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Aerobic and Ligand-free Manganese-Catalyzed Homocoupling of Arenes or Aryl Halides via *in-situ* Formation of Aryllithiums

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ABSTRACT: Ligand-free manganese-catalyzed homocoupling of arenes or aryl halides can be carried out under aerobic conditions via the *in situ* formation of the corresponding aryllithiums. A wide range of biaryls and derivatives has been obtained and a mechanism involving monomeric manganese-oxo complexes has been proposed on the basis of DFT calculations.

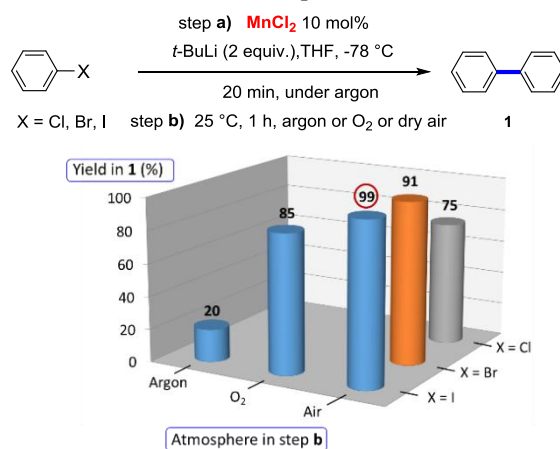
Manganese, a cheap, abundant and non-toxic transition metal, is an excellent alternative to precious metals for homogeneous catalysis and an ever increasing number of methods allowing the manganese catalyzed C-H, C-O, C-N, C-X or C-C bond formation has been reported over the last five years.¹ Among them, in a strive towards more sustainable processes, several reactions involving the combination of catalytic amounts of Mn salts and ambient air have been successfully developed, such as the hydroxyazidation of olefins,² the oxytrifluoromethylation of styrene derivatives,³ the cyclization of unsaturated oximes⁴ or the coupling of Grignard reagents.⁵ Mn-dioxygen complexes are also under strong investigation due to their role in biological photosynthetic processes.⁶ In this context we wondered whether air-sensitive aryllithium reagents could be employed under MnCl₂/O₂ conditions in order to provide a highly versatile and green entry to biaryls. The latter are found in numerous natural products, biologically active compounds, agrochemicals, commercial dyes, organic conductors and semi-conductors.⁷ Biaryls are usually obtained via transition metal catalyzed coupling reactions employing organometallic compounds⁷ including in some cases organolithium derivatives.⁸ In this field the most recent work dedicated to the synthesis of symmetrical biaryls has been reported with a catalytic system combining an aryl halide, *tert*-butyllithium and palladium associated with carbene type ligands.^{8k}

We herein present our preliminary results on the ligand-free MnCl₂/O₂ catalyzed homocoupling of aryllithium derivatives *in-situ* generated from aryl halides or via activation of aromatic C-H bonds. The mechanism of this system, less costly and more favourable for toxicity issues than the methods based on palladium, has been investigated by ESI-MS and DFT calculations.

For the preliminary trials iodobenzene (X = I) and a simple and readily available manganese salt (MnCl₂; purity 99,998 %) were chosen as the model substrate and precatalyst, respectively (Figure 1). After addition of THF, the temperature of the

mixture, first maintained at -78 °C for the generation under argon of the phenyllithium with *t*-BuLi (step a), was then increased up to 25 °C and the reaction medium was stirred under argon for 1 hour (step b). Under these conditions, the expected biphenyl **1** was obtained but only with a 20 % yield.

Figure 1. Mn-catalyzed synthesis of biphenyl **1** from chloro-, bromo- or iodobenzene, in the presence of *t*-BuLi.^a



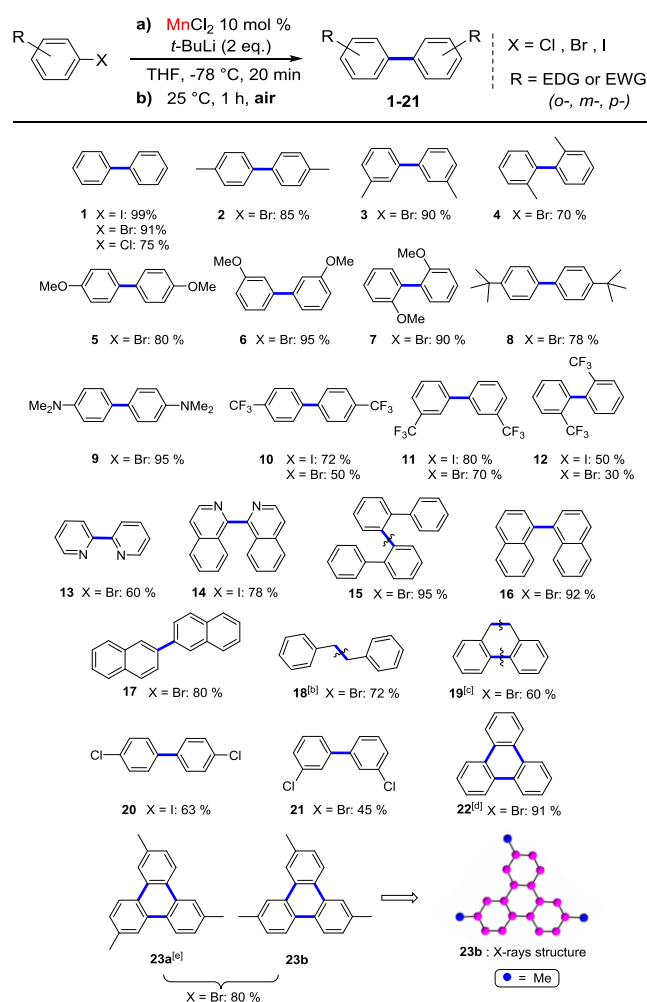
^a **Step a**) Ar-X (0.5 mmol), MnCl₂ (0.05 mmol, 99,998 %, Sigma Aldrich), *t*-BuLi (1.0 mmol), THF (2 mL), -78 °C, 20 min, under argon; **step b**) 25 °C, 1 h, argon, O₂ or dry air. ^b Yield determined by ¹H NMR using 1,3,5-trimethoxybenzene as internal standard.

The presence of one equivalent of a potential ligand (1,10-phenanthroline), or of a neutral Lewis base (TMEDA or trimethylamine) did not improve the system (see the Table S1 in SI). A very significant enhancement of the yield for **1** (85 %) was obtained when argon was exchanged by dioxygen (O₂) once the mixture reached 25 °C (step b). Finally, when step b was performed under atmospheric, dry air, we were pleased to observe the almost quantitative formation of biphenyl (99 %) and this was also the case starting from the less reactive bro-

mobenzene (X = Br: 91%). Remarkably, a good yield in bi-phenyl **1** (75 %) was achieved from the even more challenging chlorobenzene (X = Cl) (Figure 1). Solutions of *s*-BuLi or *n*-BuLi also provided biphenyl **1** in good yields but this was not the case with the other manganese salts we tested (see the Table S1 and Figure S1 in SI). Finally, complete absence of **1** was observed when blank experiments were carried out without manganese.

We next studied the substrate scope applying the optimized reaction conditions to various substrates with both electron-donating (EDG) and electron-withdrawing (EWG) groups on the aromatic ring (Table 1). With bromotolyl and bromoanisyl derivatives, the reaction was successfully performed to give the expected products **2-7** with good to excellent yields wherever the substituents (-Me and -OMe) were located (*ortho*-, *meta*-, *para*-position).

Table 1. Mn-catalyzed homocoupling of aryl- and benzylic halides in the presence of *t*-BuLi : synthesis of compounds 1-21 and triphenylene derivatives 22-23.^a

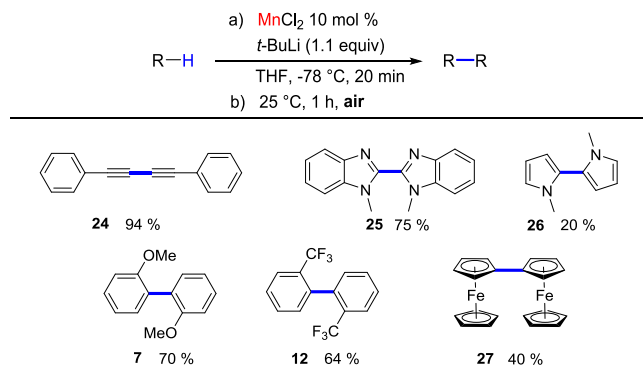


Isolated yields. ^a Reaction conditions: a) ArX (1.0 mmol), MnCl₂ (0.1 mmol, 99.998 %, Sigma Aldrich), *t*-BuLi (2.0 mmol), THF (4 mL), -78 °C, 20 min, under argon; b) 25 °C, 1 h, dry air. Starting material: ^b benzyl bromide; ^c 1-bromo-2-(bromomethyl)benzene; ^d *o*-chlorobromobenzene; ^e 3-bromo-4-chlorotoluene.

A high yield (78%) was obtained with *tert*-butyl in the *para* position to generate 4,4'-di-*tert*-butyl-1,1'-biphenyl **8** which is a direct precursor of Freeman's reagent⁹ and we succeeded in

scaling up to 10 mmol without decreasing the output. *N,N,N',N'*-tetramethyl-[1,1'-biphenyl]-4,4'-diamine **9** was also obtained almost quantitatively. We then attempted substrates with electron-withdrawing groups. Good yields were achieved from *p*- and *m*-trifluoromethyl bromobenzene (biphenyls **10**, **11**). When the trifluoromethyl group was in the *ortho*-position, only 30 % of the corresponding biaryl **12** was obtained. The reduction product and a small amount of corresponding phenol derivative were then also observed. Starting from the iodide derivative, for which the lithium-halide exchange rate is higher than the bromide derivative,¹⁰ led to an increase in the yields of **12** to 50 %. Two heteroaryl halides were successfully transformed to 2,2'-bipyridine and 1,1'-biisoquinoline (**13**, **14**), which are well known as ligands for transition metal complexes.¹¹ We then carried out the homocoupling reactions with larger substrates such as 2-bromo-1,1'-biphenyl, 1-bromonaphthalene and 2-bromonaphthalene and excellent yields were acquired (**15**, **16**, **17**). These products are common material precursors and are used to synthesize large size polycyclic aromatic compounds.¹² In addition, the reaction works well for benzyl bromide leading to 1,2-diphenyl ethane **18**. This offers an alternative approach to the known methods¹³ for the synthesis of 9,10-dihydrophenanthrene **19**, which we obtained via the double dimerization of 1-bromo-2-(bromomethyl)benzene. To extend again the application field of the method, we also performed some tests on polyhalobenzenes. The latter are promising substrates, as the resulting biaryls can be readily further functionalised. Starting from the *p*-chloriodobenzene and *m*-chlorobromobenzene, fair to good yields of expected 4,4'- and 3,3'-dichlorobiphenyl (**20**, **63** %; **21**, 45 %) were obtained. With the *o*-chlorobromo analogue we did not observe any homocoupling product but instead the polycyclic aromatic triphenylene **22** was obtained in 91 %. As triphenylene derivatives are attractive compounds in supramolecular and material fields,¹⁴ we then tested a methyl-substituted *o*-chlorobromobenzene and the corresponding two triphenylene isomers (**23a** and **23b**) were obtained with a 80 % yield and ratio 1/3. **23b** was recrystallized and its X-ray structure showed that the molecules are essentially planar and stacked in layers parallel to the plane (see Figures S2, S3 in SI). Within these planes they are arranged in chains connected by very weak van der Waals interactions between methyl moieties (Figure S4).

Table 2. Mn-catalyzed homocoupling of acetylene or arene via C-H activation.^a

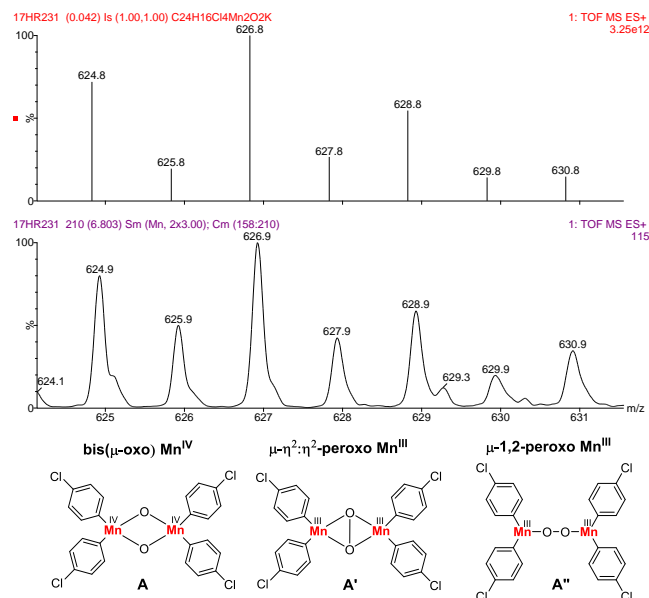


Isolated yields. ^a a) phenylacetylene or arene (1.0 mmol), MnCl₂ (0.1 mmol, 99.998 %, Sigma Aldrich), *t*-BuLi (1.1 mmol), THF (4 mL), -78 °C, 20 min, under argon; b) 25 °C, 1 h, dry air.

In further substrate scope studies, we succeeded in applying the catalytic system to acetylene or arene derivatives possessing an activated C-H bond (Table 2). We have thus performed the homocoupling reactions of phenylacetylene and of 1-methyl-1H-benzo[d]imidazole to give 1,4-diphenylbuta-1,3-diyne **24** and 1,1'-dimethyl-1H,1'H-2,2'-bibenzo[d]imidazole **25**, respectively, in very good yield. Starting from *N*-methylpyrrole, only poor yield of corresponding product **26** was obtained. However 2,2'-dimethoxy-1,1'-biphenyl **7** was synthesized directly from anisole via directed *ortho* metalation.¹⁵ It is worth noting that from trifluoromethylbenzene, for which the strong electron-withdrawing inductive effect of CF₃ promotes the formation of *ortho*-lithiated intermediate, 2,2'-ditrifluoromethyl-1,1'-biphenyl **12** was obtained in higher yields than starting from arylhalides.¹⁶ Interestingly, ferrocene **27**, investigated in the field of molecular electronics¹⁷ and usually gained through the use of haloferrocenes via an Ullmann coupling reaction,¹⁸ was synthesized using this catalytic system via C-H activation on the cyclopentadienyl ring.

To interpret the role of dioxygen, a key factor for the efficiency of this system in the homocoupling reactions, we monitored the reaction by electrospray ionization mass spectrometry (ESI-MS). Various aryl halides were tested and in order to detect more easily the potential formation of metal intermediates, a stoichiometric amount of MnCl₂ (50 mol%) was used. After exposure of the reaction mixture to air, the most interpretable spectrum was obtained when 1-chloro-4-iodobenzene was used as substrate due to the existence of isotopes of chlorine atom, which facilitates the identification of the intermediate compounds. In this case a peak at *m/z* = 624.8309 corresponding to an empirical formula C₂₄H₁₆Cl₄Mn₂O₂K was observed (Figure 2). It is worth noting that the experimental spectrum matches well with the theoretical one.

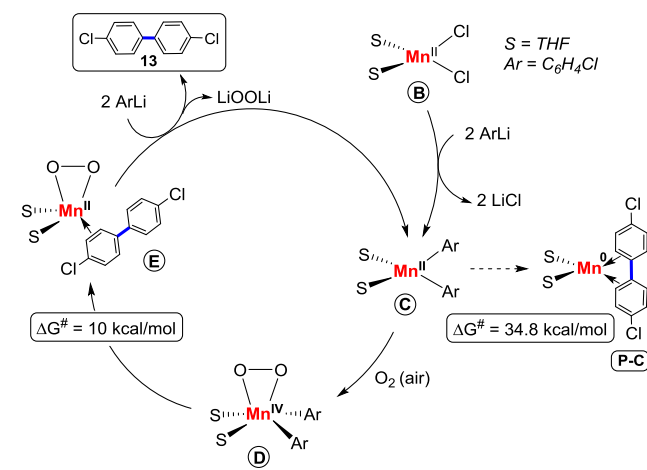
Figure 2. Theoretical (above) and observed (below) spectra of ESI-MS analysis of possible manganese dimers **A**, **A'** or **A''**.



The formula of this compound, that we could not detect under Mn-catalytic conditions, corresponds to either a bis(μ -oxo) manganese (IV) dimer **A**, or a μ - η^2 : η^2 -peroxo manganese (III) dimer **A'**, or a μ -1,2-peroxo manganese (III) dimer **A''** (Figure 2). If the existence of a structure as dimer **A'** has not been

proven yet, the related dimers **A** and **A''** have been already described with polydentate thiolate and nitrogen ligands.⁶ DFT(PBE-D3) calculations were then carried out on the dimer to elucidate the nature of the bonding pattern.¹⁹ Despite many attempts, no linear structure such as **A''** could be located on the potential energy surface. A symmetric structure, **Dimer-1**, similar to structure **A**, could be optimized as a singlet. The four Mn-O bond distances are identical (1.745 Å) and there is no significant bonding interaction between the two oxygen atoms (O...O = 2.560 Å) (see Figure S5 in the SI). A triplet geometry, **Dimer-2**, was located at $\Delta G = -6.4$ kcal mol⁻¹ with respect to **Dimer-1**. In the distorted triplet, the O...O distance is still too long (2.670 Å) to invoke any bonding interaction. The spin density (Figure S6 in the SI) is evenly shared between the two Mn atoms (1.077), and **Dimer-2** can be described as an oxo-bridged Mn^{IV}-Mn^{IV} dimer. Another triplet structure, **Dimer-3**, could be optimized at $\Delta G = -23.3$ kcal mol⁻¹ with respect to **Dimer-1**. This structure presents two different Mn centers, with one having two long Mn-O bond distances (2.028 Å) and the other having two short Mn-O bond distances (1.662 Å). The O...O distance is still too long (2.592 Å) to invoke any bonding interaction. The spin density (Figure S6) is not evenly shared between the two Mn atoms (4.076 vs. -1.621) and **Dimer-3** is best described as a Mn^{II} / Mn^{VI} dimer. The DFT calculations are thus indicating that the dimer observed in the ESI-MS experiment is most likely a formally Mn^{II} / Mn^{VI} structure without any direct O...O nor Mn...Mn interaction. However, attempts to locate transition state structures associated to C-C bond formation on any of the Mn centers in **Dimer-3** failed. Therefore calculations could not support that such dimeric structure is a competent catalyst for the biaryl formation.

Scheme 1. Proposed mechanism for biaryl formation as deduced from the DFT calculations.



DFT calculations were then carried out to probe the mechanistic hypothesis depicted in Scheme 1 based on the involvement of Mn monomeric species. *In situ* generated aryllithium would first react with MnCl₂ salt probably coordinated with the solvent (S = THF) to generate a catalytic amount of diarylmanganese(II) **C** intermediate.²⁰ From **C**, a transition state structure, **TS-C**, associated to C-C bond formation could be located with an activation barrier of $\Delta G^\ddagger = 34.8$ kcal mol⁻¹. This transformation is only slightly exergonic ($\Delta G = -1$ kcal mol⁻¹) and the product of the reaction, **P-C**, is a complex between the biaryl **13** and a Mn(0) fragment (Mn(THF)₂). The

value of the activation barrier is not compatible with a reaction time of 1 hour at room temperature. This is in perfect agreement with the lack of catalytic activity under inert atmosphere. However, DFT showed a more favourable route for which the oxidation of **C** in the presence of dioxygen leads to the exergonic ($\Delta G = -42.6 \text{ kcal mol}^{-1}$) formation of a η^2 -oxo manganese (IV) intermediate **D**.⁵ The activation barrier for C-C bond formation through **TS-D** on this oxidized manganese complex is significantly reduced with $\Delta G^\ddagger = 10.0 \text{ kcal mol}^{-1}$. The transformation is exergonic ($\Delta G = -12.6 \text{ kcal mol}^{-1}$) and the product **E** is a π -complex of the biaryl **13** on the Mn(II) oxo complex $\text{Mn}(\text{O}_2)(\text{THF})_2$. In the presence of two equivalents of aryl lithium, the biaryl would be expelled and the catalytic species **C** regenerated, releasing the lithium peroxide (Li_2O_2). The dimer observed in the ESI-MS experiment under non-catalytic conditions could be the result of an O-O oxidative addition in **D** stabilized by interaction with **C** resulting in the Mn(II)/Mn(IV) dimer.

In conclusion, we have disclosed original conditions for the synthesis of a wide range of symmetrical biaryls and derivatives such as ferrocene, 9,10-dihydrophenanthrene or even triphenylene derivatives. These molecules are obtained by using a ligand-free manganese catalytic system allowing the homocoupling of arenes (C-H activation) or aryl halides (C-X activation), via the intermediate formation of aryllithiums derivatives. The experiments together with the DFT calculations highlight the crucial role of dioxygen in the catalytic process. A mechanistic hypothesis based on the involvement of Mn monomeric species and on a Mn(II)/Mn(IV) sequence has been proposed. Work is in progress in our laboratory to further extend the application field of the system and to gain a deeper understanding of the mechanism.

EXPERIMENTAL SECTION

General Information. All reactions were performed in flame-dried Schlenk flasks under an atmosphere of argon. THF was distilled from sodium/benzophenone, stored on 4 Å activated molecular sieves under an argon atmosphere. MnCl_2 (99.998%) was purchased from Sigma-Aldrich[®], stored in a Schlenk flask under an atmosphere of argon. All other reagents were purchased from Sigma-Aldrich[®], Alfa Aesar[®] or Acros[®] and used as received, without further purification. All reagents were weighed in the air. ^1H , ^{13}C and ^{19}F NMR spectra were recorded on a Bruker AC 400 MHz spectrometer in CDCl_3 . For ^1H NMR (400 MHz), CHCl_3 and TMS served as internal standards ($\delta = 7.27$ and 0 ppm) and data are reported as follows: chemical shift (in ppm), multiplicity (s = singlet, br s = broad singlet, d = doublet, t = triplet, m = multiplet), coupling constant (in Hz), and integration. For ^{13}C NMR (101 MHz), CHCl_3 was used as internal standard ($\delta = 77.2$ ppm) and spectra were obtained with complete proton decoupling. High-resolution mass spectra (HRMS) were recorded on an Agilent 6210 ESI TOF (time of flight) mass spectrometer or on a JEOL JMS-DX300 mass spectrometer (3 keV, xenon) in an *m*-nitrobenzylalcohol matrix. For the ESI-MS mechanistic studies high resolution ESI-MS spectra were recorded on a hybrid tandem quadrupole/time-of-flight (Q-TOF) instrument, equipped with a pneumatically assisted electrospray (Z-spray) ion source (Micromass, Manchester, UK) operated in positive mode. Flash column chromatography was performed on Silicycle silica gel (230–400 mesh) or Merck Geduran Si 60 silica gel (40–63 μm) and analytical thin-layer chromatography

(TLC) was carried out using 250 μm silica gel plates. Visualization of the developed chromatograms was performed by UV irradiation (254 nm).

General Note on Safety. Organolithium compounds are highly reactive and generally pyrophoric, the use of them thus requires great caution and proper lab bench conditions.²¹ *Tert*-butyllithium can easily catch fire and form peroxides on exposure to air and react violently with water, so the first step of the reactions should be carried out under strict air-free and water-free conditions.^{21b} In our case, before exposure the reaction mixture to dry air, *tert*-butyllithium has already reacted with aryl halides and turned to the corresponding aryllithium compounds which are much less pyrophoric. In addition, at the end of reaction we did not observe the formation of peroxides - a test was performed before the work-up of the reaction mixture.

General procedure 1 for the synthesis of symmetrical biaryls from arylhalides. After standard cycles of evacuation and back-filling with dry and pure argon, an oven-dried Schlenk flask equipped with a magnetic stirring bar was charged with MnCl_2 (0.1 mmol, 0.1 equiv.). The flask was evacuated and back-filled with argon, then dry THF (4 mL) and aryl halide (1.0 mmol, 1.0 equiv.). Then the flask was stirred, cooled to -78°C and *t*-BuLi (2.0 mmol, 2.0 equiv. 1.1 ml of a 1.9 M solution in pentane) or *s*-BuLi (2.0 mmol, 2.0 equiv., and 1.5 ml of a 1.3 M solution in cyclohexane/hexane – 92/8) was added under a stream of argon by syringe. The reaction mixture was stirred for about 20 minutes at -78°C and then heated to room temperature. The air was introduced when the screwed cap of flask was replaced by a guard tube filled with silica gel. The reaction mixture was stirred at room temperature for 1 hour. Then, 1, 3,5-trimethoxybenzene (16.8 mg, 0.1 mmol) was added as internal standard. The resulting mixture was diluted with Et_2O (10mL) and washed with NH_4Cl saturated solution (3 x 15 mL). The aqueous layer was washed with Et_2O (3 x 10mL). The organic layer was dried over anhydrous MgSO_4 and diethyl ether was evaporated under reduced pressure (rotary evaporator). The residue was purified by column chromatography to give the desired symmetrical biaryl.

General procedure 2 for the synthesis of symmetrical biaryls via C-H activation. After standard cycles of evacuation and back-filling with dry and pure argon, an oven-dried Schlenk flask equipped with a magnetic stirring bar was charged with MnCl_2 (0.1 mmol, 0.1 equiv.). The flask was evacuated and back-filled with argon, then dry THF (4 mL) and aryl halide (1.0 mmol, 1.0 equiv.). Then the flask was stirred, cooled to -78°C and *t*-BuLi (1.0 mmol, 1.0 equiv. 0.55 ml of a 1.9 M solution in pentane) was added under a stream of argon by syringe. The reaction mixture was stirred for about 20 minutes at -78°C and then heated to room temperature. The air was introduced when the screwed cap of flask was replaced by a guard tube filled with silica gel. The reaction mixture was stirred at room temperature for 1 hour. Then, 1, 3,5-trimethoxybenzene (16.8 mg, 0.1 mmol) was added as internal standard. The resulting mixture was diluted with Et_2O (10mL) and washed with NH_4Cl saturated solution (3 x 15 mL). The aqueous layer was washed with Et_2O (3 x 10mL). The organic layer was dried over anhydrous MgSO_4 and diethyl ether was evaporated under reduced pressure (rotary evaporator). The residue was purified by column chromatography to give the desired symmetrical biaryl.

1,1'-biphenyl (1).^{5a} Yield: 152.6 mg, 99% (X = I); 140.3 mg, 91% (X = Br); 115.7 mg, 75% (X = Cl). ¹H NMR (400 MHz, CDCl₃) δ: 7.59 (d, *J* = 7.1 Hz, 4H), 7.44 (t, *J* = 7.6 Hz, 4H), 7.34 (t, *J* = 7.4 Hz, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 141.4, 128.9, 127.43, 127.35. GC-MS: rt = 7.17 min, m/z = 154. Column chromatography: SiO₂, *n*-Pentane 100%.

4,4'-dimethyl-1,1'-biphenyl (2).²² Yield: 154.9 mg, 85% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.56 (d, *J* = 8.1, 4H), 7.31 (d, *J* = 8.1, 4H), 2.46 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 138.4, 136.9, 129.6, 127.0, 21.3. GC-MS: rt = 8.36 min, m/z = 182. Column chromatography: SiO₂, *n*-Pentane 100%.

3,3'-dimethyl-1,1'-biphenyl (3).²² Yield: 164.0 mg, 90% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.46-7.44 (m, 4H), 7.37 (t, *J* = 7.5, 2H), 7.21 (t, *J* = 7.5, 2H), 2.47 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 141.5, 138.4, 128.8, 128.14, 128.08, 124.5, 21.7. GC-MS: rt = 8.24 min, m/z = 182. Column chromatography: SiO₂, *n*-Pentane 100%.

2,2'-dimethyl-1,1'-biphenyl (4).²² Yield: 127.6 mg, 70% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.28 – 7.19 (m, 6H), 7.10 (d, *J* = 6.8 Hz, 2H), 2.06 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 141.8, 136.0, 130.0, 129.5, 127.3, 125.7, 20.0. GC-MS: rt = 7.36 min, m/z = 182. Column chromatography: SiO₂, *n*-Pentane 100%.

4,4'-dimethoxy-1,1'-biphenyl (5).²³ Yield: 171.4 mg, 80% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.49 (d, *J* = 8.8 Hz, 4H), 6.98 (d, *J* = 8.8 Hz, 4H), 3.86 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 158.9, 133.7, 127.9, 114.4, 55.5. GC-MS: rt = 9.77 min, m/z = 214. Column chromatography: SiO₂, *n*-Pentane/DCM 50/50.

3,3'-dimethoxy-1,1'-biphenyl (6).²⁴ Yield: 203.5 mg, 95% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.40 (t, *J* = 7.9 Hz, 2H), 7.23 (d, *J* = 7.9 Hz, 2H), 7.18 (t, *J* = 2.4 Hz, 2H), 6.95 (dd, *J* = 8.2, 2.4 Hz, 2H), 3.90 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 160.1, 142.8, 129.9, 119.8, 113.1, 112.9, 55.4. GC-MS: rt = 9.61 min, m/z = 214. HRMS (ESI⁺) m/z: [M+H]⁺ Calcd. for C₁₄H₁₅O₂ 215.1072; Found : 215.1074. Column chromatography: SiO₂, *n*-Pentane/DCM 50/50.

2,2'-dimethoxy-1,1'-biphenyl (7).^{5a} Yield: 192.8 mg, 90% (X = Br); 150.0 mg, 70% (X = H). ¹H NMR (400 MHz, CDCl₃) δ: 7.38-7.32 (m, 2H), 7.27 (dd, *J* = 7.5, 1.7 Hz, 2H), 7.06 – 6.97 (m, 4H), 3.79 (s, 6H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 157.2, 131.6, 128.8, 128.0, 120.5, 111.3, 55.9. GC-MS: rt = 8.67 min, m/z = 214. HRMS (ESI⁺) m/z: [M+H]⁺ Calcd. for C₁₄H₁₅O₂ 215.1072; Found : 215.1073. Column chromatography: SiO₂, *n*-Pentane/DCM 50/50.

4,4'-di-tert-butyl-1,1'-biphenyl (8).²⁴ Yield: 207.8 mg, 78% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.56 (d, *J* = 8.4 Hz, 4H), 7.48 (d, *J* = 8.4 Hz, 4H), 1.39 (s, 18H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 150.1, 138.4, 126.9, 125.8, 34.7, 31.6. GC-MS: rt = 10.37 min, m/z = 266. Column chromatography: SiO₂, *n*-Pentane 100%.

N,N,N',N'-tetramethyl-[1,1'-biphenyl]-4,4'-diamine (9).²⁴ Yield: 228.3 mg, 95% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.49 (d, *J* = 8.5 Hz, 4H), 6.83 (d, *J* = 8.5 Hz, 4H), 3.00 (s, 12H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 149.4, 130.0, 127.1, 113.3, 41.0. GC-MS: rt = 11.41 min, m/z = 240. HRMS (ESI⁺) m/z: [M+H]⁺ Calcd. for C₁₆H₂₁N₂ 241.1705; Found :

241.1703. Column chromatography: SiO₂, *n*-Pentane/EtOAc 70/30.

4,4'-bis(trifluoromethyl)-1,1'-biphenyl (10).²² Yield: 209.0 mg, 72% (X = I); 145.1 mg, 50% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.77-7.71 (m, 8H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 143.4, 130.5 (q, *J* = 32.7 Hz), 127.8, 126.1 (q, *J* = 3.7 Hz), 124.1 (q, *J* = 272.0 Hz). ¹⁹F NMR (377 MHz, CDCl₃) δ: -62.56. GC-MS: rt = 7.16 min, m/z = 290. Column chromatography: SiO₂, *n*-Pentane 100%.

3,3'-bis(trifluoromethyl)-1,1'-biphenyl (11).²² Yield: 232.2 mg, 80% (X = I); 203.1 mg, 70% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.85 (d, *J* = 0.5 Hz, 2H), 7.79 (d, *J* = 7.7 Hz, 2H), 7.68 (d, *J* = 7.8 Hz, 2H), 6.61 (t, *J* = 7.7 Hz, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 140.8, 131.7 (q, *J* = 32.4 Hz), 130.7, 129.7, 124.9 (q, *J* = 3.7 Hz), 124.23 (q, *J* = 272.4 Hz), 124.20 (q, *J* = 3.8 Hz). ¹⁹F NMR (377 MHz, CDCl₃) δ: -62.68. GC-MS: rt = 6.94 min, m/z = 290. Column chromatography: SiO₂, *n*-Pentane 100%.

2,2'-bis(trifluoromethyl)-1,1'-biphenyl (12).²² Yield: 145.1 mg, 50% (X = I); 87.1 mg, 30% (X = Br); 185.7 mg, 64% (X = H). ¹H NMR (400 MHz, CDCl₃) δ: 7.76 (dd, *J* = 7.6, 1.5 Hz, 2H), 7.54 (dd, *J* = 7.5, 1.5 Hz 4H), 7.31 (d, *J* = 7.5 Hz, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 137.7, 131.7, 130.8, 129.0 (q, *J* = 30.1 Hz), 128.3, 126.2 (m), 124.1 (q, *J* = 274.2 Hz). ¹⁹F NMR (377 MHz, CDCl₃) δ: -58.12. GC-MS: rt = 7.16 min, m/z = 290. Column chromatography: SiO₂, petroleum ether 100%.

2,2'-bipyridine (13).²⁵ Yield: 93.7 mg, 60% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 8.69 (d, *J* = 4.4 Hz, 2H), 8.40 (d, *J* = 8.0 Hz, 2H), 7.81 (ddd, *J* = 7.9, 2.8, 1.4 Hz, 2H), 7.30 (ddd, *J* = 7.4, 4.8, 1.2 Hz, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 156.3, 149.3, 137.1, 123.9, 121.2. GC-MS: rt = 7.51 min, m/z = 156. Column chromatography: Al₂O₃, *n*-pentane/EtOAc 80/20.

1,1'-biisoquinoline (14).²⁶ Yield: 199.9 mg, 78% (X = I). ¹H NMR (400 MHz, CDCl₃) δ: 8.72 (d, *J* = 5.7 Hz, 2H), 7.93 (d, *J* = 8.3 Hz, 2H), 7.80 (d, *J* = 5.7 Hz, 2H), 7.76 (dd, *J* = 8.5, 0.5 Hz, 2H), 7.69 (ddd, *J* = 8.3, 6.8, 1.1 Hz, 2H), 7.47 (ddd, *J* = 8.3, 6.8, 1.2 Hz, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 158.3, 142.1, 136.9, 130.4, 127.9, 127.6, 127.3, 127.0, 121.1. GC-MS: rt = 12.22 min, m/z = 256. Column chromatography: Al₂O₃, petroleum ether/EtOAc 70/30.

1,1':2',1'':2'',1'''-quaterphenyl (15).²⁷ Yield: 291.1 mg, 95% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.45-7.40 (m, 2H), 7.39-7.31 (m, 4H), 7.20-7.15 (m, 2H), 7.09 (t, *J* = 7.3 Hz, 2H), 7.01 (t, *J* = 7.4 Hz, 4H), 6.62 (d, *J* = 7.2 Hz, 4H). ¹³C{¹H} NMR (101 MHz, CDCl₃) d: 141.2, 141.1, 140.2, 131.9, 130.1, 129.4, 127.63, 127.59, 127.2, 126.1. GC-MS: rt = 11.50 min, m/z = 306. Column chromatography: SiO₂, *n*-Pentane 100%.

1,1'-binaphthalene (16).²⁴ Yield: 234.0 mg, 92% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 7.98-7.95 (m, 4H), 7.65-7.57 (m, 2H), 7.52 – 7.47 (m, 4H), 7.41 (d, *J* = 8.5 Hz, 2H), 7.34-7.28 (m, 2H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ: 138.7, 133.7, 133.0, 128.3, 128.1, 128.0, 126.8, 126.2, 126.0, 125.6. GC-MS: rt = 11.41 min, m/z = 254. Column chromatography: SiO₂, *n*-Pentane 100%.

2,2'-binaphthalene (17).^{5a} Yield: 203.5 mg, 80% (X = Br). ¹H NMR (400 MHz, CDCl₃) δ: 8.19 (s, 2H), 7.99 – 7.95 (m,

4H), 7.93 – 7.86 (m, 4H), 7.59 – 7.48 (m, 4H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 138.6, 133.9, 132.9, 128.7, 128.4, 127.9, 126.6, 126.3, 126.2, 125.9. GC-MS: *rt* = 12.78 min, *m/z* = 254. Column chromatography: SiO_2 , *n*-Pentane 100%.

*1,2-diphenylethane (18)*²⁸ Yield: 131.2 mg, 72% (*X* = Br). ^1H NMR (400 MHz, CDCl_3) δ : 7.39-7.32 (m, 4H), 7.30-7.25 (m, 6H), 3.00 (s, 4H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 142.0, 128.6, 128.5, 126.1, 38.1. GC-MS: *rt* = 7.89 min, *m/z* = 182. Column chromatography: SiO_2 , *n*-Pentane 100%.

*9,10-dihydrophenanthrene (19)*²⁹ Yield: 108.2 mg, 60% (*X* = Br). ^1H NMR (400 MHz, CDCl_3) δ : 7.81 (d, *J* = 7.7 Hz, 2H), 7.39-7.33 (m, 2H), 7.29-7.27 (m, 4H), 2.93 (s, 4H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 137.6, 134.7, 128.3, 127.6, 127.1, 123.9, 29.2. GC-MS: *rt* = 8.77 min, *m/z* = 180. Column chromatography: SiO_2 , *n*-Pentane 100%.

*4,4'-dichloro-1,1'-biphenyl (20)*³⁰ Yield: 140.6 mg, 63% (*X* = Cl). ^1H NMR (400 MHz, CDCl_3) δ : 7.49 (d, *J* = 8.6 Hz, 4H), 7.42 (d, *J* = 8.6 Hz, 4H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 138.6, 133.9, 129.2, 128.4. GC-MS: *rt* = 9.239 min, *m/z* = 223. Column chromatography: SiO_2 , *n*-Pentane 100%.

*3,3'-dichloro-1,1'-biphenyl (21)*³¹ Yield: 100.4 mg, 45% (*X* = Br). ^1H NMR (400 MHz, CDCl_3) δ : 7.56-7.55 (m, 2H), 7.46-7.34 (m, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 141.8, 135.0, 130.3, 128.1, 127.5, 125.5. GC-MS: *rt* = 9.218 min, *m/z* = 222. Column chromatography: SiO_2 , *n*-Pentane 100%.

*Triphenylene (22)*³² Yield: 207.7 mg, 91% (*X* = Br). ^1H NMR (400 MHz, CDCl_3) δ : 8.68 (dd, *J* = 6.2, 3.4 Hz, 6H), 7.68 (dd, *J* = 6.3, 3.3 Hz, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 130.0, 127.4, 123.5. GC-MS: *rt* = 11.89 min, *m/z* = 228. Column chromatography: SiO_2 , *n*-Pentane/DCM 90/10.

2,6,10-trimethyltriphenylene (23a) / *2,6,11-trimethyltriphenylene (23b) (1/3)*³³ Yield: 216.3 mg, 80% (*X* = Br). M.p. of mixture : 128°C (lit. for **23a**: 181 °C^{34a}; lit. for **23b**: 142 °C)^{34b,c} ^1H NMR (400 MHz, CDCl_3) δ : 8.53 (d, *J* = 8.3 Hz, 2H), 8.52 (d, *J* = 8.2 Hz, 2H), 8.49 (d, *J* = 8.3 Hz, 2H), 8.48 (d, *J* = 8.2 Hz, 2H), 8.44 (br s, 2H), 8.41 (br s, 2H), 7.48-7.44 (m, 4H), 2.64 (s, 6H), 2.63 (s, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 136.8, 136.7, 136.43, 136.37, 130.1, 130.0, 129.7, 129.5, 128.63, 128.57, 128.33, 128.27, 127.9, 127.7, 127.4, 127.2, 123.40, 123.35, 123.3, 123.24, 123.19, 123.17, 123.1, 22.0. HRMS (ESI⁺) *m/z*: [M+H]⁺ Calcd. for $\text{C}_{21}\text{H}_{19}$ 271.1487; Found : 271.1481. Column chromatography: SiO_2 , *n*-Pentane/DCM 90/10. A small crop of crystals suitable for X-ray diffraction studies of **23b** were obtained by slow diffusion of pentane into a dichloromethane solution of the mixture.

*1,4-diphenylbuta-1,3-diyne (24)*³⁵ Yield: 192.1 mg, 95% (*X* = H). ^1H NMR (400 MHz, CDCl_3) δ : 7.60-7.53 (m, 4H), 7.43-7.34 (m, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 132.7, 129.4, 128.6, 122.0, 81.7, 74.1. GC-MS: *rt* = 10.20 min, *m/z* = 202. Column chromatography: SiO_2 , *n*-Pentane/DCM 50/50.

*1,1'-dimethyl-1H,1'H-2,2'-bibenzof[*d*]imidazole (25)*³⁶ Yield: 196.7 mg, 75% (*X* = H). ^1H NMR (400 MHz, CDCl_3) δ : 7.89 (d, *J* = 7.6 Hz, 2H), 7.51 (d, *J* = 7.6 Hz, 2H), 7.52-7.35 (m, 4H), 4.35 (s, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 143.5, 142.8, 136.4, 124.2, 123.1, 120.5, 110.3, 32.6. GC-MS: *rt* = 12.61 min, *m/z* = 262. Column chromatography: SiO_2 , *n*-Pentane/EtOAc 50/50.

1,1'-dimethyl-1H,1'H-2,2'-bipyrrrole (26) Yield: 32.0 mg, 20% (*X* = H). ^1H NMR (400 MHz, CDCl_3) δ : 6.74-6.73 (m, 2H), 6.21-6.17 (m, 4H), 3.53 (s, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 125.9, 122.9, 110.7, 107.5, 34.6. GC-MS: *rt* = 6.941 min, *m/z* = 160. HRMS (ESI⁺) *m/z*: [M+H]⁺ Calcd. for $\text{C}_{10}\text{H}_{13}\text{N}_2$ 161.1079; Found : 161.1079. Column chromatography: SiO_2 , *n*-Pentane/DCM 20/80.

Biferrocenyl (27) Yield: 148.0 mg, 40% (*X* = H). ^1H NMR (400 MHz, CDCl_3) δ : 4.38-4.35 (m, 4H), 4.19-4.17 (m, 4H), 4.01 (s, 10H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ : 77.4, 69.4, 67.8, 66.6. GC-MS: *rt* = 12.687 min, *m/z* = 370. HRMS (ESI⁺) *m/z*: [M+H]⁺ Calcd. for $\text{C}_{20}\text{H}_{19}\text{Fe}_2$ 371.0118; Found : 371.0107. Column chromatography: SiO_2 , *n*-Pentane/EtOAc 95/5.

ASSOCIATED CONTENT

Supporting Information

Optimization tables, NMR spectra for all synthetic compounds, X-ray diffraction and mechanistic study details for ESI-MS and DFT. **CCDC 1564505** contains the supplementary crystallographic data for this paper. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interests.

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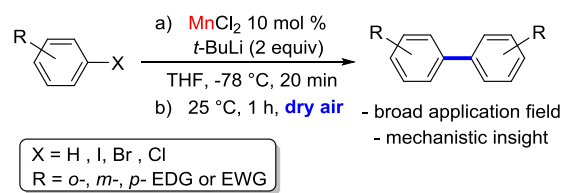
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