactions. Key bond distances (Å) and angles (°): Mg1–N6, 2.043(5); Mg1–N1, 2.048(5); Mg1–C58, 2.220(5); Mg1–Na1, 3.168(3); Mg1–Na4, 3.199(3); Mg2–N3, 2.032(5); Mg2–N4, 2.040(5); Mg2–C55, 2.219(5); Mg2–Na3, 3.164(3); Mg2–Na2, 3.212(3); Na1–N1, 2.531(5); Na1–N2, 2.585(12); Na1–C58, 2.683(6); Na1–Na2, 3.860(3); Na2–N2, 2.185(15); Na2–N3, 2.539(5); Na2–C55, 2.675(6); Na2–C56, 3.012(5); Na3–N5, 2.479(5); Na3–N4, 2.534(5); Na3–C55, 2.697(6); Na3–Na4, 3.899(3); Na4–N5, 2.288(5); Na4–N6, 2.529(5); Na4–C58, 2.693(6); Na4–C59, 3.017(6); N6–C50, 1.481(8); N6–Mg1–N1, 142.67(19); N6–Mg1–C58, 107.9(2); N1–Mg1–C58, 109.4(2); N6–Mg1–Na1, 164.37(14); N1–Mg1–Na1, 52.92(13); C58–Mg1–Na1, 56.48(16); N6–Mg1–Na4, 52.20(13); N1–Mg1–Na4, 164.85(15); C58–Mg1–Na4, 56.17(16); Na1–Mg1–Na4, 112.35(7); N3–Mg2–N4, 142.5(2); N3–Mg2–C55, 107.7(2); N4–Mg2–C55, 109.7(2); N3–Mg2–Na3, 164.44(15); N4–Mg2–Na3, 53.10(14); C55–Mg2–Na3, 56.94(15); N3–Mg2–Na2, 52.21(14); N4–Mg2–Na2, 164.98(14); C55–Mg2–Na2, 55.44(15); Na3–Mg2–Na2, 112.32(7); N1–Na1–N2, 166.7(4); N1–Na1–C58, 83.79(17); N2–Na1–C58, 108.9(4); C58–Na1–Na2, 76.44(12); N2–Na2–C55, 123.5(4); N3–Na2–C55, 82.33(16); N5–Na3–N4, 166.38(18); N5–Na3–C55, 109.45(16); N4–Na3–C55, 83.49(16); N4–Na3–Na4, 157.49(14); N5–Na4–N6, 156.68(19); N5–Na4–C58, 119.89(17); N6–Na4–C58, 82.57(16); Mg1–N1–Na1, 86.89(17); Mg2–N3–Na2, 88.55(17); Mg2–N4–Na3, 86.82(17); Na4–N5–Na3, 109.71(19); Mg1–N6–Na4, 88.14(16); Na2–N2–Na1, 107.8(6); Mg2–C55–Na2, 81.46(17); Mg2–C55–Na3, 79.46(17); Na2–C55–Na3, 160.7(2); Mg1–C58–Na1, 79.90(18); Mg1–C58–Na4, 80.62(17); Na1–C58–Na4, 159.4(2).



Scheme 5 Optimised syntheses of iodonaphthalenes *via* novel inverse crown intermediates.

Na:Mg stoichiometry within the metal-amido rings in **1a**/**b**[85]) the isolated yields of the inverse crowns were improved (to 73% and 88%, for C_6H_6 and $C_6H_5CH_3$, respectively). It is well known that NaTMP is insoluble in hydrocarbon solvents at ambient temperature;[164] however, on adding NaTMP to a hydrocarbon solution of **7** at ambient temperature, homogeneity was achieved, most likely indicating that the amide has co-complexed with the pre-existing sodium magnesiate species **7**. Thus far we have been unable to isolate crystalline/solid material from **7**·NaTMP, but ^1H NMR spectroscopic studies of the reaction mixture in *cyc*-C_6D_{12} reveal that the equilibrium shown in Scheme 4 could be involved as a new species appears to form (broad singlet at −0.43 ppm attributed to a α-CH_2 from a new *n*-butyl from Na_2MgTMP_3^{n}Bu) and a reduced quantity of free NaTMP is observed (see, ESI†).

In order to probe the deprotonative capability of the bimetallic complexes, **7** and **7**·NaTMP, each was reacted with an equimolar amount of naphthalene in methylcyclohexane solution. To the best of our knowledge (*vide supra*), using conventional alkyllithium or existing organo-bimetallic bases, naphthalene has only been regioselectively mono-metalated at the 2-position or di-metallated at 2,6-positions.[119,120] On utilising **7**, we have established a new unprecedented metallation pattern for naphthalene, namely selective 1,4-di-metallation. Along with this novel regioselectivity, the reaction produces a novel new inverse crown in [{$Na_4Mg_2(TMP)_4(TTHP)_2$}(1,4-$C_{10}H_6$)] **8** (Fig. 6) (where TTHP is 2,2,6-trimethyl-1,2,3,4-tetrahydropyridide). The 12-atom $Na_4Mg_2N_6$ ring is slightly bent and the naphthalenedi-ide group lies in an orthogonal manner to the mean plane of the poly-amido-metallic ring. The di-cationic ring forms a six-pointed star with those corresponding outer N atoms and inner Mg and Na atoms. In **8**, the C–H missing bonds from the naphthalene are replaced by strong C–Mg σ-bonds (mean distance, 2.220 Å) and are comparable to those in **1a**/**b** (2.196 Å). The Mg atoms adopt distorted trigonal-planar geometries and the N–Na–N units are coplanar with the magnesiated carbons to maximize the C–Na π-interactions. The sodium atoms in **8** lie above and below the metallated aromatic ring faces, and engage π-interactions with the C atoms in 1, 2- and 3, 4-positions (Na–C, 2.674–3.265 Å). The Na–N TMP bonds within the inverse crown structure (mean distance, 2.534 Å) are 0.493 Å longer than those strong N–Mg TMP (mean 2.041 Å) bonds.

This compound was isolated in a 51% yield. Matching previous results, **8** was isolated in higher yield (76%) by reacting equimolar quantities of **7**·NaTMP and naphthalene. At first glance, the X-ray determined structure of **8** displays a 12-atom $Na_4Mg_2N_6$ cationic metal-amido ring which appears identical to that in **1a**/**b**;[85] however, two of the six amide ligands appear to have formally lost methane to produce TTHP anions. It should be stressed that this reaction leading to **8** is completely reproducible and that an inverse crown with six all intact TMP ligands has not been isolated when naphthalene has been utilized as the arene substrate. This perhaps suggests that the arene's increased steric bulk (with respect to benzene or toluene in **1a** and **b**, respectively) has forced a sterically-driven demethylation of the amide. To the best of our knowledge this is the first time that a complex which contains a demethylated TMP ligand has been characterized; however, Shiner and co-workers have previously shown some indirect evidence for a demethylation process involving LiTMP.[165] Returning to **8**, its ^1H NMR spectrum obtained from a *cyc*-C_6D_{12} solution appears to show that the complex remains intact in solution. Most indicative of this fact is that a sharp resonance for the two Me groups present on the α-C(sp^3) of the 2,2,6-trimethyl-1,2,3,4-tetrahydropyridide ligand are situated over the π-face of the arene rendering them highly shielded causing an upfield shift to 0.06 ppm (see ESI). As expected, the spectrum also shows a singlet and two multiplets (7.92, 7.95 and 7.29 ppm, respectively) in the aromatic region in a 1 : 1 : 1 ratio assignable to a 1,4-dideprotonated naphthalene consistent with the 1,4-dimagnesiation of the arene observed in the crystal structure. The ^{13}C NMR spectrum replicate the situation indicated by the appearance of the ^{1}H NMR spectrum. An intriguing question to ask is "why does the sodium magnesiate induce a two-fold deprotonation whilst the assumed more reactive potassium magnesiate solution only mono-metallates naphthalene?" One plausible explanation is that the larger rings formed in the potassium case allow the heavier, softer alkali metal to maximise its stabilisation *via* π-arene interactions, especially as the reaction medium is free of donor atoms. Fig. 5a implies that each K centre receives a double helping of π-interactions, a situation that would not be possible if Na was simply replaced by K in **8** (Fig. 6). Moreover in comparing **6** with **8** and speculating on the nature of their pre-inverse-crowns (presumably **5** for K) it must be stressed that we are not comparing like with like as the K case has a 1 : 1, K:Mg stoichiometry; whereas in the Na case, the corresponding ratio is 2 : 1.

Reactivity studies of the new inverse crowns

Turning to the utility of the potassium system **6** in synthesis (Scheme 5), when an *in situ* methylcyclohexane suspension of **6** is reacted with iodine in THF solution, 2-iodonaphthalene[119,120,166–169] **9** was isolated in 67% yield. When the reaction was repeated using isolated **6** suspended in methylcyclohexane, **9** was obtained in a significantly higher yield (84%).

To assess the potential synthetic utility of the sodium system **7**, an *in situ* solution mixture of **7**·NaTMP in methylcyclohexane and naphthalene were reacted and subsequently treated with iodine in THF. After work-up, the formation of 1,4-diiodonaphthalene **10** in an 86% yield was accomplished.[170] When isolated **8** suspended in methylcyclohexane was reacted with iodine in THF solution, a marginally improved conversion to **10** was observed (to 89% yield).

Conclusions

In summary, by synthesising and managing to isolate crystalline alkali metal magnesiates containing a combination of two TMP ligands and one *n*-butyl ligand but no donor solvent ligands, we have gained access to valuable precursors to inverse crown macrocyclic complexes. The idea that these unsolvated bimetallic compounds could function as pre-inverse-crowns came from the remarkable structural chemistry of $[KMg(TMP)_2{}^{n}Bu]$, with three oligomeric states revealed (tetrameric, hexameric and polymeric), with architectural features closely akin to existing inverse crowns but with the deprotonated entity substituted by an active alkyl base ligand. Confirmation of their pre-inverse-crown status was established through reactions with naphthalene that in executing regioselective mono- and di-deprotonation of the arene produced novel new types of inverse crown. With these new pre-inverse-crowns in hand, and others likely to follow, the floodgates for broadening the scope of inverse crown chemistry have been opened wide.†

Acknowledgements

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