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Tandem Mn-I exchange and homocoupling processes mediated by a synergistically operative lithium manganate

Marina Uzelac,^{*[a]} Pasquale Mastropierro,^[b] Marco de Tullio,^[c] Ivana Borilovic,^[d,e] Marius Tarres,^[c] Alan R. Kennedy,^[c] Guillem Aromí^[d,f] and Eva Hevia^{*[b,c]}

Dedicated to the memory of Professor Gerard Cahiez, a true pioneer on organomanganese chemistry

- [a] Dr M. Uzelac
EastCHEM School of Chemistry, University of Edinburgh,
Edinburgh EH9 3FJ, United Kingdom
- [b] Dr M. de Tullio, Dr M. Tarres, Dr A. R. Kennedy,
WestCHEM, Department of Pure and Applied Chemistry
University of Strathclyde
295 Cathedral Street, G1 1XL, Glasgow, UK
- [c] P. Mastropierro, Prof. E. Hevia
Department für Chemie und Biochemie, Universität Bern
CH3012, Bern, Switzerland
E-mail: eva.hevia@dcb.unibe.ch
- [d] Dr I. Borilovic, Prof G. Aromí
Departament de Química Inorgànica
Universitat de Barcelona
Diagonal 645, 08028 Barcelona, Spain
- [e] Dr I. Borilovic
Department of Chemistry
University of Manchester and Photon Science Institute,
Oxford Road, Manchester, M13 9PL, UK
- [f] Prof G. Aromí
Institute of Nanoscience and Nanotechnology
of the University of Barcelona (IN2UB)

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Abstract: Pairing lithium and manganese(II) to form lithium manganate $[\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4]$ (**2b**) enables the efficient direct Mn-I exchange of aryl iodides, affording (aryl)lithium manganate intermediates which in turn undergo spontaneous C-C homocoupling at room temperature to furnish a range of symmetrical (bis)aryl species in good yields under mild reaction conditions. EPR and X-ray crystallography have revealed the mixed Li/Mn nature of the organometallic intermediates involved in these reactions, while the homocoupling step was thought to occur via single-metal Mn aryl species. These studies have illuminated how Li and Mn work together to facilitate both the Mn-I exchange and C-C the bond forming steps. Both steps are subtlety synchronised, with the alkyl iodide $\text{ICH}_2\text{SiMe}_3$ concomitantly generated during the Mn-I exchange, being essential to enable the aryl homocoupling process by acting as an external oxidant.

Introduction

Metal-halogen exchange constitutes one of the most powerful and widely used methods for regioselective functionalization of aromatic halides. Represented usually as an equilibrium, these kinetic processes are driven by the formation of the more stabilised aryl organometallic intermediates.^[1] For decades this methodology has been essentially the exclusive domain of the classical highly polar organometallic reagents organolithium RLi or Grignard reagents RMgX. However more recent reports have shown that pairing a lower polarity metal M such as Zn, La, Sm or Ce with Li, can also promote low polarity metal-halogen exchange

to access M-aryl intermediates that can in turn be employed in C-C bond forming processes, usually with the aid of transition metal catalysis.^[2] While Mn(II) organometallic compounds have shown considerable promise in organic synthesis, with seminal contributions from Cahiez and Normant on their applications in acylation, addition and other C-C bond forming processes,^[3] their ability to promote Mn-halogen exchange with aromatic halides has not yet been established. This is somehow surprising considering the comparable electronegativities and sizes of Mg(II) and Mn(II) as well as the reactivity patterns mentioned above for which these high-spin Mn(II) reagents have been previously described as soft Grignard reagents.^[4] Earlier work by Oshima^[5] and Hosomi^[6] has shown that lithium manganates can undergo metal-halogen exchange with allyl bromides and other activated substrates such as *gem*-dibromocyclopropanes although the constitutions of the organometallic intermediates and the exchange reagent have remained concealed.

In parallel to these studies, seminal work by Cahiez has shown that Mn(II) salts such as $\text{MnCl}_2 \cdot 2\text{LiCl}$ can catalyse the homocoupling of aryl Grignard reagents using atmospheric oxygen,^{[4],[7]} providing a sustainable route to access synthetically relevant symmetrical bis(aryl) molecules.^[8] More recent work by Tailler has also proposed that *in situ* generated ArLi species can undergo homocoupling in the presence of catalytic amounts of MnCl_2 .^[9] Supported by computational studies,^{[9],[10]} these reactions have been proposed to occur via the formation of MnAr_2 intermediate species which in turn can undergo oxidative homocoupling in the presence of oxygen. However limited tangible experimental evidence is available on the actual

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formation of these compounds which are proposed to be generated by salt-metathesis in the presence of a large excess of the polar organometallic aryl reagent.

Merging these two fundamental types of transformations, here we describe the first examples of direct Mn-halogen exchange reactions of aryl iodides based on aryl manganate species that in turn can undergo oxidative homocoupling to access synthetically valuable symmetrical bis(aryl) compounds in good yields. In addition, structural and spectroscopic studies on the organometallic intermediates involved in this tandem protocol uncover some of the *hitherto* unknown constitution of the intermediates involved in these reactions.

Results and Discussion

Assessing Mn-I exchange with iodoarenes. Considering that an important limitation to the stability of alkylmanganese compounds is their tendency to undergo β -hydride elimination,^[11] we started our studies probing the reactivity of 4-iodoanisole (**1a**) with MnR_2 ($\text{R} = \text{CH}_2\text{SiMe}_3$).^[12] Containing bulky monosilyl substituents with no protons in the β -position, this bis(alkyl) Mn(II) species has previously been used as a precursor to access sodium and potassium manganates and has shown remarkable thermal stability.^[13] Our reactions were initially carried out at -78 °C in THF (Table 1).^[14]

Table 1. Optimization of the reaction conditions for the I/Mn exchange using manganese reagents containing CH_2SiMe_3 ligands

| Entry | n | MR_x | Yield ^[a] |
|-------|------|--|--------------------------------------|
| 1 | 1 | $\text{Mn}(\text{CH}_2\text{SiMe}_3)_2$ | 0 ^[b] |
| 2 | 1 | $\text{LiCH}_2\text{SiMe}_3$ | 62 |
| 3 | 1 | $\text{LiMn}(\text{CH}_2\text{SiMe}_3)_3$ (2a) | 56 ^[c] |
| 4 | 1 | $\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4$ (2b) | 95 |
| 5 | 0.25 | $\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4$ (2b) | 86 |
| 6 | 0.33 | $\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4$ (2b) | 94 |
| 7 | 0.33 | $\text{Li}_2\text{Mg}(\text{CH}_2\text{SiMe}_3)_4$ | 82 |
| 8 | 0.33 | 4 eq $\text{Me}_3\text{SiCH}_2\text{MgCl} + \text{MnCl}_2$ | 0 ^[c] (18) ^[d] |
| 9 | 0.33 | 4 eq $\text{Me}_3\text{SiCH}_2\text{MgCl} + \text{MnCl}_2 \cdot 2\text{LiCl}$ | 0 ^[c] (83) ^[d] |
| 10 | 0.33 | $\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4$ (2b) + 2 eq TMEDA | 93 |
| 11 | 0.33 | $\text{Li}_2\text{Mn}(\text{CH}_2\text{SiMe}_3)_4$ (2b) + 4 eq 12-c-4 | 0 |

[a] Yields have been determined by GC analysis of reaction aliquots after an aqueous quench using hexamethylbenzene as internal standard. Formation only of anisole and unreacted **1a** were observed. [b] 20 °C. [c] -20 °C. [d] if the reaction is allowed to stir at room temperature for 5h, only homocoupled product **3a** is detected along with starting material **1a**.

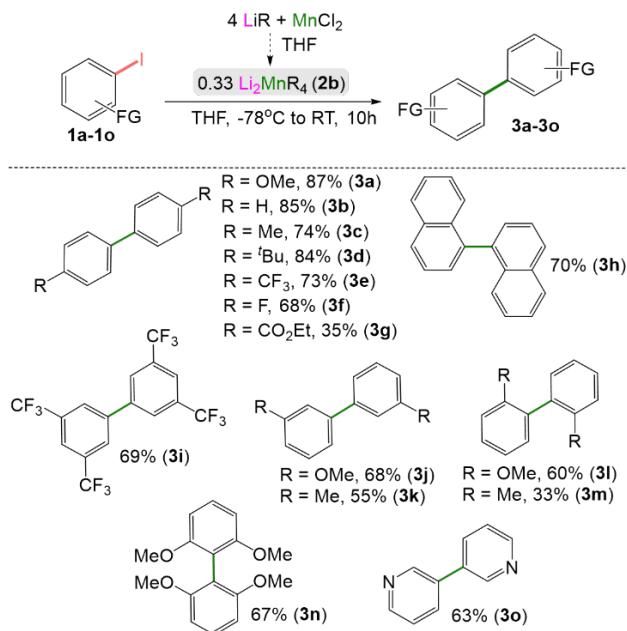
Under these conditions homometallic MnR_2 failed to promote Mn-I exchange of **1a** even when the temperature was increased to 20 °C (entry 1). Building on previous work in s-block organometallic chemistry which has shown that ate activation can enable effective Mg- and Zn-halogen exchange reactions,^[15] we

next reacted equimolar amounts of **1a** with triorganomanganate LiMnR_3 (**2a**) (prepared *in situ* by reaction of 3 equivalents of LiR and MnCl_2) leading to a 53% conversion after 15 min at -20 °C (entry 3). This conversion could then be enhanced almost quantitatively when using *in-situ* prepared lithium-rich manganate Li_2MnR_4 (**2b**) (95%, entry 4) even at -78 °C. Furthermore, the exchange also works using substoichiometric amounts of **2b** showing conversions of 86 and 94% when 0.25 and 0.33 equivalents of **2b** were employed respectively, supporting the view that the four alkyl groups present in **2b** engage in the exchange, making the process atom economical (entries 5 and 6). Significantly, it is noteworthy that under the conditions of the study these conversions were higher than using LiR on its own (entry 2) or using the magnesium analog of **2b**, Li_2MgR_4 (entry 7) revealing that under these reaction conditions Mn-I exchange occurs more effectively than Li-I or Mg-I exchange.

Since **2b** is prepared *in situ* by salt metathesis with MnCl_2 , we next pondered if this approach could also work using 4 equivalents of the Grignard reagent RMgCl as a precursor. Surprisingly, no exchange was observed at lower temperatures (from -78 to -20 °C) while allowing the reaction mixture to stir at room temperature for 5 h showed a modest 18% conversion (entry 8). The latter can then be boosted to 83% when adding 2 equivalents of LiCl, hinting at a crucial role for Li to facilitate this transformation (entry 9). Further evidence was found when assessing the influence of Lewis donors as additives when combined with **2b**. While bidentate TMEDA (*N,N,N',N'*-tetramethylethylenediamine) showed no observable effect, 12-crown-4 which has the ability to coordinate and sequester the lithium cations, completely shuts down the exchange process, suggesting that the cooperation and/or close proximity between Li and Mn may also be a key factor (entries 10 and 11).

Allowing the reaction of **1a** with 0.33 equivalents of **2b** to reach room temperature and to stir for a further 5h formed bis(aryl) 4,4'-dimethoxybiphenyl (**3a**) in 87% isolated yield, indicating that as the temperature is raised, in addition to the Mn-I exchange, a C-C bond forming homocoupling process occurs (Scheme 1). This approach can be also extended to a range of substituted aromatic iodides, bearing electron-donating or electron-withdrawing groups, affording the relevant symmetric bis(aryls) **3a-3o** in good to excellent yields (33-87% yields, Scheme 1).

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Scheme 1. Reaction of various iodoarenes with Li_2MnR_4 (**2b**) prepared in situ by addition of LiR to MnCl_2 in a 4:1 ratio in THF.

Steric effects seem to play a detrimental role as indicated by the contrasting yields obtained when using different iodotoluene substrates. Thus, **3c** with the methyl group located at the C4 position is obtained in 74% yield, whereas a modest 33% is reached for **3m** when starting with 2-iodotoluene. The same trend is observed for the homocoupled anisole derivatives **3a**, **3j**, and **3l** (87, 68, and 60% yield respectively); whereas no reaction is observed at all when 2-iodomesitylene was employed. This method is also compatible with electron withdrawing groups such as CF_3 or F furnishing bis(aryls) **3e**, **3f** and **3i** in 73, 68, and 69% yields, respectively, although in the case of **3g** containing a CO_2Et substituent a significantly lower yield was observed (30%). Interestingly, **2b** also reacts with 3-iodopyridine (**1o**) affording homocoupled product **3o** (63%), along with 3-silylpyridine **3o'**. The latter is a minor product (20%) resulting from the coupling between the $\text{C}(\text{sp}^2)$ atom of the substrate and the $\text{C}(\text{sp}^3)$ center of a CH_2SiMe_3 group (see Supporting Information for details).

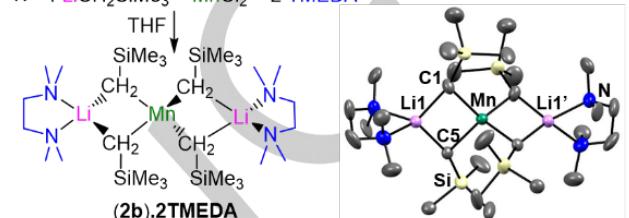
Prompted by these intriguing observations we next set out to identify the constitution of bimetallic intermediates formed in these mixtures. Lithium manganate **2b·2TMEDA** could be isolated as a crystalline solid in two different ways: co-complexation of 2 equivalents of LiR and TMEDA with MnR_2 in hexane or by salt metathesis using a 4:1 mixture of LiR and MnCl_2 in THF in the presence of 2 equivalents of TMEDA (Figure 1i). It should be noted that while the synthesis and EPR characterisation of **2b** has been reported by Wilkinson in a seminal paper from 1976,^[12a] its structure in the solid state has remained concealed.

X-ray crystallographic studies confirmed the bimetallic constitution of **2b·2TMEDA**, exhibiting the same classical “Weiss motif” previously reported for its Mg analogue $[(\text{TMEDA})_2\text{Li}_2\text{MgR}_4]$,^[16] with a C4-coordinated Mn atoms flanked by two TMEDA-solvated Li cations, displaying a nearly linear $\text{Li}\cdots\text{Mn}\cdots\text{Li}$ arrangement [176.082(2) $^\circ$] with each alkyl group bridging Mn with a Li centre (Figure 1i) with an average Mn-C distance of 2.275 Å. These structural features are typical of high-

spin Mn(II) and this magnetic state was confirmed by SQUID magnetometry and EPR spectroscopy (Fig S1-S3 in Supporting Information). **2b·2TMEDA** is also isostructural with a series of lithium manganates reported by Girolami^[17] containing Me, Et or $\text{CH}_2\text{CH}_2\text{Bu}$ alkyl groups although as far as we can ascertain the reactivity of these compounds has barely been studied.

By contrast, underscoring the complexity of these metathetical processes, when 4 equivalents of RMgCl are treated with MnCl_2 in THF, heteroleptic mixed-metal $[(\text{THF})_4\text{MgCl}_2\text{MnR}_2]$ (**4**) was obtained as a crystalline solid along with variable amounts of the adduct $[(\text{THF})_2\text{MgCl}_2]$ (Figure 1ii).

(i) 4 $\text{LiCH}_2\text{SiMe}_3$ + MnCl_2 + 2 TMEDA



(ii) 4 $\text{CIMgCH}_2\text{SiMe}_3$ + MnCl_2

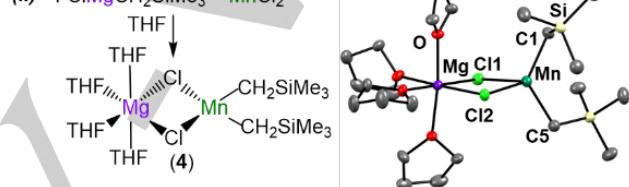


Figure 1. Salt-metathesis reactions of MnCl_2 with (i) 4 eq of $\text{LiCH}_2\text{SiMe}_3$ and 2 eq TMEDA and (ii) with 4 eq of $\text{CIMgCH}_2\text{SiMe}_3$ to give **2b·2TMEDA** and **4** respectively. Molecular structure of **2b·2TMEDA** and **4** with thermal ellipsoids drawn at the 50% probability level, all hydrogen atoms omitted for clarity. In **2b·2TMEDA** minor disorder components in TMEDA ligand and SiMe_3 group have been omitted. Symmetry operator: x-, y+1, -z+2. The unit cell of **4** contains two crystallographically independent molecules with identical connectivity, only one is shown here.

Established by X-ray crystallography, the molecular structure of **4** (Figure 1ii) displays Mn and Mg connected by two Cl bridges with Mn completing its distorted tetrahedral geometry with two terminal monosilyl groups. Instead, Mg is solvated by four molecules of THF giving rise to a distorted octahedral environment. Thus, compound **4** can be envisaged as a co-complex between MgCl_2 and MnR_2 .^[18] The contrasting constitutions of **2b·2TMEDA** and **4** when both are prepared by reacting 4 equivalents of either RLi or RMgCl with MnCl_2 can help explain their different reactivity towards Mn-I exchange (Table 1, entries 8 and 10); **2b·2TMEDA** having a Mn centre attached to four alkyl groups can be expected to be significantly more reactive than **4**, which possesses two such anions. Consistent with this, previous work in s-block bimetallic chemistry has shown the excellent ability of lithium tri- and tetra-alkyl magnesiates and zincates to promote direct metal-halogen exchange.^[15]

Manganate-mediated aryl-aryl oxidative homocouplings. Germane to the formation of bis(aryls) **3a-3o**, work on Mn(II)-catalysed homocoupling of ArM (M= Li, MgX) has shown that atmospheric oxygen is required in order to facilitate the $\text{Csp}^2\cdots\text{Csp}^2$ bond forming process.^{[7], [9], [10]} Since our experiments were carried out under strict inert atmosphere conditions, it should then be the alkyl iodide $\text{Me}_3\text{SiCH}_2\text{I}$ concomitantly generated during the Mn-I exchange process which acts as an oxidant *in situ*.

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generated lithium aryl manganates Li_2MnAr_4 (**I**), facilitating the homocoupling process (Figure 2*i*). Previous work by Zhou has also shown that MnCl_2 can catalyse homocoupling of Grignard reagents using dichloroethane (DCE) as an external oxidant.^[19] Interestingly in our case, the C-C bond forming step seems to occur very quickly as soon as the temperature raises from -78 °C to RT, thus all attempts to trap and characterize intermediate **I** led to the isolation of the relevant homocoupling product as well as to variable amounts of LiI , which in the presence of TMEDA crystallises as $\{(\text{TMEDA})\text{LiI}\}_2$.

Aiming to advance the understanding of the homocoupling process we next attempted to prepare Li_2MnAr_4 (**I**) via an indirect route using a salt-metathesis approach in order to probe its reactivity towards $\text{ICH}_2\text{SiMe}_3$. Reacting 4 equivalents of aryl lithium $\text{Li}(2\text{-OMe-C}_6\text{H}_4)$ with MnCl_2 in diethyl ether produced pale orange crystals of $[\text{Li}_2\text{Mn}(2\text{-OMe-C}_6\text{H}_4)_4(\text{OEt}_2)]$ (**5**) (Figure 2*ii*). This compound exhibits a contacted ion pair manganate structure in which distorted tetrahedral Mn is bonded to four *ortho*-metallated molecules of anisole by short (strong) bonds [average Mn-C distance: 2.111 Å]. Each lithium has a different coordination environment. Li1 binds to the O donors of three OMe substituents from the aryl fragments, whereas Li2 coordinates to the remaining OMe group as well as to the *ortho*-C's of two other aryls. The corresponding C-Li-C plane is perpendicular with respect to the concerned aromatic rings. The distinct bonding modes of the Li atoms must contribute towards the marked nonlinearity of the Li···Mn···Li vector [91.09(15)°] which contrasts with the nearly linear arrangement found in **2b**-**2TMEDA** (Li···Mn···Li, 176.082(2)°, Figure 1*i*) and other related lithium manganates.^[17]

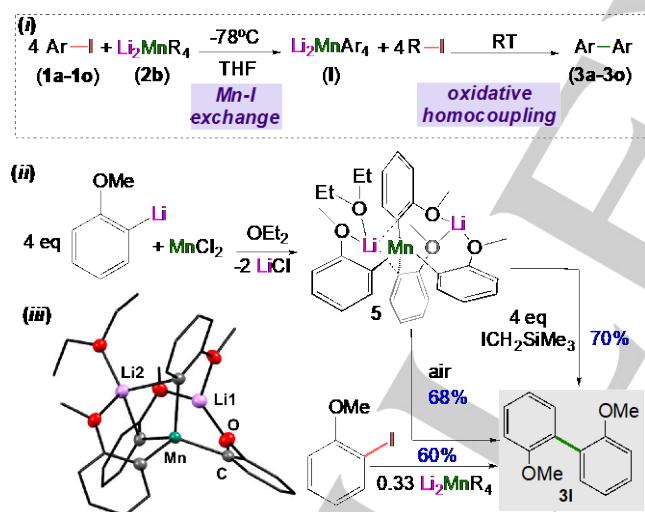


Figure 2. (i) Proposed ate-mediated reaction sequence for the formation of symmetrical bis(aryl) **3a-3o** from iodoarenes **1a-1o**; (ii) indirect synthesis of **5** via salt-metathesis and formation of **3l**; and (iii) molecular structure of **5** with thermal ellipsoids drawn at the 50% probability level. All hydrogen atoms omitted and all but contact atoms shown wireframe for clarity.

Interestingly, while **5** is stable at room temperature in solution under inert atmosphere conditions, it rapidly proceeds to form bis(aryl) **3l** when reacted with $\text{ICH}_2\text{SiMe}_3$ or by being exposed to air. The yields observed for **3l** (70 and 68% respectively) are comparable with those seen when **2b** is reacted with 2-iodoanisole (Scheme 1). Furthermore, the EPR spectrum of **5** in THF at 80K is identical to that observed for a mixture of **2b** and 4 equivalents of 2-iodoanisole at 80K (see Fig Sx), offering further

credence to the view that **5** is an intermediate in the homocoupling processes.

In previous MnCl_2 -catalysed homocoupling studies of ArLi and ArMgX under air, it has been proposed that reactions take place via a Mn(IV) bis(aryl)oxo complex where the O_2 is η^2 -bonded to Mn.^{[7],[9],[10]} However, taking into account that the polar aryl reagent ArM ($\text{M} = \text{Li, MgX}$) is present in a large excess in comparison to the MnCl_2 catalyst (10-20 mol%), we ponder whether a more accurate scenario may involve lithium (or magnesium) manganate intermediates. In an attempt to further understand the fate of Mn during the homocoupling process when atmospheric oxygen is used as an oxidant, an *in-situ* prepared solution of **5** was exposed to dry air for 15 min at -78 °C using a drying tube charged with oven-dried CaCl_2 . This led to the isolation of unusual bimetallic clusters $[(\text{THF})\text{Li}_4\text{Mn}_2\text{Ar}_6(\mu_6\text{-O})]$ (**6**) and $[(\text{THF})_4\text{Li}_4\text{Mn}_2\text{Ar}_4\text{Cl}_2(\mu_4\text{-O}_2)]$ (**7**) (Figure 3) containing reduced oxide anions which co-crystallised with variable amounts of homocoupling product bis(aryl) **3l**.

Though both **6** and **7** are dimers, Mn in **6** exhibits the +2 oxidation state, while in **7** the oxidation state is +3. In **6** μ_6 -oxide is trapped in the core of a dicationic $\{\text{Li}_4\text{Mn}_2\text{Ar}_6\}^{2+}$ cage where the metals are connected by ambidentate 2-anisoly ligands that bind to Mn exclusively via their C atoms and to Li by a combination of Li-O and Li-C bonds (Figure 3, LHS). The central μ_6 -oxide exhibits a distorted octahedral geometry with the two tetrahedrally coordinated Mn atoms occupying the axial positions [mean Mn-O, 2.072 Å; Mn-O-Mn, 175.7(2)°]; whereas the equatorial positions are filled by the four Li atoms [mean Li-O, 1.91 Å; sum of LiOLi angles, 360.2°].

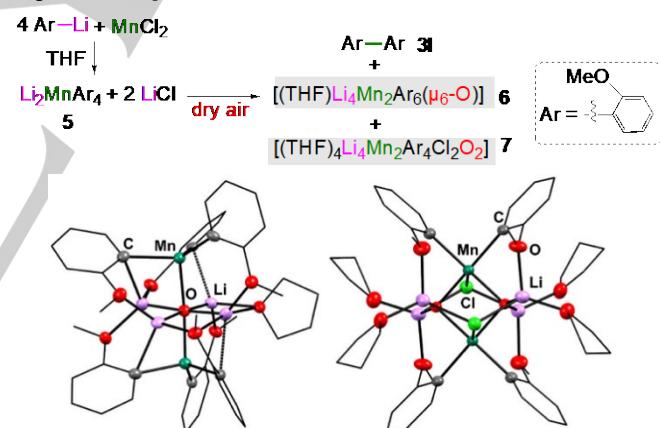


Figure 3. Formation of oxygen insertion products **6** and **7** and their molecular structures with thermal ellipsoids drawn at the 50% probability level. All hydrogen atoms omitted and aromatic and THF rings shown wireframe for clarity. Co-crystallised molecule of THF in both **6** and **7** and minor disorder components in THF ligands in **7** have been omitted for clarity.

In contrast, **7** incorporates LiCl in its constitution (present in the reaction media as co-product of the synthesis of the Li_2MnAr_4 precursor) (Figure 3, RHS). It comprises two antiferromagnetically coupled Mn(III) centres connected/bridged by two oxo and two chloride anions. In addition, 4 anisoly ligands coordinate through their *ortho* C and the O of the OMe group to Mn and Li, respectively (Fig S4 in Supporting Information). Each Li atom present in the structure completes its coordination sphere by bonding to a THF molecule. As far as we can ascertain **6** and **7** constitute the first structurally defined potential intermediates of Mn(II) mediated homocoupling processes in the presence of air,

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providing the first insights into the possible fate of Mn during these transformations. Furthermore, their bimetallic composition and the structure of **5** support that, unlike previously proposed,^{[7],[9],[10]} manganate intermediates generated by salt-metathesis may better represent the active species involved in catalytic reactions of ArM (M= Li, MgX) with substoichiometric amounts of MnCl₂. Furthermore, even under stoichiometric conditions, when treating two equivalents of PhMgCl with MnCl₂ in THF the mixed-metal complex [(THF)₄MgCl₂MnPh₂] (**8**) was isolated in 51% yield (Figure 4).

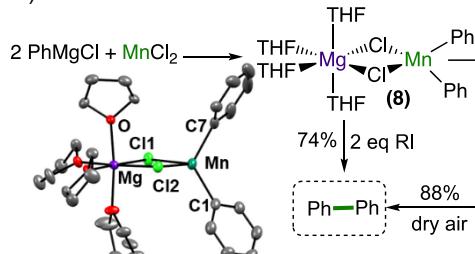
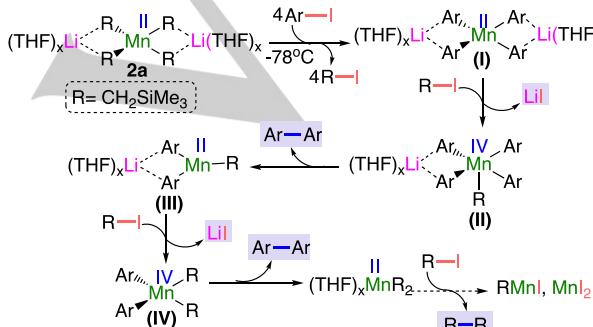


Figure 4. Salt-metathesis reaction of MnCl₂ with 2 eq of PhMgCl to give **8** and homocoupling reactions to give biphenyl. Molecular structure of **8** with thermal ellipsoids drawn at 50% probability level. All hydrogen atoms and minor disorder component in one of THF ligands are omitted for clarity.

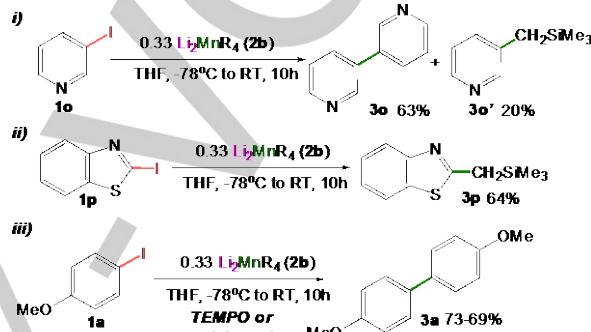
Crystallographic characterisation of **8** revealed a structure almost identical to that of **4** (*vide supra*), when replacing the CH₂SiMe₃ alkyls by Ph groups, showing that complexation of (THF)₄MgCl₂ to MnR₂ reagents is likely to be a general trend. Compound **8** can be envisaged as a dianionic manganate with a tetrahedral Mn(II) centre formally bonded to four anionic ligands (2Cl, 2 Ph). Interestingly, exposure of mixed Mg/Mn complex **8** to air or reaction with two equivalents of RI led to the formation of biphenyl in 88 and 74% respectively (Figure 4, see Supporting Information for details).

Regarding previously proposed mechanisms for the homocoupling of aryls using an alkylhalide as an external oxidant, Zhou's initial reports for DCE-driven Mn-catalysed homocoupling of ArMgX tentatively proposed the involvement of MnAr₂ species undergoing reductive elimination to furnish the relevant bis(aryl) and a Mn(0) reactive intermediate that can react in turn with DCE to regenerate MnCl₂.^[19] However, more recently Valyaev and Lugan have suggested an alternative mechanism via a Mn(II)/Mn(IV) redox manifold, with the initial formation of a tris(aryl) magnesium manganate. The latter can react with DCE to form an unstable Mn(IV) intermediate, which subsequently could undergo reductive elimination to give the homocoupling product and MnAr₂ that via co-complexation with the excess of ArMgCl can regenerate the reactive manganate species.^[3] A similar mechanism could be envisaged for our stoichiometric studies with the initial formation of [Li₂MnAr₄] (**I**) followed by a sequence of oxidative addition/reductive elimination steps (Scheme 2) involving Mn(II)/Mn(IV) species with concomitant elimination of LiI, along with Me₃SiCH₂CH₂SiMe₃ (whose formation could be detected by GC-MS spectrometry).



Scheme 2. Proposed mechanism for oxidative homocoupling of Li₂MnAr₄(I) driven by ICH₂SiMe₃ which is generated via Mn-I exchange of ArI (**1a-1o**) with **2b**.

This proposal could also explain the formation of 3-monosilylpyridine **3o'** as a side product when **2b** is reacted with 3-iodopyridine, resulting from heterocoupling of the pyridyl fragment with a monosilyl group. Interestingly if **2b** is reacted with 2-iodobenzothiazole, only the relevant heterocoupling product is obtained in a 64% yield (see SI for details) (Scheme 3i and 3ii).



Scheme 3. Reactivity studies of **2b** with (i) 3-iodopyridine (**1o**); and (ii) 2-iodobenzothiazole (**1p**). (iii) Homocoupling of **1a** in the presence of TEMPO.

While SET-dehalogenation reactions induced by magnesium manganates have been reported in the literature,^{[3],[5c][20]} this scenario seems to be unlikely here, as suggested by carrying the reaction of **1a** with **2b** in the presence of radical scavengers such as TEMPO or galvinoxyl, which allowed the isolation of bis(aryl) **3a** in yields comparable to those reported in Table 1 (Scheme 3iii). Finally, in order to gain further understanding on this tandem Mn-I exchange/C-C coupling process we monitored the reaction of **2b** and 2-idoanisole (**1l**) by X-band cw EPR at 80 K. Initial spectra of **2b** in a frozen THF solution confirm the presence of an axially anisotropic high-spin S=5/2 Mn(II) species ($D=0.20\text{ cm}^{-1}$, $E=0\text{ cm}^{-1}$), as seen previously for related tetraalkyl Mn(II) compounds reported by Girolami and Wilkinson (Fig 5, left, S7).^[12a, 17b] *In situ* addition of 2-idoanisole to **2b** at low temperature enables the formation of more rhombic Mn(II) species which can be confidently identified as compound **5** from the comparison of its EPR spectrum with that of a frozen solution of isolated crystals of **5** in THF ($D=0.18\text{ cm}^{-1}$, $E=0.042\text{ cm}^{-1}$, Fig 5 middle and Supporting Information). Thus, the Mn(II) oxidation state remains during the Mn-I exchange of all four alkyl groups. By allowing the *in situ* generated solution of **5** to warm up at room temperature new drastic modifications of EPR spectrum are detectable (Figs 5right-S12). This includes a significant decrease in intensity and the generation of a complex pattern which can be attributed to the mixture of an anisotropic mononuclear RMnI ($D=0.47\text{ cm}^{-1}$, $E=0.16\text{ cm}^{-1}$, Fig S8) and a MnI_x species (Fig S9-S10) and/or to heteroleptic Mn(II) iodide and alkyl oligomers. In the latter case, dominant antiferromagnetic interactions populate the S=0 ground state at low temperatures which causes the decrease of intensity.^[12b, 21] It should also be noted that the same changes in

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the EPR spectra are observed if 4 molar equivalents of RI are added at room temperature to a solution of isolated crystals of **5**.

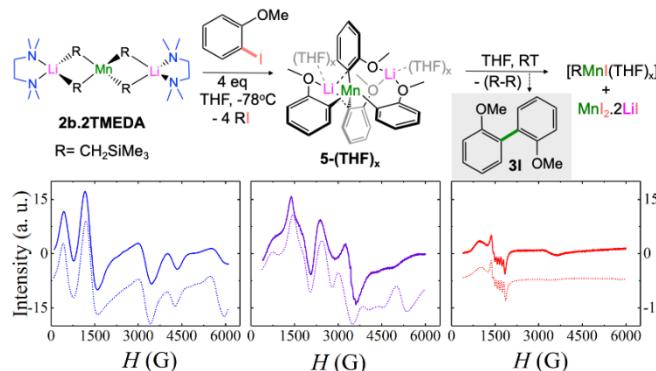


Figure 5. EPR monitoring (X-band, $f = 9.412$ GHz) of the reaction of **2b**·**2TMEDA** with four equivalents of 2-iodoanisole (**1I**) acquired in frozen THF solutions at 80 K (Full line in the EPR spectra represents experimental data while simulated spectra are shown using dashed line).

These findings were additionally corroborated by studying the reaction of **2b** and **2b**·**2TMEDA** with 3-iodopyridine (Figs S5-S6). Here, the initial addition of substrate at low temperature generates one broad isotropic resonance ($D=0.03\text{ cm}^{-1}$, $E=0\text{ cm}^{-1}$) centered at $g=2.00$ attributed to the $\text{Li}_2\text{Mn}^{\text{II}}\text{Ar}_4$ (**I**) species formed of nearly T_d symmetry, which precludes any possibility of SET-induced radical intermediates. By allowing the reaction mixture to reach room temperature, the homocoupling process occurs causing significant reduction of intensity of the EPR signals, giving rise to a poorly resolved rhombic spectrum originating from the previously identified alkyl and iodo Mn(II) final products. Further support to this interpretation and to the proposed mechanism was found when analyzing the mixture in the end reaction products by mass spectrometry (MALDI-TOF negative mode), which unveiled the presence of several LiI and Mn(II) iodide species, $\{\text{MnI}_3\}^-$ being the major species (Fig S13). The absence of any alkyl Mn(II) oligomers among the products is likely due to fragmentation and their sensitivity to air and moisture, as reported previously by Godfrey and McAuliffe. They indeed isolated $[\text{HNMe}_3][\text{MnI}_3(\text{NMe}_3)]$ from its parent diiodo compound, for which a dimeric structure is established in THF with various of amines.^[22] In addition, detection of Mn(III) species in the positive mode of MALDI-TOF hints the possibility of partial oxidation of the resulting Mn(II) products to their Mn(III) analogues at the expense of the reduction of the remaining RI species to the coupled R-R product, as detected by GC-MS.

Conclusion

A new Mn-mediated protocol to access symmetrical bis(arenes) has been uncovered, which relies on the synergistic partnership between Li and Mn(II). Higher order lithium manganate Li_2MnR_4 (**2b**) promotes direct Mn-I exchange reactions of aryl iodides, a type of reactivity typically considered the exclusive domain of polar RLi or RMgX reagents. These exchanges occur with an excellent atom economy, forming the relevant Li_2MnAr_4 intermediates that in the presence of RI (concomitantly generated in the Mn-I exchange) undergo oxidative homocoupling furnishing a range of symmetrical bis(aryl) compounds in excellent yields. Structural and magnetic insights on the constitution of the mixed

Li/Mn organometallic intermediates involved in these reactions revealed that the formation of contacted ion pair lithium manganates is not only key to promote the Mn-I exchange but also in favoring more effectively the Csp^2 - Csp^2 bond forming process.

These studies also advance our understanding on how Mn(II) aryl complexes promote homocoupling processes in the presence of atmospheric oxygen, a type of reactivity previously noted in the literature but for which the constitution of the organomanganese intermediates involved had *hitherto* proved elusive.

(Full experimental details and copies of NMR, EPR spectra and SQUID measurements are included in the Supporting Information.)

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Keywords: manganates • lithium • cooperative effects • metallation • homocoupling

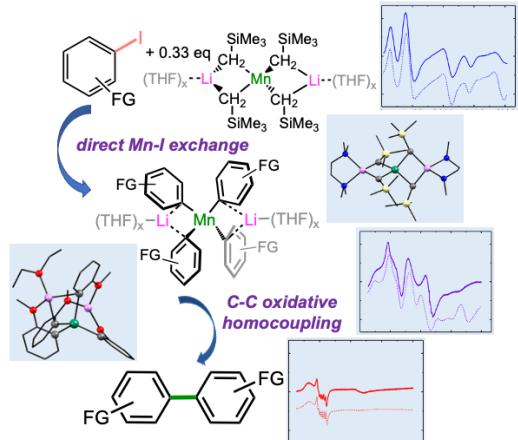
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Two steps at a time Exploiting chemical cooperative between Li and Mn(II), a series of symmetrical bis(aryls) has been prepared via a tandem protocol involving first a direct Mn-I exchange step followed by oxidative homocoupling C-C bond formation. Trapping of key reaction intermediates demonstrates the involvement of lithium manganate species, shedding light on Li and Mn work together to facilitate these transformations.

Institute and/or researcher Twitter usernames:@DCBunibern @EvaHaviaGroup @marina_uzelac @StrathChem