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Air-Stable Nickel Precatalysts for Fast and Quantitative Cross-Coupling of Aryl Sulfamates with Aryl Neopentylglycolboronates at Room Temperature

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Supporting Information

ABSTRACT: A library containing 10 air-stable Ni^{II}X(Aryl)(PCy$_3$)$_2$ σ-complexes as precatalysts (X = Cl, Br, OTs, OMs, aryl = 1-naphthyl, 2-naphthyl; X = Cl, 1-acenaphthenyl, 1-(2-methoxynaphthyl), 9-phenanthrenyl, 9-anthracyl) was synthesized and demonstrated to quantitatively cross-couple 2-methoxyphenyl dimethylsulfamate with methyl 4-(5,5-dimethyl-1,3,2-dioxaborinane-2-yl)benzoate at 23 °C in dry THF in the presence of K$_3$PO$_4$(H$_2$O)$_{3.2}$ in less than 60 min. Lower or higher amounts of H$_2$O in K$_3$PO$_4$ and as received THF mediate the same transformation in a maximum three times longer reaction time.

Since its discovery in 1995,[1] the Ni-catalyzed Suzuki–Miyaura[2] reaction has evolved into an attractive synthetic method for borylation,[3] cross-coupling of a variety of unreactive electrophiles based on carbon–oxygen bonds,[4] and even aryl fluorides.[5] Therefore, Ni catalysis provides both a less expensive and a more reactive variant than Pd catalysis. The mixed-ligand[4h,6] Ni(COD)$_2$/PCy$_3$[7] and the precatalyst[8−10] based on the σ-complex *trans*-chloro(1-naphthyl) bis(triphenylphosphine)Ni^{II} [9,10] (precatalyst **4**) together with PCy$_3$ mixed-ligand, [Ni^{II}Cl(1-naphthyl)(PPh$_3$)$_2$]/PCy$_3$,[10] facilitated entries into room temperature cross-coupling reactions of carbon–oxygen based electrophiles[4a,10] with a diversity of boron-based nucleophiles.[4e,10] Since Ni^0 catalysts including Ni(COD)$_2$ are air sensitive, σ-complexes obtained by oxidative addition of aryl electrophiles to Ni^0 species generated an attractive approach to reactive and air stable nickel precatalysts. Inspired by the Ni^{II}Cl(1-naphthyl)(PPh$_3$)$_2$/PCy$_3$ precatalyst/mixed-ligand system,[10] we report here the discovery of a library of air stable Ni^{II}X(Aryl)(PCy$_3$)$_2$ (X = Cl, Br, OTs, OMs, aryl = 1-naphthyl, 2-napththyl; X = Cl, aryl = 1-acenaphthenyl, 1-(2-methoxynaphthyl), 9-phenanthrenyl, 9-anthracenyl) precatalysts that mediate the quantitative cross-coupling of *ortho*-substituted aryl sulfamates with aryl neopentylglycolboronates in less than 1 h at room temperature (23 °C) in dry THF. The *ortho*-substituted aryl sulfamate electrophile was selected because of its synthetic versatility[4c] and lower reactivity compared with aryl mesylates[4a,l] and aryl halides.[4l] The aryl neopentylglycolboronate nucleophile, synthesized from the in situ prepared neopentylglycolborane by a method inspired by the procedure reported for pinacolborane,[11] was used due to its lower reactivity when compared with other arylboron nucleophiles.[4l] This selection will allow the preliminary results reported here to be used to estimate the reactivity of these precatalysts in cross-couplings of other electrophiles[4a] and nucleophiles.[4l]

Ni^{II}Cl(1-naphthyl)(PPh$_3$)$_2$ was synthesized by the left-hand route depicted in Scheme 1,[10] while Ni^{II}Cl(1-naphthyl)(PCy$_3$)$_2$ was obtained both by the top and right routes. All other precatalysts were synthesized by the right-hand route.

Cross-coupling with Ni(COD)$_2$/mixed-ligand, **4**/mixed-ligand, **5**/mixed-ligand, and **6**/mixed-ligand indicated that PCy$_3$ may exchange for COD or PPh$_3$ to create precatalyst **6** in situ (Scheme 2).

The synthesis of **6** demonstrated that indeed in the absence of the mixed ligands PPh$_3$ and COD, this precatalyst is more reactive than Ni(COD)$_2$, **4** and **5** with PCy$_3$ as mixed ligand.

Water is known to be involved in the cross-coupling catalytic process.[4e,12] Therefore, a series of samples of K$_3$PO$_4$ with various amounts of water of hydration were used to perform Ni-catalyzed cross-coupling experiments with both dry and as-received wet and inhibited THF (Scheme 3).

Scheme 4 compares the role of X (Cl, OTs, OMs) and excess PCy$_3$ in cross-coupling reactions as monitored by GC to quantitative conversion. It was observed that precatalysts **6**–**11** yield quantitative conversions in 50–60 min regardless of the nature of X when no excess of PCy$_3$ was used or even in 30–50 min when excess PCy$_3$ was used.

Additional recrystallization of precatalyst **7**, isolated by precipitation in hexane when prepared by left or right route from Scheme 1, does not change its activity (Scheme 4). Exchange of Cl from **6** and **7** for tosylate in **8** and **9** and mesylate in **10** and **11** maintains the same catalytic activity.

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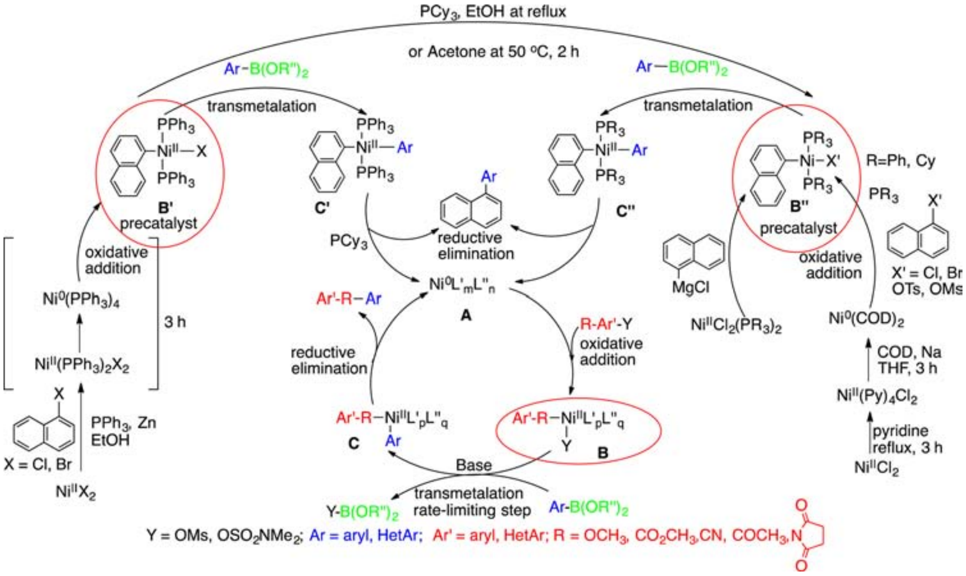
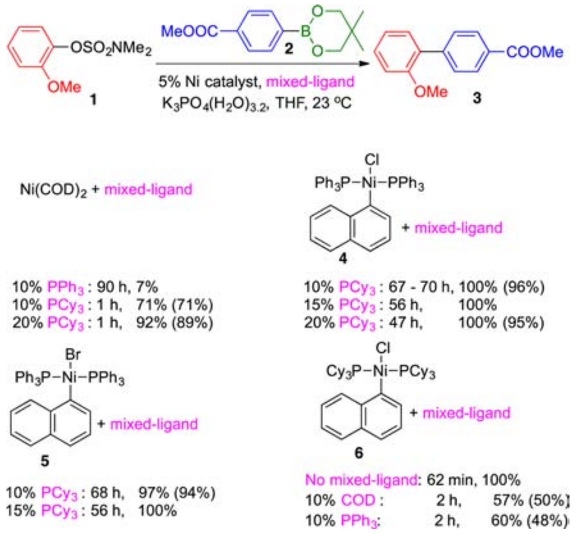
Scheme 1. Synthesis of *trans*-$Ni^{II}X(1\text{-naphthyl})(PR_3)_2$ σ-Complexes (X = Br, Cl, OMs, OTs) and the Proposed Mechanism of Nickel-Catalyzed Suzuki–Miyaura Cross-Coupling

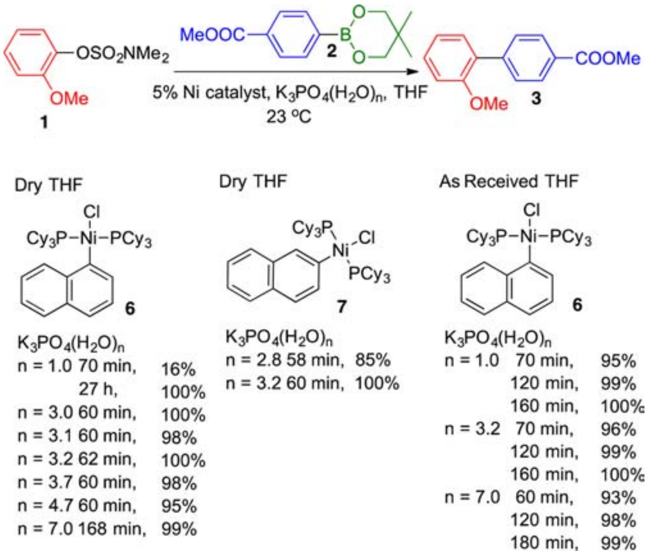


Scheme 2. Cross-Coupling of 2-Methoxyphenyl Dimethylsulfamate with Methyl 4-(5,5-Dimethyl-1,3,2-dioxaborinan-2-yl)benzoate at 23 °C in THF Catalyzed by Ni Precatalysts and Mixed-Ligand Systems[a]



[a]Reaction conditions: aryl sulfamates (0.30 mmol), aryl neopentylglycolboronates (0.32 mmol), Ni precatalyst (0.015 mmol), mixed ligand (10 to 20 mol %) vs aryl sulfamate, $K_3PO_4(H_2O)_{3.2}$ (191 mg), THF (1.0 mL). Conversion by GC, isolated yield in parentheses.

Scheme 3. Effect of Water on Ni-Catalyzed Cross-Coupling of 2-Methoxyphenyl Dimethylsulfamate with Methyl 4-(5,5-Dimethyl-1,3,2-dioxaborinan-2-yl)benzoate at 23 °C in THF[a]



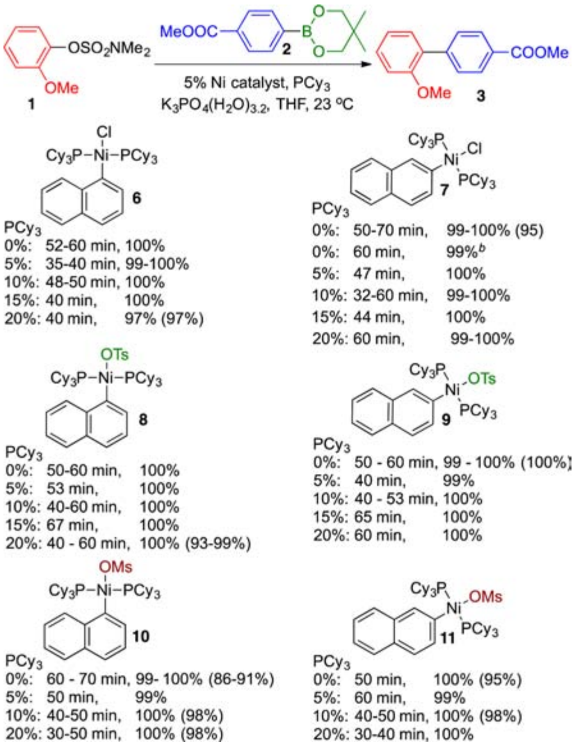
[a]Reaction conditions: aryl sulfamates (0.30 mmol), aryl neopentylglycolboronates (0.32 mmol), Ni precatalyst (0.015 mmol), $K_3PO_4(H_2O)_n$ (191 mg), THF (1.0 mL). Conversion by GC.

The efficient activation of precatalyst **6** is depicted in Scheme 5. Upon mixing with dioxaborinane **2**, precatalyst **6** generates quantitatively the active species $Ni^0(PCy_3)_2$ in less than 5 min (Scheme 5). This coordinatively unsaturated Ni^0 species, in contrast with the coordinatively saturated $Ni^0(PCy_3)_3$,[13] may act as the active catalyst in the subsequent cross-coupling reaction (Scheme 1). Additional mechanistic investigations are required to support this hypothesis.

In order to elucidate the role of substitution of the naphthyl groups of these precatalysts, several electron-rich substituents and extra fused aromatic rings were incorporated in the structure of **6**. Therefore, precatalysts **12**–**15** were prepared and tested in the same cross-coupling reaction (Scheme 6). Additional *ortho*-substitution on the 1-naphthyl group of precatalyst **13** leads to slightly lower reactivity, while *para*-substitution (precatalyst **12**) has no effect. An additional fused aromatic ring as in precatalysts **14** and **15** does not significantly change reactivity but does decrease the atom economy of the catalytic system (Scheme 6).

In summary, a library of 10 Ni precatalysts which mediate quantitative cross-coupling of *ortho*-substituted aryl sulfamates with aryl neopentylglycolboronates in the presence of $K_3PO_4(H_2O)_{3.2}$ in less than 60 min at room temperature was reported. Precatalyst **6** was prepared by both the left and right

Scheme 4. Activity of $Ni^{II}X(naphthyl)(PCy_3)_2$ Precatalysts in Cross-Coupling of 2-Methoxyphenyl Dimethylsulfamate with Methyl 4-(5,5-Dimethyl-1,3,2-dioxaborinane-2-yl)benzoate at 23 °C in THF[a]

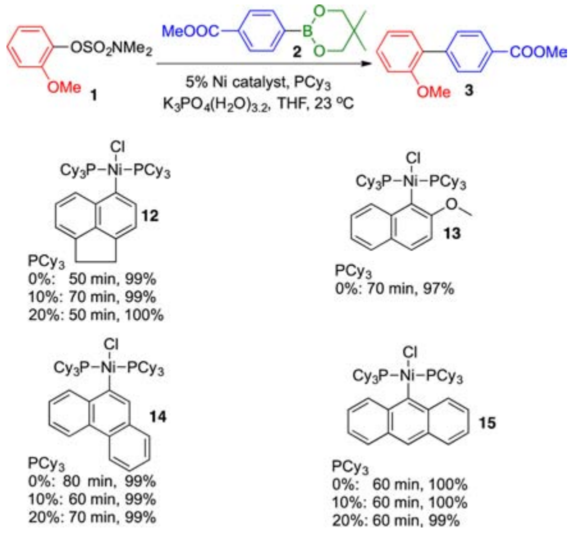


[a]Reaction conditions: aryl sulfamates (0.30 mmol), aryl neopentylglycolboronates (0.32 mmol), Ni precatalyst (0.015 mmol), $K_3PO_4(H_2O)_{3.2}$ (191 mg), THF (1.0 mL). Conversion by GC, isolated yield in parentheses. [b]Precatalyst was recrystallized from toluene/hexanes (**1**:**10**).

Scheme 5. Activation of Precatalyst 6[a]

[a]Conditions 1: **6** (0.10 mmol), **2** (0.20 mmol), $K_3PO_4(H_2O)_{3.2}$ (0.30 mmol), dry THF (1.0 mL). **16** was isolated in 0.088 mmol in 12 h. Conditions 2: **6** (0.015 mmol), **2** (0.32 mmol) $K_3PO_4(H_2O)_{3.2}$ (191 mg), dry THF (1.0 mL). 100% conversion was obtained in 5 min as determined by ^1H NMR.

Scheme 6. Activity of $Ni^{II}X(R\text{-}naphthyl)(PCy_3)_2$ Precatalysts in Cross-Coupling of 2-Methoxyphenyl Dimethylsulfamate with Methyl 4-(5,5-Dimethyl-1,3,2-dioxaborinan-2-yl)benzoate at 23 °C in THF[a]



[a]Reaction conditions: aryl sulfamates (0.30 mmol), aryl neopentylglycolboronates (0.32 mmol), Ni precatalyst (0.015 mmol), $K_3PO_4(H_2O)_{3.2}$ (191 mg), THF (1.0 mL). Conversion by GC.

routes from Scheme 1, while the other was prepared by the right route that is recommended for aryl tosylates, aryl mesylates, and more reactive aryl chlorides such as 9-chloroanthracene. It is remarkable that precatalysts **6**−**15** maintain their reactivity after being stored for 1 year at room temperature in air, despite the sensitivity of free PCy_3 to oxygen. Furthermore, precatalyst **4** has not changed reactivity even after 4 years in air. Previously reported Ni precatalysts were stable in air for at least 2 weeks at 0 °C.[8c] The simple synthesis of the precatalysts reported here, their much higher reactivity than that of the corresponding π-complex,[4b,c,h] their air stability, and their ability to achieve complete conversion at room temperature in dry and in as received THF will most probably make them valuable for cross-coupling reactions in medicinal, materials, supramolecular, and macromolecular synthesis. Additional Ni precatalysts and electrophilic and nucleophilic substrates are under investigation.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Synthesis of precatalysts, conversions monitored in time, supporting data for Scheme 2, and experimental procedures and spectral data for all new compounds (^1H NMR, ^{13}C NMR, HRMS, elemental analysis). 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 interest.

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