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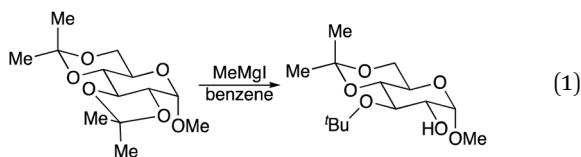
Sequential olefination–dimerisation of benzylic dithioacetals by the nickel-catalysed reaction with methyl Grignard or zinc reagent†

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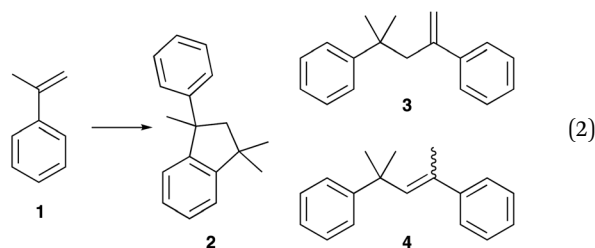
Products of main group elements from cross-coupling reactions have been shown to serve as Lewis acids, mediating further reactions of organic coupling products. Thus, the nickel-catalysed olefination of benzylic dithioacetal with MeMgI in benzene in a sealed Schlenk tube at 130 °C generates magnesium mercaptide which regioselectively converts 2-arylpropene into a dimer in good yield. Aryl iodide reacts with 2-propenylmagnesium bromide in the presence of 1,2-ethanedithiol and NiCl₂(PPh₃)₂ to yield the same dimer. Replacement of the Grignard reagent by an organozinc reagent gives the dimers in a better yield.

Introduction

Transition metal-catalysed cross coupling reactions have significantly contributed to the formation of carbon–carbon bonds.^{1–3} In general, these reactions require an organic electrophile, a transition-metal catalyst, and a main group organometallic compound as a nucleophile. After the reaction is complete, the main group element is converted into the corresponding inorganic salt or equivalent. To illustrate this, Mg(II) and Zn(II) are produced from Kumada–Corriu–Tamao² and Negishi³ reactions, respectively. These *in situ* generated inorganic salts can serve as a Lewis acid catalyst⁴ or a reagent to mediate further reactions of the cross-coupling product. In particular, these Lewis catalysed reactions can even take place in strong basic conditions. For example, the regioselective ring-opening of acetals of contiguous polyols, such as monosaccharides or inositols, by a Grignard reagent is well documented (eqn (1)).⁵



Dimerisation of α -methylstyrene **1** under various conditions, leading to different kinds of products **2–4**, has been extensively studied (eqn (2)).^{6–8} Under strong acidic conditions or longer reaction times, indane derivative **2** is obtained predominantly, if not exclusively.⁶ Regioisomers **3** and **4** are occasionally isolated as a mixture under acid-catalysed conditions.^{6a–c,7} Notably, these pentene derivatives are industrially important to serve as chain-transfer agents or molecular weight regulators for styrene-based polymers or copolymers.^{6–8}



Compound **1** can readily be obtained by the nickel-catalysed olefination^{9,10} of benzylic dithioacetals **5** with excess MeMgI under conditions similar to those of the Kumada–Corriu–Tamao reaction (eqn (3)).² As previously mentioned, Mg(II) salt will be generated from this reaction. Compound **1** may be vulnerable to further transformation under these reaction conditions. Since Mg(II) can be considered as a mild Lewis acid, it is envisaged that dimerisation might take place to give **3** and/or **4**, but not the Friedel–Crafts product **2**. In this paper, we wish to report for the first time the direct conversion of **5** to **6** regioselectively under cross-coupling reaction conditions.

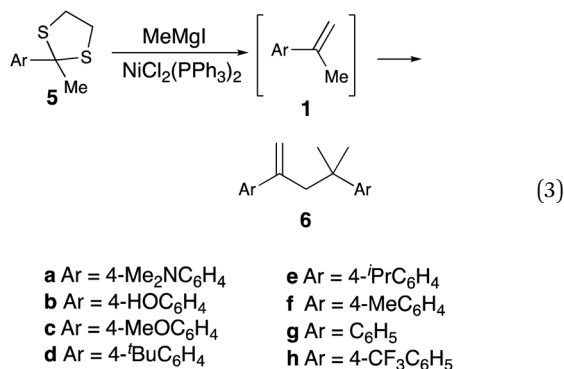
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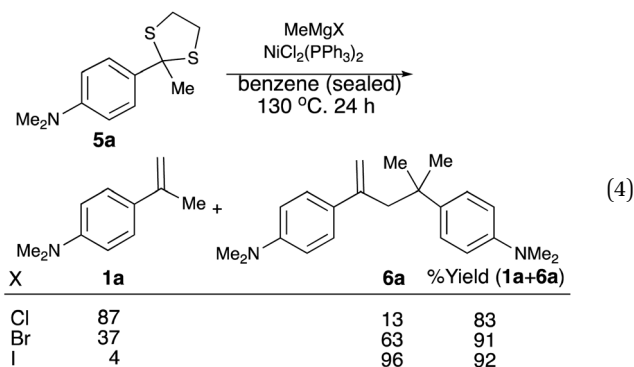
Results and discussion

NiCl₂(PPh₃)₂MeMgI catalysed olefination–dimerisation reactions with 5a

Treatment of 5a with MeMgI in the presence of 10 mol% of NiCl₂(PPh₃)₂ in refluxing benzene gave 67% of the corresponding dimer 6a. The isolation of 6a from the reaction under the conditions of the Kumada–Tamao reaction^{2a} is striking. The reaction mixture may contain a Grignard reagent or a Mg(II), Ni(II) or Ni(0) catalyst, Ph₃P, and ⁻SCH₂CH₂S⁻. It seems likely that some of these components might be responsible for promoting the formation of 6 from 1. Our initial aim was to find suitable conditions to give 6 predominantly, if not exclusively.

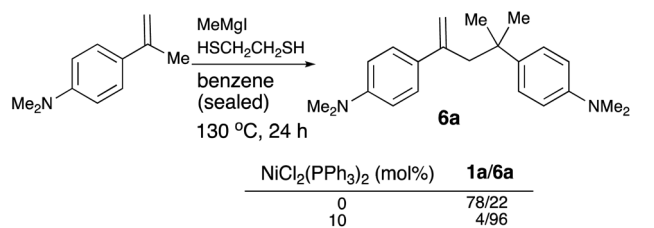
Effect of halide X in MeMgX on the dimerisation step

The halogen atom in the Grignard reagent has been shown to play an important role in the reactivity of the reaction (eqn (4)). A sealed Schlenk tube was chosen for the reaction of 5a with the Grignard reagent in benzene and the reaction tube was immersed in an oil bath at 130 °C for 24 h. When MeMgCl was employed, the ratio of 1a to 6a was 87/13. The ratio changed to 37/63 if MeMgBr was used. MeMgI, on the other hand, gave excellent selectivity with 1a/6a = 4/96. The magnesium ion liberated during the course of the cross-coupling reaction would interact with the negatively charged halide and/or sulfide moieties. Apparently, when these softer anions are associated with magnesium ion, the reactivity of the magnesium ion would be enhanced and dimer 6a would be formed preferentially.



Effect of ⁻SCH₂CH₂S⁻ on the reactivity of dimerisation of 1a

Since ⁻SCH₂CH₂S⁻ would be generated from the olefination of dithiolanes, it seems likely that the sulfide moiety might also bind to the magnesium ion that might promote the formation of dimer 6. Dimerisation of 1a to 6a has been carefully examined. Notably, there is no sulfur atom in 1a. In the absence of 1,2-ethanedithiol, no dimerisation took place. Interestingly, a benzene solution of 1a, MeMgI, and HSCH₂CH₂SH (1 : 3 : 1) in a sealed Schlenk tube was heated to 130 °C for 24 h. Only 23% of conversion of 1a was observed and the ratio of dimer 6a *versus* unreacted 1a was 22 to 78. When 10 mol% of NiCl₂(PPh₃)₂ was added to the reaction mixture, only 3% of the starting 1a was recovered and the yield of 6a was improved to 67%. It is worth mentioning that no dimer 6a was detected from the mixture without MeMgI. In other words, NiCl₂(PPh₃)₂-HSCH₂CH₂SH alone does not catalyse the dimerisation of 1a at all. Presumably, the direct displacement of the chloride by a mercaptan would generate HCl that would not be a favored process.



Examples of sequential olefination–dimerisation reactions

Being successful in this transformation shown in eqn (5), we tested the generality of this catalyst system for sequential olefination–dimerisation. The reaction mixture consists of excess Grignard reagent and the medium should, therefore, be basic. The Lewis acidity of magnesium may not be active enough to promote the dimerisation process. It is envisaged that zinc might be a stronger Lewis acid. Accordingly, the reactivity of the organozinc reagent obtained by the addition of ZnI₂ to the above Grignard reagent was also examined and the results are compared in Table 1.

Substrates with highly electron-donating substituents gave the corresponding 6 in a much better yield than those with alkyl substituents. The compound with an electron withdrawing group, such as the CF₃ group, gave the corresponding olefination product 1h only. These results imply that the dimerisation reaction may proceed *via* a carbocation-like mechanism. Notably, organozinc reagent appears to be more potent than the corresponding Grignard reagent in these sequential olefination–dimerisation reactions.

Nickel-catalysed sequential cross coupling-dimerisation of aryl iodide 7 with H₂C=C(Me)MgBr/ZnI₂

Dimer 6a could also be obtained from the reaction of 7a with 7 equiv. each of the 2-propenyl Grignard reagent and ZnI₂ in the presence of 10 mol% of NiCl₂(PPh₃)₂, and 1 equiv. of 1,2-ethanedithiol at rt for 6 h. The temperature was then raised to 130 °C



Experimental section

General information

All melting points were measured on an SGW X-4A apparatus and were uncorrected. ^1H and ^{13}C NMR nuclear magnetic resonance (NMR) spectra were recorded on a Bruker Advance 400 MHz spectrometer at ambient temperature. Chemical shifts (δ) and coupling constants (J) were expressed in units of ppm and Hz, respectively. Samples for measurements were dissolved in CDCl_3 . The residual peak of CHCl_3 at δ 7.26 was used as the reference for ^1H NMR chemical shifts and the central peak at δ 77.16 of CDCl_3 was used as the reference for ^{13}C NMR chemical shifts. Infrared spectra were taken on a Nicolet 700 FT infrared spectrophotometer using a KBr plate for solid samples or forming a film on a NaCl window.

Materials

Compounds **5b**, **5e**, **5f** and **5g** were prepared according to a literature procedure.⁷

General procedure for the synthesis of dithioacetals

To a chloroform solution (50 mL) of acetophenone derivative (20 mmol) and 1,2-ethanedithiol (density = 1.123 g cm^{-3} , 22–44 mmol), boron trifluoride etherate (density = 1.15 g cm^{-3} , 14–34 mmol) was added. The mixture was stirred at rt overnight. The solution was washed twice with 10% aqueous sodium hydroxide (30 mL) and the aqueous layer was extracted twice with DCM (20 mL). The combined organic layers were washed twice with water (50 mL), dried (Na_2SO_4) and filtered. The solvent was removed *in vacuo* and the residue was chromatographed on silica gel using petroleum ether and ethyl acetate as the eluent to give the corresponding dithioacetals.

2-[4-(Dimethylamino)phenyl]-2-methyl-1,3-dithiolane (**5a**).

In a manner similar to that described in the general procedure, a mixture of 4-(dimethylamino)acetophenone (3.26 g, 20 mmol), 1,2-ethanedithiol (density = 1.123 g cm^{-3} , 1.8 mL, 22 mmol), and boron trifluoride etherate (density = 1.15 g cm^{-3} , 4.2 mL, 34 mmol) was converted to **5a** (4.20 g, 88%) as a yellow solid: mp 47–48 °C; ^1H NMR (CDCl_3 , 400 MHz) δ 7.63–7.60 (m, 2H), 6.68–6.66 (m, 2H), 3.52–3.36 (m, 4H), 2.94 (s, 6H), 2.15 (s, 3H) ppm; ^{13}C NMR (CDCl_3 , 101 MHz) δ 149.6, 132.8, 127.7, 111.8, 68.4, 40.6, 40.4, 33.9 ppm; HRMS (ESI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{12}\text{H}_{18}\text{S}_2$: 240.0875, found 240.0869.

2-Methyl-2-(4-*t*-butylphenyl)-1,3-dithiolane (5d**).** In a manner similar to that described in the general procedure, a mixture of 4-*t*-butylacetophenone (3.53 g, 20 mmol), 1,2-ethanedithiol (density = 1.123 g cm^{-3} , 1.8 mL, 22 mmol), and boron trifluoride etherate (density = 1.15 g cm^{-3} , 1.7 mL, 14 mmol) was converted to **5d** (4.13 g, 81%) as a white solid: mp 73–74 °C; ^1H NMR (CDCl_3 , 400 MHz) δ 7.74 (d, J = 8.4 Hz, 2H), 7.40 (d, J = 8.4 Hz, 2H), 3.57–3.38 (m, 4H), 2.22 (s, 3H), 1.38 (s, 9H) ppm; ^{13}C NMR (CDCl_3 , 101 MHz) δ 149.9, 142.8, 126.5, 125.0, 68.4, 40.5, 34.5, 34.1, 31.4 ppm; IR (KBr, cm^{-1}): 2961, 1499, 1396, 1363, 1267, 1111, 1071, 1012, 829, 729; HRMS (ESI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{14}\text{H}_{21}\text{S}_2$: 253.1079, found 253.1085.

2-Methyl-2-(4-isopropylphenyl)-1,3-dithiolane (5e**).** In a manner similar to that described in the general procedure, a mixture of 4-propylacetophenone (3.25 g, 20 mmol), 1,2-ethanedithiol (density = 1.123 g cm^{-3} , 1.8 mL, 22 mmol), and boron trifluoride etherate (density = 1.15 g cm^{-3} , 1.7 mL, 14 mmol) was converted to **5e** (4.17 g, 87%) as a colourless oil: ^1H NMR (CDCl_3 , 400 MHz) δ 7.58–7.56 (m, 2H), 7.08–7.06 (m, 2H), 3.41–3.17 (m, 4H), 2.80 (d, J = 6.9 Hz, 1H), 2.06 (s, 3H), 1.15 (d, J = 6.9 Hz, 6H) ppm; ^{13}C NMR (CDCl_3 , 101 MHz) δ 147.7, 143.2, 126.8, 126.1, 68.5, 40.4, 34.1, 33.7, 24.0 ppm; IR (KBr, cm^{-1}): 2959, 1503, 1411, 1275, 1075, 1016, 833, 698; HRMS (APCI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{13}\text{H}_{19}\text{S}_2$: 239.0923, found 239.0917.

General procedure for the $\text{NiCl}_2(\text{PPh}_3)_2$ -catalysed reaction of dithioacetal **5** with MeMgX

In a sealed Schlenk tube, a benzene solution of dithioacetal (0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (0.05 mmol), and MeMgI (3 M in ether, 2–3 mmol) was immersed in an oil bath at 130 °C for 24 or 48 h. The mixture was then poured into saturated Na_2CO_3 solution. The organic layer was separated and the aqueous layer was extracted twice (10 mL) with diethyl ether. The combined organic portions were washed twice each (10 mL) with 10% NaOH and brine (10 mL), and dried (Na_2SO_4). The solvent was removed *in vacuo* and the residue was chromatographed on silica gel (petroleum ether and EtOAc) to give the product.

2,4-Bis-(4-dimethylaminophenyl)-4-methylpent-1-ene (6a**).** In a manner similar to that described in the general procedure, a mixture of **5a** (120 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was immersed in an oil bath at 130 °C for 24 h. After workup, the product **6a** (71 mg, 88%) was obtained as a colourless solid: mp 47–48 °C; ^1H NMR (CDCl_3 , 400 MHz) δ 7.15–7.11 (m, 4H), 6.61–6.53 (m, 4H), 5.04–5.00 (br, 1H), 4.58 (br, 1H), 2.84 (s, 6H), 2.82 (s, 6H), 2.67 (s, 2H), 1.10 (s, 6H) ppm; ^{13}C NMR (CDCl_3 , 101 MHz) δ 149.7, 148.6, 146.3, 138.6, 131.9, 127.3, 126.5, 113.9, 112.6, 112.2, 49.4, 40.9, 40.7, 37.9, 28.9 ppm; IR (KBr, cm^{-1}): 3290, 1610, 1512, 1435, 1362, 1222, 1177, 895, 829; HRMS (ESI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{22}\text{H}_{31}\text{N}_2$: 323.2482, found 323.2480.

2,4-Bis-(4-hydroxyphenyl)-4-methylpent-1-ene (6b**).** In a manner similar to that described in the general procedure, a mixture of **5b** (104 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), and MeMgI (1 mL, 3 M in ether, 3 mmol) was immersed in an oil bath at 130 °C for 24 h. After workup, the product **6b** (61 mg, 82%) was obtained as a white solid: mp 130–131 °C (lit^{7b} 127.8 °C); ^1H NMR (CDCl_3 , 400 MHz) δ 7.12–7.07 (m, 4H), 6.68–6.66 (m, 4H), 5.07 (d, J = 1.6 Hz, 1H), 4.97 (br, 1H), 4.85 (s, 1H), 4.72 (s, 1H), 2.74 (s, 2H), 1.20 (s, 6H) ppm; ^{13}C NMR (CDCl_3 , 101 MHz) δ 154.3, 153.0, 146.2, 141.6, 136.0, 127.8, 127.2, 115.4, 114.8, 114.5, 50.1, 37.9, 28.9; IR (KBr, cm^{-1}): 3291, 1611, 1513, 1435, 1367, 1222, 1179, 895, 829; HRMS (ESI, m/z): $[\text{M} + \text{Na}]^+$ calculated for $\text{C}_{18}\text{H}_{20}\text{NaO}_2$: 291.1356, found 291.1361. The spectroscopic properties of **6b** were identical to those reported in the literature.^{7b}

2,4-Bis-(4-methoxyphenyl)-4-methylpent-1-ene (6c**).** In a manner similar to that described in the general procedure, a mixture of **5c** (113 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05



mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was immersed in an oil bath at 130 °C for 48 h. After workup, the product **6c** (39 mg, 52%) was obtained as a brown oil: $^1\text{H NMR}$ (CDCl_3 , 400 MHz) δ 7.21–7.14 (m, 4H), 6.79–6.73 (m, 4H), 5.08 (d, $J = 2.0$ Hz, 1H), 4.70 (br, 1H), 3.78 (s, 3H), 3.76 (s, 3H), 2.76 (s, 2H), 1.19 (s, 6H); $^{13}\text{C NMR}$ (CDCl_3 , 101 MHz) δ 158.6, 157.3, 146.1, 141.7, 136.0, 127.6, 126.9, 115.4, 113.4, 113.1, 55.2, 49.8, 38.1, 28.9, ppm; IR (KBr, cm^{-1}): 2959, 1607, 1509, 1463, 1243, 1179, 1034, 892, 827; HRMS (ESI, m/z): $[\text{M} + \text{Na}]^+$ calculated for $\text{C}_{20}\text{H}_{24}\text{NaO}_2$: 319.1669, found 319.1657. The spectroscopic properties of **6c** were identical to those reported in the literature.^{7b}

2,4-Bis-(4-*t*-butylphenyl)-4-methylpent-1-ene (6d). In a manner similar to that described in the general procedure, a mixture of **5d** (126 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 10 mol%), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was immersed in an oil bath at 130 °C for 48 h. After workup, the product **6d** (42 mg, 48%) was obtained as a yellow oil: $^1\text{H NMR}$ (CDCl_3 , 400 MHz) δ 7.18–7.08 (m, 8H), 5.09 (br, 1H), 4.71 (br, 1H), 2.72 (s, 2H), 1.24–1.19 (m, 18H), 1.14 (s, 6H) ppm; $^{13}\text{C NMR}$ (CDCl_3 , 101 MHz) δ 149.7, 148.0, 146.7, 146.4, 140.4, 126.1, 125.5, 124.8, 124.6, 116.2, 49.4, 38.2, 34.4, 34.2, 31.5, 31.4, 28.7; IR (KBr, cm^{-1}): 2959, 1736, 1459, 1173, 832; HRMS (APCI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{26}\text{H}_{34}\text{N}$: 366.3155, found 366.3149. The spectroscopic properties of **6d** were identical to those reported in the literature.^{7b}

2,4-Bis-4-isopropylphenyl-4-methylpent-1-ene (6e). In a manner similar to that described in the general procedure, a mixture of **5e** (119 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was immersed in an oil bath at 130 °C for 48 h. After workup, the product **6e** (34 mg, 43%) was obtained as a yellow oil: $^1\text{H NMR}$ (CDCl_3 , 400 MHz) δ 7.35–7.26 (m, 4H), 7.22–7.15 (m, 4H), 5.27 (br, 1H), 4.91 (br, 1H), 3.07–2.87 (m, 4H), 1.46–1.28 (m, 18H) ppm; $^{13}\text{C NMR}$ (CDCl_3 , 101 MHz) δ 147.4, 146.6, 145.7, 140.8, 126.35, 125.9, 125.8, 125.7, 116.1, 49.6, 38.2, 33.8, 33.5, 28.7, 24.0, 24.0; IR (KBr, cm^{-1}) 2959, 1510, 1460, 1362, 1053, 1016, 896, 828, 700; HRMS (APCI, m/z): $[\text{M} + \text{NH}]^+$ calculated for $\text{C}_{24}\text{H}_{36}\text{N}$: 338.2842, found 338.2838. The spectroscopic properties of **6e** were identical to those reported in the literature.^{7b}

2,4-Bis-(4-methylphenyl)-4-methylpent-1-ene (6f). In a manner similar to that described in the general procedure, a mixture of **5f** (137 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), and MeMgI (1 mL, 3 M in ether, 3 mmol) was immersed in an oil bath at 130 °C for 24 h. After workup, the product **6f** (14 mg, 21%) was obtained as a yellow oil: $^1\text{H NMR}$ (CDCl_3 , 400 MHz) δ 7.21–7.17 (m, 4H), 7.07–7.05 (m, 4H), 5.14 (d, $J = 1.9$ Hz, 1H), 4.75 (br, 1H), 2.80 (s, 2H), 2.33 (s, 3H), 2.31 (s, 3H), 1.20 (s, 6H) ppm; $^{13}\text{C NMR}$ (CDCl_3 , 101 MHz) δ 146.8, 146.5, 140.7, 136.5, 134.8, 128.7, 128.5, 126.4, 125.8, 116.1, 49.6, 38.4, 28.8, 21.1, 20.8; IR (KBr, cm^{-1}): 2922, 1512, 1019, 897, 815, 733; HRMS (APCI, m/z): $[\text{M} + \text{NH}]^+$ calculated for $\text{C}_{20}\text{H}_{28}\text{N}$: 282.2216, found 282.2209. The spectroscopic properties of **6f** were identical to those reported in the literature.^{7b}

2,4-Diphenyl-4-methylpent-1-ene (6g). In a manner similar to that described in the general procedure, a mixture of **5g** (98 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 10 mol%), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was immersed in an oil bath at

130 °C for 24 h. After workup, the product **6g** (6 mg, 10%) was obtained as a colourless oil: $^1\text{H NMR}$ (CDCl_3 , 400 MHz) δ 7.25–7.07 (m, 10H), 5.06 (d, $J = 1.9$ Hz, 1H), 4.70 (d, $J = 1.9$ Hz, 1H), 2.75 (s, 2H), 1.14 (s, 6H) ppm; $^{13}\text{C NMR}$ (CDCl_3 , 101 MHz) δ 149.4, 146.7, 143.5, 128.0, 127.9, 126.9, 126.5, 126.0, 125.5, 116.9, 49.6, 38.7, 28.8; IR (KBr, cm^{-1}): 2963, 1260, 1112, 1015, 795; HRMS (APCI, m/z): $[\text{M} + \text{H}]^+$ calculated for $\text{C}_{18}\text{H}_{21}$: 237.1638, found 237.1632. The spectroscopic properties of **6g** were identical to those reported in the literature.^{7b}

General procedure for the nickel-catalysed reaction of dithioacetal with organozinc reagent

In a manner of the same procedure as described above except ZnI_2 (0–3 mmol) was added to the reaction mixture, which was heated at 130 °C for 24 h.

Compound 6a. In a manner similar to that described in the general procedure, a mixture of **5a** (120 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (638 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6a** (61 mg, 76%).

Compound 6b. In a manner similar to that described in the general procedure, a mixture of **5b** (104 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (957 mg, 3 mmol), and MeMgI (1 mL, 3 M in ether, 3 mmol) was converted to **6b** (66 mg, 89%).

Compound 6c. In a manner similar to that described in the general procedure, a mixture of **5c** (113 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (638 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6c** (60 mg, 81%).

Compound 6d. In a manner similar to that described in the general procedure, a mixture of **5d** (126 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 10 mol%), ZnI_2 (638 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6d** (58 mg, 67%).

Compound 6e. In a manner similar to that described in the general procedure, a mixture of **5e** (119 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (638 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6e** (62 mg, 78%).

Compound 6f. In a manner similar to that described in the general procedure, a mixture of **5f** (137 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (957 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6f** (49 mg, 74%).

Compound 6g. In a manner similar to that described in the general procedure, a mixture of **5g** (98 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 10 mol%), ZnI_2 (638 mg, 2 mmol), and MeMgI (0.7 mL, 3 M in ether, 2.1 mmol) was converted to **6g** (38 mg, 64%).

General procedure for the reaction of aryl halides with 2-propenylmagnesium bromide in the presence of $\text{NiCl}_2(\text{PPh}_3)_2$, ZnI_2 and 1,2-ethanedithiol

THF was removed from the solution of 2-propenylmagnesium bromide (3.5 mL, 1 M in THF, 3.5 mmol) and benzene (1 mL)



was then added. To a Schlenk tube containing aryl halide (0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (0.05 mmol), ZnI_2 (3.5 mmol) and 1,2-ethanedithiol (0.5 mmol) in benzene (1 mL), the benzene solution of 2-propenyl Grignard reagent was added. The mixture was then poured into saturated Na_2CO_3 solution. The organic layer was separated and the aqueous layer was extracted twice (10 mL) with diethyl ether. The combined organic portions were washed twice each (10 mL) with 10% NaOH and brine (10 mL), and dried (Na_2SO_4). The solvent was removed *in vacuo* and the residue was chromatographed on silica gel (petroleum ether and EtOAc) to give the product.

Reaction of 7a. In a manner of the general procedure as described above, to a mixture of 2-propenylmagnesium bromide (3.5 mmol), 4-iodo-*N,N*-dimethylaminebenzene **7a** (124 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (1.11 g, 3.5 mmol) and 1,2-ethanedithiol (0.04 mL, 0.5 mmol) in benzene (1 mL), the benzene solution of 2-propenyl Grignard reagent was added. The mixture was stirred for 6 h at rt and the temperature was raised to 130 °C and the mixture was stirred for 42 h. After workup, the mixture compound was chromatographed on silica gel (petroleum ether : EtOAc = 9 : 1) to give **1a** (6 mg, 7%) and **6a** (58 mg, 72%).

Reaction of 7c. In a manner of the general procedure as described above, a mixture of 2-propenylmagnesium bromide (3.5 mmol), 4-iodoanisole **7c** (117 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (1.11 g, 3.5 mmol) and 1,2-ethanedithiol (0.04 mL, 0.5 mmol) in benzene was stirred for 6 h at rt and the temperature was raised to 130 °C and the mixture was stirred for 42 h. After workup, the mixture compound was chromatographed on silica gel (petroleum ether) to give **1c** (12 mg, 16%) and **6c** (35 mg, 47%).

Reaction of 7d. In a manner of the general procedure as described above, a mixture of 2-propenylmagnesium bromide (3.5 mmol), 4-*tert*-butyliodobenzene **7d** (130 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (1.11 g, 3.5 mmol) and 1,2-ethanedithiol (0.04 mL, 0.5 mmol) in benzene was stirred for 6 h at rt and the temperature was raised to 130 °C and the mixture was stirred for 42 h. After workup, the mixture compound was chromatographed on silica gel (petroleum ether) to give **1d** (26 mg, 30%) and **6d** (32 mg, 37%).

Reaction of 8a. In a manner of the general procedure as described above, a mixture of 2-propenylmagnesium bromide (3.5 mmol), 4-bromo-*N,N*-dimethylaminebenzene **8a** (100 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (1.11 g, 3.5 mmol) and 1,2-ethanedithiol (0.04 mL, 0.5 mmol) in benzene was stirred for 6 h at rt and the temperature was raised to 130 °C and the mixture was stirred for 42 h. After workup, the mixture compound was chromatographed on silica gel (petroleum ether : EtOAc = 9 : 1) to give **1a** (14 mg, 17%) and **6a** (45 mg, 56%).

Reaction of 8b. In a manner of the general procedure as described above, a mixture of 2-propenylmagnesium bromide (3.5 mmol), 4-isopropylbromobenzene **8b** (100 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), ZnI_2 (1.11 g, 3.5 mmol) and 1,2-ethanedithiol (0.04 mL, 0.5 mmol) in benzene was stirred for 6 h at rt and the temperature was raised to 130 °C and the mixture was stirred for 42 h. After workup, the mixture

compound was chromatographed on silica gel (petroleum ether) to give **1e** (44 mg, 55%) and **6e** (27 mg, 34%).

Effect of the halide in MeMgX on the product distribution of the reaction of 5a in the presence of $\text{NiCl}_2(\text{PPh}_3)_2$. A mixture of **5a** (120 mg, 0.5 mmol), $\text{NiCl}_2(\text{PPh}_3)_2$ (33 mg, 0.05 mmol), and MeMgCl (0.7 mL, 3.0 M in ether, 2.1 mmol) was immersed in an oil bath at 130 °C for 24 h. After workup, the ratio of **1a** to **6a** was 87 to 13. The ratio was changed to 37 to 63 when the same amount of MeMgBr was used. When MeMgI was employed, the ratio of **1a** to **6a** changed to 4 to 96.

Author's contributions

T.-Y. L. and G.-Q. L. contributed to the conception and design of this study in addition to the data analysis. P. Z. and Z. L. contributed intellectually and took the responsibility to supervise L. Y., a graduate student, working on this project in the laboratory. All co-authors actively participated in writing the manuscript.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- (a) A. de Meijere and F. Diederich, *Metal-catalyzed cross coupling reactions; 2nd completely revised and enlarged edition*, vol. 1 and 2, Wiley-VCH, Mannheim, 2004; (b) Y. Nishihara, *Applied cross coupling reactions*, Springer, 2013; (c) J. Cossy, *Grignard reagents and transition metal catalysts: formation of C-C Bonds by Cross Coupling*, de Gruyter, 2016.
- (a) K. Tamao, K. Sumotani and M. Kumada, *J. Am. Chem. Soc.*, 1972, **94**, 4374; (b) R. J. P. Corriu and J. P. Masse, *J. Chem. Soc., Chem. Commun.*, 1973, 144.
- (a) E.-i. Negishi and L. Anastasia, *Chem. Rev.*, 2003, **103**, 1979–2017; (b) E.-i. Negishi, *Angew. Chem., Int. Ed.*, 2011, **50**, 6738.
- Y. Motoyama and H. Nishiyama, in *Lewis Acids in Organic Synthesis*, ed., H. Yamamoto, Wiley-VCH, 2000, ch. 3.
- (a) Y.-H. Chen, T.-Y. Luh, G.-H. Lee and S.-M. Peng, *J. Chem. Soc., Chem. Commun.*, 1994, 2369; (b) S.-M. Yeh, G.-H. Lee, Y. Wang and T.-Y. Luh, *J. Org. Chem.*, 1997, **62**, 8315.
- (a) C. Peppe, E. S. Lang, F. M. de Andrade and L. B. de Castro, *Synlett*, 2004, **10**, 1723; (b) M. Higashimura, K. Imamura, Y. Yokogawa and T. Sakakibara, *Chem. Lett.*, 2004, **33**, 728; (c) Q. H. Cai, J. Li, F. X. Bao and Y. K. Shan, *Appl. Catal., A*, 2005, **279**, 139; (d) H.-B. Sun, B. Lin, R. Hua and Y. W. Yin, *Eur. J. Org. Chem.*, 2006, 4231; (e) F. Howard, S. Sawadjoon and J. S. M. Samec, *Tetrahedron Lett.*, 2010, **51**, 4208; (f) A. Tarlani, M. P. Zarabadi, J. Muzart, E. Lotfalipour and



- F. Darkhosh, *Catal. Commun.*, 2011, **14**, 89; (g) B. V. Ramulu, L. Mahendar and G. Satyanarayana, *Asian J. Org. Chem.*, 2016, **5**, 207.
- 7 (a) H. M. Wang, P. Cui, G. Zou, F. Yang and J. Tang, *Tetrahedron*, 2006, **62**, 3985; (b) Y. Miyake, T. Moriyama, Y. Tanabe, G. Onodera and Y. Nishibayashi, *Organometallics*, 2011, **30**, 5972.
- 8 (a) E. Bergmann, H. Taubadel and H. Weiss, *Ber.*, 1931, **64**, 1493; (b) J. Hukki, *Acta Chem. Scand.*, 1949, **3**, 279; (c) A. Zwierzak and H. Pines, *J. Org. Chem.*, 1963, **28**, 3392; (d) N. H. Werstiuk and G. Timmins, *Can. J. Chem.*, 1988, **33**, 2309–2312; (e) B. Chaudhuri, *Org. Process Res. Dev.*, 1999, **3**, 220–223; (f) N. G. Grigor'eva, R. R. Galyautdinova, A. V. Vosmerikov, L. L. Korobitsina, B. I. Kutepov and U. M. Dzhemilev, *Pet. Chem.*, 2008, **48**, 366.
- 9 (a) T.-Y. Luh, *Acc. Chem. Res.*, 1991, **24**, 257; (b) T.-Y. Luh and C.-F. Lee, *Eur. J. Org. Chem.*, 2005, 3875.
- 10 (a) Z.-J. Ni and T.-Y. Luh, *J. Chem. Soc., Chem. Commun.*, 1987, 1515; (b) Z.-J. Ni, P.-F. Yang, D. N. P. Ng, Y.-L. Tzeng and T.-Y. Luh, *J. Am. Chem. Soc.*, 1990, **112**, 9356; (c) Z.-J. Ni, N.-W. Mei, X. Shi, Y.-L. Tzeng, M.-C. Wang and M. T.-Y. Luh, *J. Org. Chem.*, 1991, **56**, 4035.

