Structural complexity of the magnesiation of furan: an octadecanuclear product with a subporphyrin-like Mg_3(2,5-fur-di-yl)$_3$ substructure†

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Subjecting furan to sodium-mediated magnesiation *via* the new heteroleptic alkyl-amido reagent [(TMEDA)·Na(CH_2SiMe_3)(TMP)Mg(TMP)] produces the remarkable dodecasodium–hexamagnesium molecule [{$(TMEDA)_3Na_6Mg_3(CH_2SiMe_3)(2,5\text{-}C_4H_2O)_3(2\text{-}C_4H_3O)_5$}$_2$], built upon a bridge network of 10 monodeprotonated and 6 twofold-deprotonated furan ligands.

Long considered to be too weakly basic and ineffectual for direct metallation purposes, magnesiation (magnesium–hydrogen exchange) is rapidly gaining a new status as a powerful tool for constructing aryl- and heteroaryl-metallo intermediates of high kinetic stability and functional group tolerance, as a foundation from which to build functionalised aromatic compounds.[1] What lies behind this transformation from inefficacy to efficacy? Essentially, the magnesium sources studied previously were simple Grignard reagents, bis-alkyls, or bis-amides of low kinetic basicity in comparison to their more reactive lithium alkyl or amido counterparts; whereas the modern reagents have more complex compositions, which greatly enhance their magnesiating abilities. Alkali metals feature prominently in these new compositions, prompting their classification as "ates",[2,3] though grouping them together in this way blurs the fact that this class of compounds boasts an extraordinarily diverse range of chemical profiles. Recent examples include the homoleptic alkyls "$Bu^n{}_3MgLi$" and "$Bu^n{}_4MgLi_2$",[4] the lithium chloride-supported turbo-Hauser base "TMPMgCl·LiCl",[5] and the heteroleptic alkylmagnesium amide [(TMEDA)·Na(Bu^n)(TMP)Mg(TMP)],[6] **1** (where TMP is 2,2,6,6-tetramethylpiperidide). Interestingly, it has been demonstrated that the reactivity of complex bases of this type can be tuned to different regioselectivities by adjusting the alkyl component. Thus dimagnesiation of toluene can be switched from *ortho–meta* to *meta–meta* positions using *in situ* "Na(R)(TMP)Mg(TMP)" mixtures, when R is changed from Bu^n to monosyl CH_2SiMe_3.[7]

Our focus in this paper is bimetallic (synergic) magnesiation of the heterocycle furan. The furan framework features frequently in a variety of agrochemicals, fragrances, natural products, and pharmaceuticals, as well as in synthetic precursors to these and other important chemicals,[8] so its metallation chemistry is an essential avenue of investigation, both fundamentally and in the development of new synthetic strategies for functionalised furans. In this area knowledge of magnesiofuran compounds[9] is scarce against the large body of literature on the lithiation of furan.[10] The potential for using magnesiation to design new structural motifs *via* α-furyl (2-C_4H_3O) building blocks was recently highlighted[11] by the reaction of the aforementioned magnesiate reagent **1** with furan: the isolated product [{{$(thf)_3\cdot Na_2$}{(TMEDA)·Mg_2}(2-C_4H_3O)$_6$}$_\infty$], **2**, established a new type of inverse crown architecture with 12-atom $(NaOCMgCO)_2$ rings hosting the furyl guests in the TMEDA-linked repeating unit of a polymeric chain. In view of the aforementioned alkyl dependency of magnesiate reagents, we have investigated the effect of replacing the butyl component within **1** by Me_3SiCH_2 in its reaction with furan. As reported herein the outcome is wholly unexpected with the crystalline product having a bizarre, unique formulation and high nuclearity structure markedly different from that of **2** or indeed any known magnesiate compound.

Prior to the reaction with furan we synthesised the new magnesiate reagent [(TMEDA)·Na(CH_2SiMe_3)(TMP)Mg(TMP)], **3**, according to eqn (1).† For completeness, we determined its crystal structure‡ (Fig. 1), finding a dinuclear ring motif closely resembling that of **1** and characteristic of certain alkali metal ate complexes.[12] Thus, TMP and alkyl bridges connect the Na and Mg atoms, the coordinations of which are completed by terminal TMEDA and TMP ligands respectively. The bridging TMP ligand is disordered though the connectivity of the structure is definite. Full details of the structure are provided in the ESI.†

$$\mathrm{NaTMP + TMP(H) + Mg(CH_2SiMe_3)_2 + TMEDA} \xrightarrow{-\mathrm{SiMe_4}} \underset{\mathbf{3}}{\mathrm{[(TMEDA)\cdot Na(CH_2SiMe_3)(TMP)Mg(TMP)]}} \qquad (1)$$

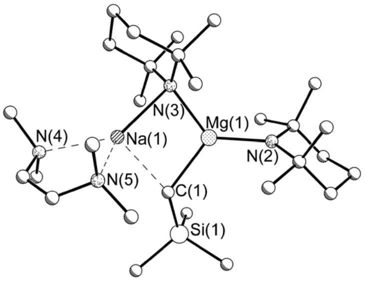

Fig. 1 Molecular structure of **3** with disorder component and hydrogen atoms omitted for clarity.

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† Electronic supplementary information (ESI) available: Synthetic procedures, ^{1}H NMR spectra and crystallographic data for **3** and **4**. CCDC reference numbers 695312 and 695313. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b812147h

With the expectation of a similar reactivity to **1** in line with the strong structural similarity between **3** and **1**, an *in situ* mixture of **3** in hexane solution was treated with an equimolar amount of furan.

Surprisingly this reaction (eqn (2)) followed a very different course to that of **1** and furan, furnishing the crystalline dodecasodium–hexamagnesium, bis-monosyl, hexa-α,α′-fur-di-yl, deca-α-furyl product [{(TMEDA)$_3$Na$_6$Mg$_3$(CH$_2$SiMe$_3$)(2,5-C$_4$H$_2$O)$_3$(2-C$_4$H$_3$O)$_5$}$_2$], **4**. Despite the complex outlandish-looking formulation of **4**, its synthesis proved reproducible in typical isolated crystalline yields of about 48%, or even higher in powder form (about 75%). This high yield, the retention of some monosyl ligands, and the requirement of 22 furan deprotonations to produce **4**, appears to rule out a disproportionation pathway as thought likely in the formation of **2**; instead **3** must act as a dual alkyl-amido base[13] in this reaction to yield **4**. This number of 22 deprotonations is a consequence of **4** containing 10 α-mono-deprotonated furyl anions and 6 α,α′-twofold-deprotonated furyl dianions. Moreover since there are only 6 Mg atoms in the structure, equating to 12 deprotonations, the reaction producing **4** must involve a combination of magnesiation and sodiation.

$$\mathrm{NaTMP + TMP(H) + Mg(CH_2SiMe_3)_2 + TMEDA + C_4H_4O} \xrightarrow{-x\mathrm{SiMe_4};\,-y\mathrm{TMP(H)}} 1/n[\{\mathrm{(TMEDA)_3Na_6Mg_3(CH_2SiMe_3)\text{-}(2,5\text{-}C_4H_2O)_3(2\text{-}C_4H_3O)_5}\}_2] \quad \mathbf{4} \tag{2}$$

X-Ray crystallographic studies§ revealed **4** to be the highest nuclearity molecular structure, possessing 12 Na and 6 Mg atoms, yet uncovered for any bimetallic product synthesised *via* alkali-metal-mediated magnesiation. Best viewed in plan form in a ChemDraw representation (Fig. 2), **4** is a centrosymmetric dimer with the inversion centre located halfway along the Mg3$\cdots$Mg3′, Na2$\cdots$Na2′, and Na5$\cdots$Na5′ connections. Fig. 3 isolates the monomeric unit. Its salient feature is a trinuclear fusion of 3 Mg atoms and 3 fur-di-yl dianions through a 12-atom (MgCOC)$_3$ ring. This ring is severely puckered with each Mg atom forming, with respect to the fur-di-yl planes, one near in-plane and one out-of-plane bond to the deprotonated α-C atoms. *Exo* the 12-atom ring, Mg1 carries a terminal CH$_2$SiMe$_3$ ligand, whereas Mg2 and Mg3 carry terminal α-furyl monoanions. In addition, making them 4-coordinate overall (all to C atoms), each Mg atom carries another α-furyl monoanion, disposed *endo* with respect to the 12-atom ring. There are 4 distinct types of Na cation present. Na1, Na2, and Na3 cap the electron-rich faces of the fur-di-yl dianions in η^5-OC$_4$ interactions, and are chelated by TMEDA molecules.

Lying on the same side of the 12-atom ring as Na1–3, Na6 is positioned centrally above this ring forming a distorted trigonal pyramid to its 3 heteroatoms (O3, O4, O7) and a distorted O$_6$ octahedral coordination overall counting contacts to the 3 *endo*-disposed furyl monoanions. Lying on the opposite side of the 12-atom ring to Na6 to which it is almost eclipsed, Na4 also binds to the 3 heteroatoms (O3, O4, O7) of this ring, and forms a short intermonomer contact to a β-C atom (C37′) of a neighbouring fur-di-yl dianion, as well as several longer intra- and inter-monomer Na–C contacts. Na5 is the major dimerisation junction engaging intramolecularly with O6 of a monoanion and the C=C bond (C49–C50) of a dianion and intermolecularly with O5A and an α-C atom (C39) of a monoanion and 2 α-C atoms (C31, C35) of two dianions. The shortest metal–carbon bond in **4** is the sole terminal Mg1–C19 involving the sp^3 alkyl group [2.177(3) Å], while the mean Mg–C(sp^2) bond length is 2.20 Å. Reflecting the looser, more ionic nature of the bonding, the shortest Na-contact (Na4–C37′) at 2.546(3) Å does not involve a deprotonated C atom, but a β-C(H) atom of a fur-di-yl dianion. Taking Na1 as a snapshot, it is seen that the η^5-interaction with the dianion face is unsymmetrical being biased towards one O–αC edge [Na1–O7, 2.588(3) Å, Na1–C47, 2.629(4) Å; *cf.* mean for other 3C atoms, 2.829 Å].

Recorded in d$_8$-THF solution, the ^{1}H NMR spectrum of **4** revealed four distinct resonances in the aromatic region: a sharp singlet at 6.22 ppm can be assigned to the equivalent H atoms of the (OC$_4$H$_2$) dianions, while the broad resonances at 7.48, 6.22 (obscured by aforementioned singlet), and 6.00 ppm can be assigned to the H$_3$, H$_5$, and H$_4$ atoms respectively of the (OC$_4$H$_3$) monoanions, with the integration ratios between the different furyl anions matching well with the stoichiometry in the crystal structure. The latter set of resonances compares favourably with those of the OC$_4$H$_3$ monoanions in **2** with corresponding chemical shifts of 7.58, 6.37, and 6.11 ppm. The

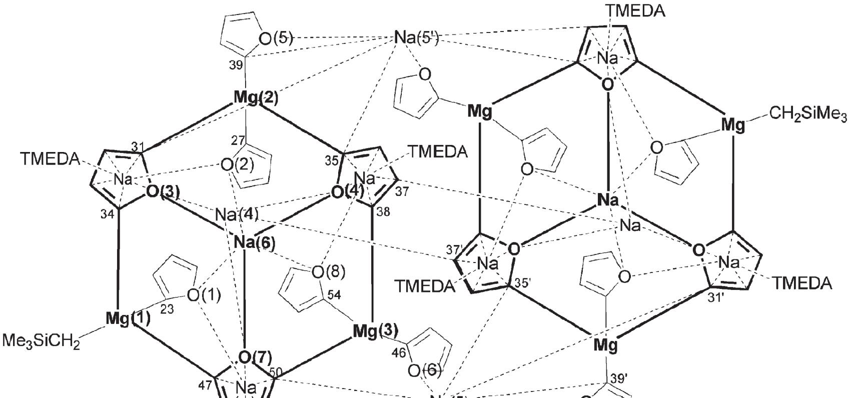

Fig. 2 ChemDraw representation of **4** showing atom labelling scheme.

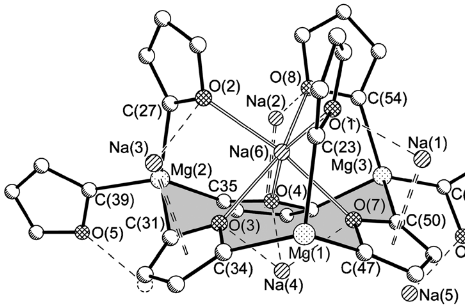

Fig. 3 Monomeric unit of **4** with hydrogen atoms, TMEDA, CH_2SiMe_3 and disordered groups omitted for clarity. The $(MgCOC)_3$ ring is shaded. Mg1–C23 2.271(4), Mg1–C34 2.214(4), Mg1–C47 2.203(3), Mg2–C27 2.185(3), Mg2–C31 2.215(3), Mg2–C35 2.201(4), Mg2–C39 2.157(4), Mg3–C38 2.237(4), Mg3–C46 2.149(6), Mg3–C50 2.186(3), Mg3–C54 2.202(3), Na1–O1 2.455(2), Na1–CT 2.469, Na2–O8 2.440(2), Na2–CT 2.496, Na3–O2 2.479(3), Na3–CT 2.484, Na4–O3 2.343(2), Na4–O4 2.470(2), Na4–O7 2.349(3), Na5–O5′ 2.341(4), Na5–O6 2.319(5), Na6–O1 2.364(2), Na6–O2 2.410(2), Na6–O3 2.440(2), Na6–O4 2.622(2), Na6–O7 2.466(2), Na6–O8 2.397(2) Å; CT = Centroid.

sharp/broad distinction of these aromatic resonances in **4** implies a greater mobility of OC_4H_3 monoanions *versus* OC_4H_2 dianions, which fits with the latter being held firmly on two sides by short, strong Mg–C bonds as opposed to only one Mg–C bond for the former. In d_6-benzene solution, the ^1H NMR spectrum of **4** is significantly more complicated with a plethora of resonances in the aromatic region. It is likely that the structure of **4** is retained in the weakly coordinating arene solvent, but broken down, at least partially, in strongly coordinating THF. A probable scenario is that THF ligation replaces the intermolecular contacts (and TMEDA ligands) to de-aggregate dimeric **4** to the monomer "$[(THF)_xNa_6Mg_3(CH_2SiMe_3)(2,5\text{-}C_4H_2O)_3(2\text{-}C_4H_3O)_5]$". A good indicator that **4** retains a high nuclearity in THF solution comes from its resistance towards electrophilic interception. Preliminary quenches with I_2 or Me_3SiCl show essentially no reaction. An interesting philosophical point is that were such quenches successful, a mixture of mono- and di-substituted furans would be produced, from which it would be assumed that magnesiation of furan yields a mixture of 2-magnesio and 2,5-dimagnesio intermediates, when in fact, both entities exist within the *same* intermediate.

With no apparent future in molecular furan functionalisation chemistry, **4** and related high nuclearity metallofurans may attract more interest as potential building blocks for supramolecular systems.[14] In that regard, it is noteworthy that the central motif of **4** closely resembles that of a subporphyrin,[15] a class of synthetic macrocycle exhibiting non-planar aromaticity of topical interest in the supramolecular arena. As the comparison in Fig. 4 shows, the Mg bridges and O heteroatoms of the former mimic the CH bridges and N heteroatoms in the latter, with both having a Lewis acidic atom in the central trigonal cavity.

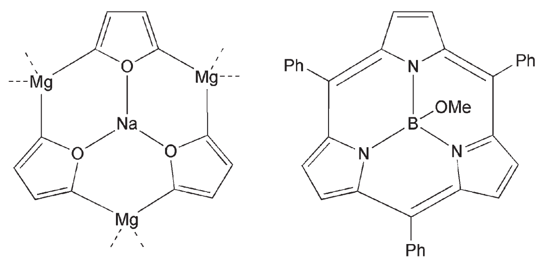

Fig. 4 Comparison of the central motif of **4** and a subporphyrin.

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Notes and references

‡ Crystal data for **3**: $C_{28}H_{63}Mg_1N_4Na_1Si_1$, M_r = 531.21, orthorhombic, space group $Pna2_1$, a = 14.8470(2), b = 19.3771(3), c = 12.0280(4) Å, V = 3460.34(14) Å^3, Z = 4, λ = 0.71073 Å, μ = 0.119 mm^{-1}, T = 123 K; 7665 reflections, final refinement to convergence on F^2 gave R = 0.0495 (F, 6037 obs. data only) and R_w = 0.1210 (F^2, all data), GOF = 1.048. The bridging TMP ligand was modelled as disordered over two sites using SADI and SAME restraints. CCDC 695312.

§ Crystal data for **4**: $C_{108}H_{160}Mg_6N_{12}Na_{12}O_{16}Si_2$, M_r = 2360.40, triclinic, space group $P\bar{1}$, a = 15.5127(6), b = 16.7993(7), c = 17.7608(8) Å, α = 61.930(5), β = 73.749(4), γ = 63.757(4)°, V = 3648.0(3) Å^3, Z = 1, λ = 0.71073 Å, μ = 0.140 mm^{-1}, T = 123 K; 21 042 reflections, 12 205 unique, R_{int} 0.0234; final refinement to convergence on F^2 gave R = 0.0565 (F, 7447 obs. data only) and R_w = 0.1662 (F^2, all data), GOF = 0.969. One TMEDA, two furans and a Na atom are modelled as disordered, each over two sites. CCDC 695313.

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