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Suzuki–Miyaura Cross-Coupling of Amides Using Well-Defined, Air- and Moisture-Stable Nickel/NHC (NHC = N-Heterocyclic Carbene) Complexes

Jonathan Buchspies, Md. Mahbubur Rahman and Michal Szostak *

Department of Chemistry, Rutgers University, 73 Warren Street, Newark, NJ 07102, USA; jonathan.buchspies@gmail.com (J.B.); rahman.mm11@gmail.com (M.M.R.)
* Correspondence: michal.szostak@rutgers.edu; Tel.: +1-973-353-5329

Received: 6 March 2020; Accepted: 25 March 2020; Published: 31 March 2020

Abstract: In this Special Issue on *N-Heterocyclic Carbenes and Their Complexes in Catalysis*, we report the first example of Suzuki–Miyaura cross-coupling of amides catalyzed by well-defined, air- and moisture-stable nickel/NHC (NHC = N-heterocyclic carbene) complexes. The selective amide bond N–C(O) activation is achieved by half-sandwich, cyclopentadienyl [CpNi(NHC)Cl] complexes. The following order of reactivity of NHC ligands has been found: IPr > IMes > IPaul ≈ IPr*. Both the neutral and the cationic complexes are efficient catalysts for the Suzuki–Miyaura cross-coupling of amides. Kinetic studies demonstrate that the reactions are complete in < 1 h at 80 °C. Complete selectivity for the cleavage of exocyclic N-acyl bond has been observed under the experimental conditions. Given the utility of nickel catalysis in activating unreactive bonds, we believe that well-defined and bench-stable [CpNi(NHC)Cl] complexes will find broad application in amide bond and related cross-couplings of bench-stable acyl-electrophiles.

Keywords: N-heterocyclic carbenes; nickel; nickel/NHC; amide bonds; Suzuki–Miyaura; cross-coupling; N–C cleavage; N–C activation; [CpNi(NHC)X]; half-sandwich; cyclopentadienyl

1. Introduction

Nickel catalysis has recently garnered significant attention, enabling cleavage of unreactive bonds by this abundant 3D transition metal [1–3]. Simultaneously, major advances have been made in amide cross-coupling, wherein highly selective oxidative addition of the N–C(O) bond enables to exploit the traditionally unreactive amides as a novel class of acyl and aryl electrophiles [4–10]. This unconventional amide bond disconnection is particularly relevant in the view of common presence of amides in natural products, pharmaceuticals, and biopolymers, where the emergence of new catalytic methods has a potentially major impact on the way chemists perceive synthetic routes.

In this context, palladium/NHC (NHC = N-heterocyclic carbene) catalysis using well-defined Pd(II)–NHC precatalysts has been established as the dominant catalytic direction in activating amide N–C(O) bonds for acyl cross-coupling [4,11–14]. However, to the best of our knowledge, there are no methods for the use of well-defined, air- and moisture-stable nickel/NHC complexes as efficient precatalysts in amide bond activation. In spite of the advances made by in situ formed Ni(0) catalysts, the lack of air-stability of $Ni(cod)_2$ severely limits the potential broad applications of the powerful Ni catalysis platform in amide bond activation [15–17].

In this Special Issue on *N-Heterocyclic Carbenes and Their Complexes in Catalysis*, we report the first example of Suzuki–Miyaura cross-coupling of amides catalyzed by well-defined, air- and moisture-stable nickel/NHC (NHC = N-heterocyclic carbene) complexes (Figure 1). We were attracted to the recent elegant advances made in the design of half-sandwich, cyclopentadienyl [CpNi(NHC)X]

complexes by Chetcuti et al. [18–24]. Herein, we demonstrate that these highly practical [CpNi(NHC)Cl] precatalysts [25–31] are capable of selective activation of amide N–C(O) bonds. The following features of our study are noteworthy: (1) The reaction represents, to the best of our knowledge, the first example of acyl-type cross-coupling achieved by half-sandwich [CpNi(NHC)X] complexes. (2) We demonstrate the following order of reactivity of NHC ligands in amide bond cross-coupling: IPr > IMes > IPaul ≈ IPr*. (3) We further establish that both the neutral and the cationic complexes are efficient catalysts for the Suzuki–Miyaura cross-coupling of amides. (4) Kinetic studies demonstrate that the reactions reach full conversion in < 1 h at 80 °C. (5) Furthermore, full selectivity in cleavage of exocyclic N-acyl bond has been observed. Our method opens up the application of a wide variety of [CpNi(NHC)X] and related half-sandwich complexes as well-defined, air- and moisture stable precatalysts for cross-coupling of amide N–C bonds.

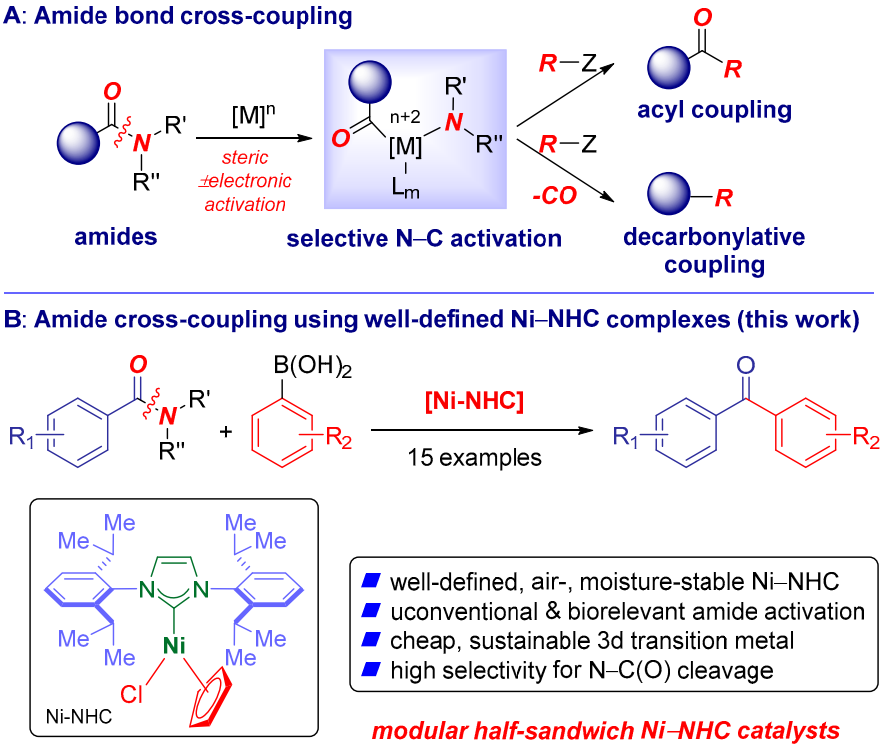


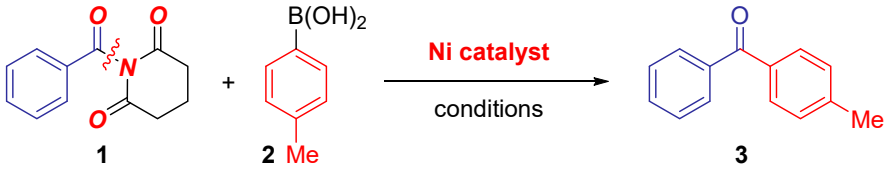
Figure 1. (**A**) Amide bond cross-coupling. (**B**) Well-defined, air- and moisture-stable Ni–NHC complexes in selective activation of amide N–C(O) bonds (this work).

2. Results

We first examined the cross-coupling of N-acyl-glutarimides as model substrates for the cross-coupling with 4-tolylboronic acid using the readily prepared [CpNi(IPr)Cl] under various conditions (Table 1, Figure 2) (IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene). Optimization revealed that the desired cross-coupling proceeds in 85% yield in the presence of [CpNi(NHC)Cl] (10 mol%) as catalyst and K_2CO_3 (3.0 equivalent) as base in toluene as solvent at 80 °C using 4-Tol-$B(OH)_2$ (3.0 equivalent) (Table 1, entry 1). Interestingly, increasing the reaction temperature to 120 °C had only a minor effect on the cross-coupling (Table 1, entries 2–4). Furthermore, although previous studies suggested the beneficial effect of phosphine ligands on the Suzuki–Miyaura $C(sp^2)$–$C(sp^2)$ cross-coupling catalyzed by Ni–NHC complexes [32], in our case the addition of phosphine had an inhibitory effect on the cross-coupling (Table 1, entries 5–7). Examination of reaction parameters revealed K_2CO_3 as the optimal base and toluene as the preferred solvent (Table 1, entries 8–15). Interestingly, the use of Ni/phosphine catalysts, such as $[Ni(PCy_3)_2Cl_2]$ and $[Ni(PPh_3)_2Cl_2]$ resulted in little or no cross-coupling (Table 1, entries 16–19). Likewise, no reaction was observed with nikelocene

(Table 1, entry 20) [33], supporting the key role of the NHC ligand on the cross-coupling. Moreover, the recently studied in cross-coupling of aryl sulfamates [Ni(dppf)(*o*-tol)Cl] [34] was unreactive under our conditions (Table 1, entry 21), while the mixed NHC/phosphine Ni(II) complex, [Ni(IPr)(PPh_3)Cl_2] [35], appeared as a potentially useful catalyst, but was less reactive than [CpNi(IPr)Cl] (Table 1, entry 22).

Table 1. Optimization of the Suzuki–Miyaura cross-coupling of amides using Ni–NHCs [1].



Entry	Catalyst	[Ni] (mol%)	Base	Solvent	*T* (°C)	Yield (%)
1	[CpNi(IPr)Cl]	10	K_2CO_3	toluene	80	85
2	[CpNi(IPr)Cl]	5	K_2CO_3	toluene	80	42
3	[CpNi(IPr)Cl]	10	K_2CO_3	toluene	120	80
4	[CpNi(IPr)Cl]	5	K_2CO_3	toluene	120	39
5 [2]	[CpNi(IPr)Cl]	10	K_2CO_3	toluene	120	40
6 [3]	[CpNi(IPr)Cl]	10	K_2CO_3	toluene	120	54
7 [3]	[CpNi(IPr)Cl]	10	K_2CO_3	toluene	80	27
8	[CpNi(IPr)Cl]	5	K_2CO_3	dioxane	120	34
9	[CpNi(IPr)Cl]	10	K_2CO_3	dioxane	120	48
10	[CpNi(IPr)Cl]	10	K_2CO_3	THF	80	<10
11	[CpNi(IPr)Cl]	10	Na_2CO_3	THF	80	20
12	[CpNi(IPr)Cl]	10	Na_2CO_3	THF	120	<5
13	[CpNi(IPr)Cl]	10	Na_2CO_3	dioxane	80	<5
14	[CpNi(IPr)Cl]	10	Na_2CO_3	dioxane	120	<5
15	[CpNi(IPr)Cl]	10	K_3PO_4	toluene	80	38
16	[Ni(PCy_3)$_2Cl_2$]	10	Na_2CO_3	dioxane	80	31
17	[Ni(PCy_3)$_2Cl_2$]	10	Na_2CO_3	dioxane	120	16
18	[Ni(PPh_3)$_2Cl_2$]	10	K_2CO_3	toluene	120	<5
19	[Ni(PPh_3)$_2Cl_2$]	10	Na_2CO_3	dioxane	80	<5
20	[NiCp$_2$]	10	K_2CO_3	toluene	120	<5
21	[Ni(dppf)(*o*-tol)Cl]	10	K_2CO_3	toluene	120	<5
22	[Ni(IPr)(PPh_3)Cl_2]	10	K_2CO_3	toluene	120	64
23	[CpNi(IPr)(NCMe)](PF_6)	10	K_2CO_3	toluene	80	44
24	[CpNi(IPr)(NCMe)](PF_6)	5	K_2CO_3	toluene	80	28
25	[CpNi(IMes)Cl]	10	K_2CO_3	toluene	80	77
26	[CpNi(IMes)Cl]	5	K_2CO_3	toluene	80	40
27	[CpNi(IPaul)Cl]	10	K_2CO_3	toluene	80	68
28	[CpNi(IPaul)Cl]	5	K_2CO_3	toluene	80	39
29	[CpNi(IPr*)Cl]	10	K_2CO_3	toluene	80	63
30	[CpNi(IPr*)Cl]	5	K_2CO_3	toluene	80	42

[1] Conditions: Amide (1.0 equivalent), 4-Tol-B(OH)$_2$ (3.0 equivalent), base (3.0 equivalent), [Ni] (5-10 mol%), solvent (0.25 M), *T*, 15 h. [2] PPh_3 (20 mol%). [3] PPh_3 (11 mol%). Yields were determined by ^{1}H NMR.

Pleasingly, the cationic complex [CpNi(IPr)(NCMe)](PF_6), readily prepared by chloride abstraction with KPF_6 according to the procedure Chetcuti [18] showed promising reactivity (Table 1, entries 23–24), indicating potential application of this class of cationic Ni–NHC catalysts in amide bond cross-coupling in the future.

Further, we were particularly interested in evaluating steric demand of NHC ligands on the performance of [CpNi(NHC)Cl] complexes in amide cross-coupling [36,37]. We found that [CpNi(IMes)Cl] is slightly less reactive than [CpNi(IPr)Cl] (Table 1, entries 25–26). Furthermore, examination of the highly attractive class of bulky but flexible NHC ligands, IPaul [38] and IPr* [39] revealed [CpNi(IPaul)Cl] and [CpNi(IPr*)Cl] as promising catalysts for N–C bond activation. Of

note, [CpNi(IPaul)Cl] is commercially-available, which should facilitate the discovery of future cross-couplings of amide bonds mediated by this precatalyst.

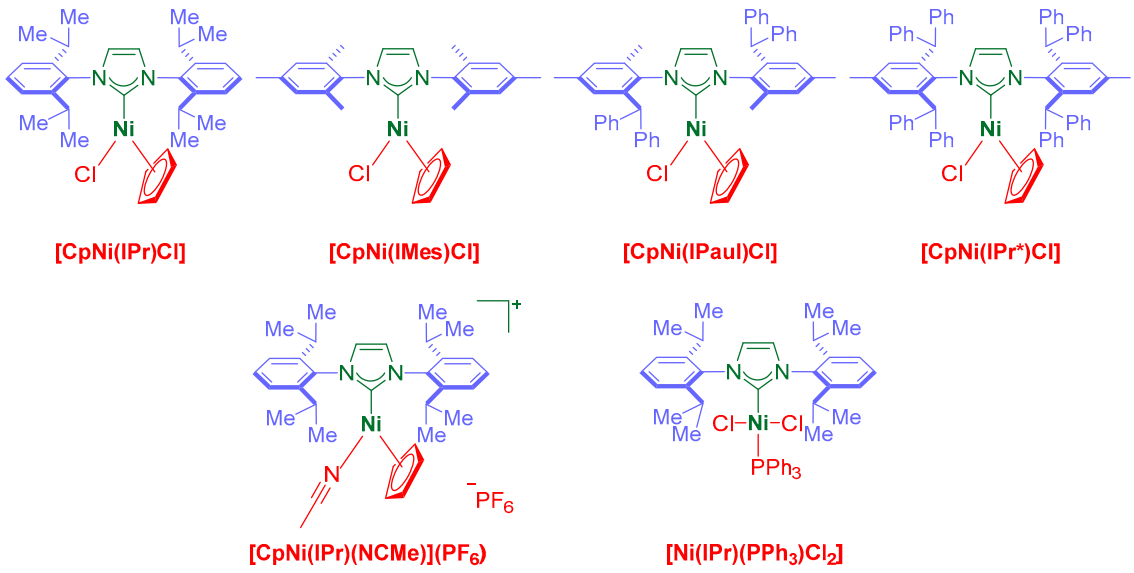
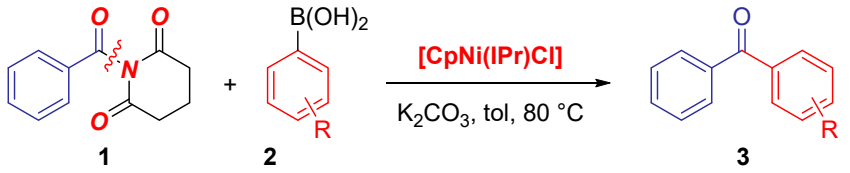


Figure 2. Structures of well-defined, air- and moisture-stable Ni–NHC catalysts.

With the optimized catalyst system in hand, we examined the scope of this Suzuki–Miyaura cross-coupling catalyzed by well-defined Ni(II)–NHC precatalysts (Tables 2 and 3, and see Supporting Information). As shown, the reaction was compatible with electron-donating groups on the boronic acid (**3a–c**). Steric-hindrance at the ortho-position of the boronic acid was well-tolerated (**3d–e**). Furthermore, fluorine functionalized boronic acids, such as 3-fluoro and 3-trifluoromethyl (**3f–g**) could be introduced by this Ni-catalyzed approach. We were further pleased that conjugated arenes, such as naphthalene and biphenyl delivered the desired biaryl ketone products in good yields (**3h–i**). Only one aliphatic boronic acid was tested, and it was incompatible with the reaction conditions (entry 10). In terms of the amide scope, pleasingly, electron-rich and electron-withdrawing groups were well-tolerated on the amide component (**3a**,**c**,**j**), while the electron-deficient amides appeared to be more reactive (*vide infra*). Steric hindrance on the ortho-position of the amide was tolerated, albeit it exerted a more pronounced effect than on the boronic acid, consistent with a decreased amide bond twist by ortho-substitution (**3d**). Furthermore, fluorine-containing amides and heterocyclic amides provided the desired products in good yields (**3k–l**). It is noteworthy that decarbonylation to give Ar–Ni after loss of CO was not observed [40], consistent with the stability of acyl-Ni(NHC) intermediate.

Next, intermolecular competition experiments were conducted to gain preliminary insight into the reaction (Schemes 1 and 2). As shown, competitions revealed electron-deficient amides to be significantly more reactive than electron-rich amides (Scheme 1, CF_3:MeO = 93:7). In contrast, a comparable reactivity of electron-rich and electron-deficient boronic acids was observed (Scheme 2, MeO:CF_3 = 58:42). These preliminary studies are consistent with oxidative addition of the N–C(O) bond as the rate limiting step of the reaction [41]. Further studies on the mechanism are ongoing.

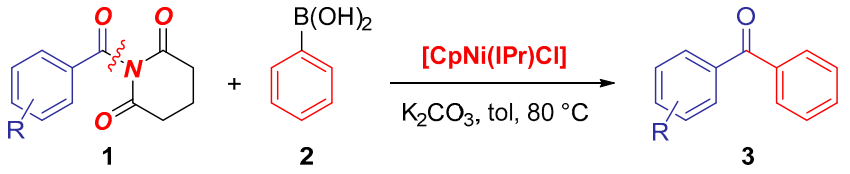
Table 2. Scope of the Suzuki–Miyaura cross-coupling of amides using [CpNi(IPr)Cl] [1].



Entry	Amide	Ar-B(OH)$_2$	3	Yield (%)
1	C_6H_5	4-Me-C_6H_4	**3a**	85
2	C_6H_5	4-*t*-Bu-C_6H_4	**3b**	87
3	C_6H_5	4-MeO-C_6H_4	**3c**	79
4	C_6H_5	2-Me-C_6H_4	**3d**	85
5	C_6H_5	2-MeO-C_6H_4	**3e**	58
6	C_6H_5	3-F-C_6H_4	**3f**	48
7	C_6H_5	3-CF_3-C_6H_4	**3g**	56
8	C_6H_5	2-Np	**3h**	71
9	C_6H_5	4-Ph-C_6H_4	**3i**	67
10[2]	C_6H_5	Cyclopentyl	-	<5

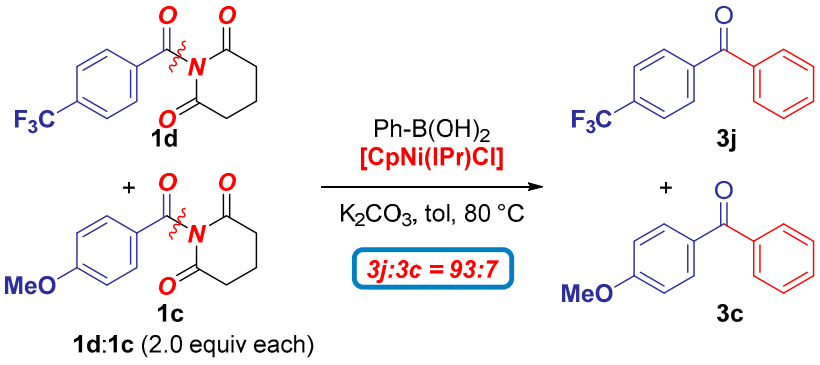
[1] Conditions: Amide (1.0 equivalent), Ar-B(OH)$_2$ (3.0 equivalent), K_2CO_3 (3.0 equivalent), [CpNi(IPr)Cl] (10 mol%), toluene (0.25 M), 80 °C, 15 h. [2] Cyclopentylboronic acid was used.

Table 3. Scope of the Suzuki–Miyaura cross-coupling of amides using [CpNi(IPr)Cl] [1].

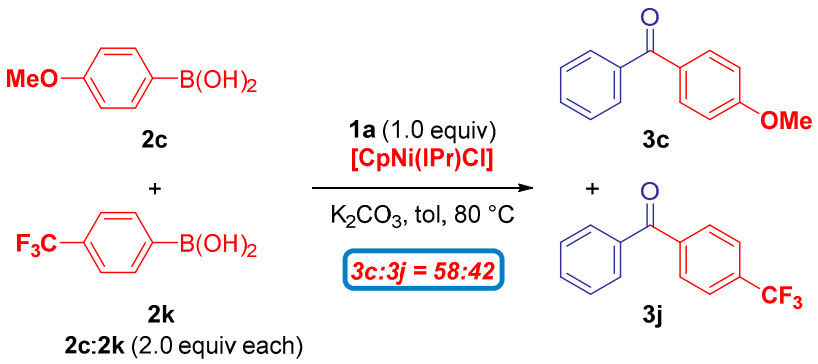


Entry	Amide	Ar-B(OH)$_2$	3	Yield (%)
1	4-Me-C_6H_4	C_6H_5	**3a**	70
2	4-MeO-C_6H_4	C_6H_5	**3c**	67
3	4-CF_3-C_6H_4	C_6H_5	**3j**	96
4	2-Me-C_6H_4	C_6H_5	**3d**	39
5	3,4-F_2-C_6H_3	C_6H_5	**3k**	70
6	2-thienyl	C_6H_5	**3l**	55

[1] Conditions: Amide (1.0 equivalent), Ar-B(OH)$_2$ (3.0 equivalent), K_2CO_3 (3.0 equivalent), [CpNi(IPr)Cl] (10 mol%), toluene (0.25 M), 80 °C, 15 h.



Scheme 1. Competition experiments—amides.



Scheme 2. Competition experiments—boronic acids.

Kinetic studies were performed to gain insight into the reaction profile (Figure 3). As shown, the reaction reached 75% conversion after 5 min, while 86% and >95% conversion was observed after 30 and 60 min, respectively, consistent with efficient generation of the reactive Ni(0)–NHC catalyst [40,41] under the reaction conditions (TON = 8.5, 10 mol%; TOF = 1.5 min^{-1}). Studies on the mechanism are underway and will be reported in due course.

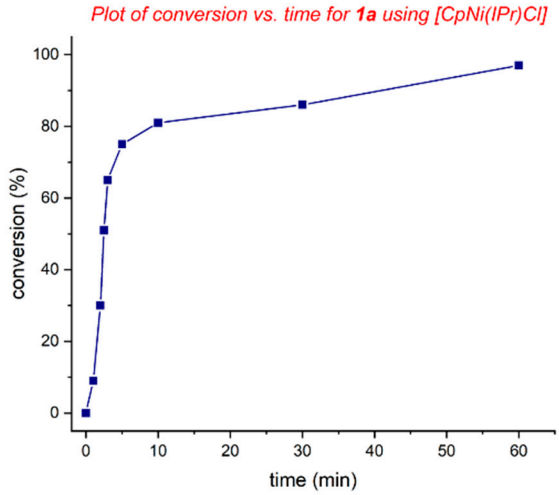
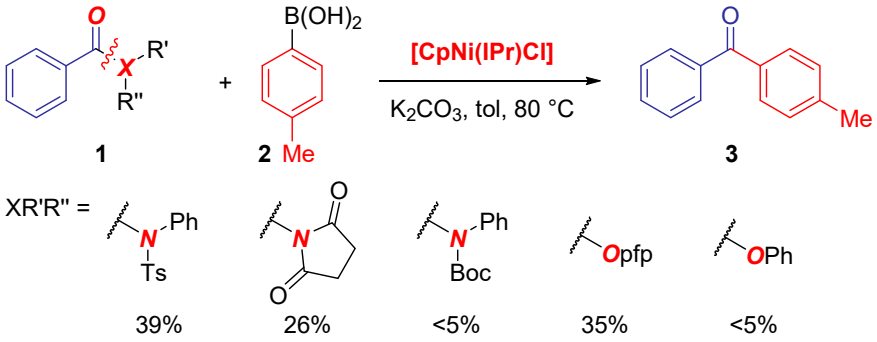


Figure 3. Kinetic profile of **1a**. Conditions: **1a**, 4-Tol-$B(OH)_2$ (3.0 equivalent), [CpNi(IPr)Cl] (10 mol%), K_2CO_3 (3.0 equivalent), toluene (0.25 M), 80 °C, 1–60 min.

Finally, we were interested to probe the effect of different acyl leaving groups on the cross-coupling (Scheme 3). N-Acyl-glutarimides have emerged as the go-to amides to develop new cross-coupling methods by N–C activation. Furthermore, the present coupling is compatible with N-sulfonyl activation in acyclic amides, such as N,N-Ph/Ts, and N-acyl-succinimides, albeit the cross-coupling product was obtained in lower yield under the present conditions. In contrast, N-Boc-carbamates, were recovered unchanged from the reaction conditions, indicating a potential for chemoselective coupling. Typically, N-Ts amides and N-acyl-succinimides are consumed under the reaction conditions, while other electrophiles were recovered unchanged. Moreover, the C–O cross-coupling is also feasible under the present conditions as demonstrated by the cross-coupling of Opfp ester (pfp = pentafluorophenyl) [42,43]. In contrast, the unactivated phenolic ester was recovered unchanged, consistent with a considerable potential of [CpNi(NHC)Cl] catalysts in chemoselective activation of C(acyl)–O electrophiles.



Scheme 3. Suzuki–Miyaura cross-coupling of different amides and esters using [CpNi(IPr)Cl].

3. Discussion

In summary, we have reported the first example of Suzuki–Miyaura cross-coupling of amides catalyzed by well-defined, air- and moisture-stable nickel/NHC complexes. The reaction delivers biaryl ketones in good yields using inexpensive nickel catalyst with excellent N–C(O) cleavage selectivity cf. endocylic amide bond and acyl vs. decarbonylative coupling. In a broad sense, this report establishes the capacity of highly attractive half-sandwich [CpNi(NHC)Cl] complexes as catalysts for activation of amide N–C(O) bonds. Furthermore, we have established the order of reactivity of NHC ligands in [CpNi(NHC)Cl] complexes as IPr > IMes > IPaul ≈ IPr*, and showed that both neutral and cationic complexes serve as efficient catalysts for amide bond cross-coupling. Reaction profile studies demonstrated that these reactions are complete in < 1 h at 80 °C. In a broader context, the present method should be evaluated in comparison with other known approaches to biaryl ketones from amides [3–10] and acyl electrophiles [15]. The use of Ni catalysis [1–3] and the beneficial performance of Ni–NHC complexes [25–29] may accelerate the development of new approaches to activating amide bonds. Considering the utility of nickel catalysis in activation of unreactive bonds, we anticipate that [CpNi(NHC)Cl] complexes will be of interest in activation of bench-stable acyl electrophiles. Further mechanistic studies, as well as efforts to expand the scope of electrophiles in cross-coupling catalyzed by well-defined Ni–NHC complexes are ongoing.

4. Materials and Methods

4.1. General Information

General methods have been published (See Supporting Information) [11].

4.2. General Procedure for [CpNi(IPr)Cl] Catalyzed Cross-Coupling of Amides

In a typical cross-coupling procedure, an oven-dried vial was charged with an amide substrate (neat, 1.0 equivalent), boronic acid (typically, 3.0 equivalent), potassium carbonate (typically, 3.0 equivalent), [CpNi(NHC)Cl] (typically, 10 mol%), placed under a positive pressure of argon or nitrogen, and subjected to three evacuation/backfilling cycles under high vacuum. Toluene (to reach 0.25 M concentration) was added at room temperature, the reaction mixture was placed in a preheated oil bath at 80 °C, and stirred at 80 °C. After the indicated time, the reaction was cooled down, diluted with CH_2Cl_2 (10 mL), filtered, and concentrated. The sample was analyzed by ^{1}H NMR ($CDCl_3$, 500 MHz) and GC-MS to obtain conversion, selectivity, and yield using internal standard and comparison with authentic samples. Unless stated otherwise, all compounds have been previously reported. All compounds have been quantified by ^{1}H NMR spectroscopy using nitromethane as internal standard (500 MHz, CD_3Cl). All reactions have been carried out in microwave vials with heavy-wall, Type I, Class A borosilicate. These vials are designed to withstand pressures up to 300 PSI (20 bars) and are equivalent to Fisher-Porter tube.

4.3. Representative Procedure for [CpNi(IPr)Cl] Catalyzed Cross-Coupling of Amides

An oven-dried vial was charged with 1-benzoylpiperidine-2,6-dione (neat, 108.6 mg, 0.5 mmol), 4-tolylboronic acid (204.0 mg, 1.5 mmol, 3.0 equivalent), K_2CO_3 (207.3 mg, 1.5 mmol, 1.5 equivalent), [CpNi(IPr)Cl] (10 mol%, 27.4 mg), placed under a positive pressure of argon, and subjected to three evacuation/backfilling cycles under high vacuum. Toluene (0.25 M, 2.0 mL) was added at room temperature, the reaction mixture was placed in a preheated oil bath at 80 °C, and stirred for 15 h at 80 °C. After the indicated time, the reaction was cooled down, diluted with CH_2Cl_2 (10 mL), filtered, and concentrated. A sample was analyzed by ^{1}H NMR ($CDCl_3$, 500 MHz) and GC-MS to obtain conversion, yield, and selectivity using internal standard and comparison with authentic samples. Purification by chromatography on silica gel (hexanes/ethyl acetate) afforded the title product. Yield 81% (79.5 mg). White solid. Characterization data are included in the section below.

4.4. Characterization Data for Products 3a–l (Tables 2-3)

The following Characterization Data are shown in Supporting Information.

Phenyl(*p*-tolyl)methanone (3a). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.82-7.80 (d, *J* = 8.1 Hz, 2 H), 7.76-7.74 (d, *J* = 8.0 Hz, 2 H), 7.62-7.59 (t, *J* = 7.5 Hz, 1 H), 7.51-7.48 (t, *J* = 7.6 Hz, 2 H), 7.32-7.28 (d, *J* = 7.9 Hz, 2 H), 2.47 (s, 3 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 196.53, 143.26, 137.98, 134.90, 132.17, 130.33, 129.95, 128.99, 128.22, 21.68.

(4-(*tert*-Butyl)phenyl)(phenyl)methanone (3b). **^{1}H NMR (500 MHz, $CDCl_3$)** δ 7.84-7.82 (d, *J* = 7.7 Hz, 2 H), 7.80-7.78 (d, *J* = 8.3 Hz, 2 H), 7.61-7.58 (t, *J* = 7.3 Hz, 1 H), 7.53-7.48 (m, 4 H), 1.39 (s, 9 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 196.45, 156.19, 137.97, 134.85, 132.17, 130.15, 129.98, 128.22, 125.26, 35.13, 31.17.

(4-Methoxyphenyl)(phenyl)methanone (3c). **^{1}H NMR (500 MHz, $CDCl_3$)** δ 7.87-7.85 (d, *J* = 8.7 Hz, 2 H), 7.79-7.77 (d, *J* = 8.2 Hz, 2 H), 7.61-7.58 (t, *J* = 6.8 Hz, 1 H), 7.51-7.48 (t, *J* = 7.6 Hz, 2 H), 7.00-6.98 (d, *J* = 8.7 Hz, 2 H), 3.92 (s, 3 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 195.59, 163.24, 138.31, 132.58, 131.90, 130.19, 129.75, 128.20, 113.57, 55.52.

Phenyl(*o*-tolyl)methanone (3d). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.84-7.82 (d, *J* = 8.3 Hz, 2 H), 7.62-7.59 (t, *J* = 7.5 Hz, 1 H), 7.50-7.47 (t, *J* = 7.9 Hz, 2 H), 7.43-7.40 (t, *J* = 7.5 Hz, 1 H), 7.35-7.31 (t, *J* = 7.8 Hz, 2 H), 7.29-7.26 (t, *J* = 7.5 Hz, 1 H), 2.36 (s, 3 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 198.67, 138.63, 137.76, 136.77, 133.14, 131.01, 130.25, 130.15, 128.53, 128.47, 125.21, 20.00.

(2-Methoxyphenyl)(phenyl)methanone (3e). ^{1}H NMR (500 MHz, $CDCl_3$)δ 7.85-7.83 (d, *J* = 7.7 Hz, 2 H), 7.59-7.56 (t, *J* = 7.5 Hz, 1 H), 7.51-7.48 (t, *J* = 7.4 Hz, 1 H), 7.47-7.44 (t, *J* = 7.2 Hz, 2 H), 7.39-7.38 (d, *J* = 7.7 Hz, 1 H), 7.08-7.05 (t, *J* = 7.2 Hz, 1 H), 7.03-7.01 (d, *J* = 7.7 Hz, 1 H), 3.75 (s, 3 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 196.48, 157.37, 137.83, 132.93, 131.88, 129.85, 129.61, 128.88, 128.22, 120.50, 111.46, 55.62.

(3-Fluorophenyl)(phenyl)methanone (3f). ^{1}H NMR (500 MHz, $CDCl_3$)δ 7.83-7.82 (d, *J* = 7.5 Hz, 2 H), 7.65-7.59 (m, 2 H), 7.54-7.47 (m, 4 H), 7.33-7.30 (t, *J* = 8.3 Hz, 1 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 164.59, 162.51 (d, J^F = 246.78 Hz), 137.05, 132.79, 130.03, 130.01, 129.95, 128.44, 125.83 (d, J^F = 2.9 Hz), 119.44 (d, J^F = 21.4 Hz), 116.77 (d, J^F = 22.3 Hz). **^{19}F NMR (471 MHz, $CDCl_3$)** δ -111.99.

Phenyl(3-(trifluoromethyl)phenyl)methanone (3g). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (s, 1 H), 8.01-7.99 (d, *J* = 7.7 Hz, 1 H), 7.88-7.86 (d, *J* = 7.8 Hz, 1 H), 7.83-7.81 (d, *J* = 7.1 Hz, 2 H), 7.67-7.64 (t, *J* = 7.6 Hz, 2 H), 7.55-7.52 (t, *J* = 7.8 Hz, 2 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 195.24, 138.29, 136.76, 133.14, 133.03, 131.01 (q, J^2 = 32.7 Hz), 130.04, 128.97, 128.86 (q, J^F = 3.5 Hz), 128.58, 126.72 (q, J^F = 3.8 Hz), 123.71 (q, J^F = 270.8 Hz). **^{19}F NMR (471 MHz, $CDCl_3$)** δ -62.74.

Naphthalen-2-yl(phenyl)methanone (3h). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.30 (s, 1 H), 7.98 (s, 2 H), 7.96-7.94 (d, *J* = 8.0 Hz, 2 H), 7.90-7.89 (d, *J* = 7.4 Hz, 2 H), 7.65 (s, 2 H), 7.60-7.53 (m, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$) δ 196.78, 137.93, 135.29, 134.85, 132.40, 132.28, 131.89, 130.12, 129.44, 128.36, 128.34, 128.32, 127.84, 126.82, 125.81.

[1,1′-Biphenyl]-4-yl(phenyl)methanone (3i). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94-7.92 (d, J = 7.2 Hz, 2 H), 7.88-7.86 (d, J = 7.5 Hz, 2 H), 7.75-7.73 (d, J = 7.3 Hz, 2 H), 7.69-7.68 (d, J = 7.7 Hz, 2 H), 7.65-7.62 (t, J = 7.1 Hz, 1 H), 7.55-7.50 (m, 4 H), 7.45-7.42 (t, J = 6.7 Hz, 1 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 196.38, 145.26, 140.01, 137.79, 136.26, 132.40, 130.75, 130.02, 128.99, 128.33, 128.21, 127.33, 126.99.

Phenyl(4-(trifluoromethyl)phenyl)methanone (3j). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.93-7.91 (d, J = 8.0 Hz, 2 H), 7.84-7.82 (d, J = 8.2 Hz, 2 H), 7.79-7.77 (d, J = 8.1 Hz, 2 H), 7.67-7.64 (t, J = 7.6 Hz, 1 H), 7.55-7.52 (t, J = 7.7 Hz, 2 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 195.55, 140.74, 136.75, 133.74 (q, J^2 = 32.5 Hz), 133.11, 130.15, 130.12, 128.55, 125.37 (q, J^3 = 3.7 Hz), 123.69 (q, J^1 = 270.9 Hz). **^{19}F NMR (471 MHz, $CDCl_3$)** δ -63.00.

(3,4-Difluorophenyl)(phenyl)methanone (3k). **^{1}H NMR (500 MHz, $CDCl_3$)** δ 7.76 (d, J = 7.7 Hz, 2 H), 7.68 (t, J = 9.0 Hz, 1 H), 7.60 (t, J = 13.0 Hz, 2 H), 7.50 (t, J = 7.7 Hz, 2 H), 7.27 (q, J = 8.3 Hz, 1 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 194.22, 154.42 (dd, J^F = 255.0, 12.5 Hz), 150.33 (dd, J^F = 255.0, 12.5 Hz), 137.01, 134.58 (t, J^F = 3.8 Hz), 132.94, 129.98, 128.63, 127.23 (q, J^F = 3.8 Hz), 119.46 (dd, J^F =17.5, 1.2 Hz), 117.41 (d, J^F = 17.5 Hz). **^{19}F NMR (471 MHz, $CDCl_3$)** δ -130.59 (d, J = 21.4 Hz), -136.17 (d, J = 21.4 Hz).

Phenyl(thiophen-2-yl)methanone (3l). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.90-7.89 (d, J = 8.2 Hz, 2 H), 7.76-7.75 (d, J = 4.9 Hz, 1 H), 7.68-7.67 (d, J = 3.7 Hz, 1 H), 7.64-7.61 (t, J = 7.5 Hz, 1 H), 7.54-7.51 (t, J = 7.7 Hz, 2 H), 7.20-7.19 (t, J = 4.8 Hz, 1 H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 188.26, 143.67, 138.18, 134.86, 134.22, 132.28, 129.20, 128.43, 127.97.

Supplementary Materials: General Methods, Characterization Data, 1H and 13C NMR Spectra are available online at http://www.mdpi.com/2073-4344/10/4/372/s1.

Author Contributions: J.B. and M.M.R. conducted experimental work and analyzed the data. M.S. supervised the project and wrote the paper. All authors contributed to the experiment design and reaction development. All authors have read and agreed to the published version of the manuscript.

Funding: Rutgers University and the NSF (CAREER CHE-1650766) are acknowledged for support. The 500 MHz spectrometer was supported by the NSF-MRI grant (CHE-1229030).

Conflicts of Interest: The authors declare no conflict of interest.

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