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Nickel-Catalyzed Cross-Coupling of Umpolung Carbonyls and Alkyl Halides

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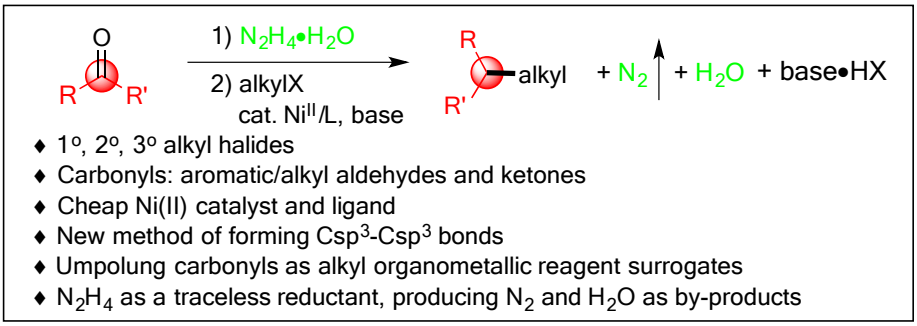


Abstract: An effective nickel-catalyzed cross-coupling of umpolung carbonyls and alkyl halides was developed. Complementary to classical alkylation techniques, this reaction utilizes umpolung carbonyls as the environmentally benign alkyl nucleophiles, providing an efficient and selective catalytic alternative to the traditional use of highly reactive alkyl organometallic reagents.

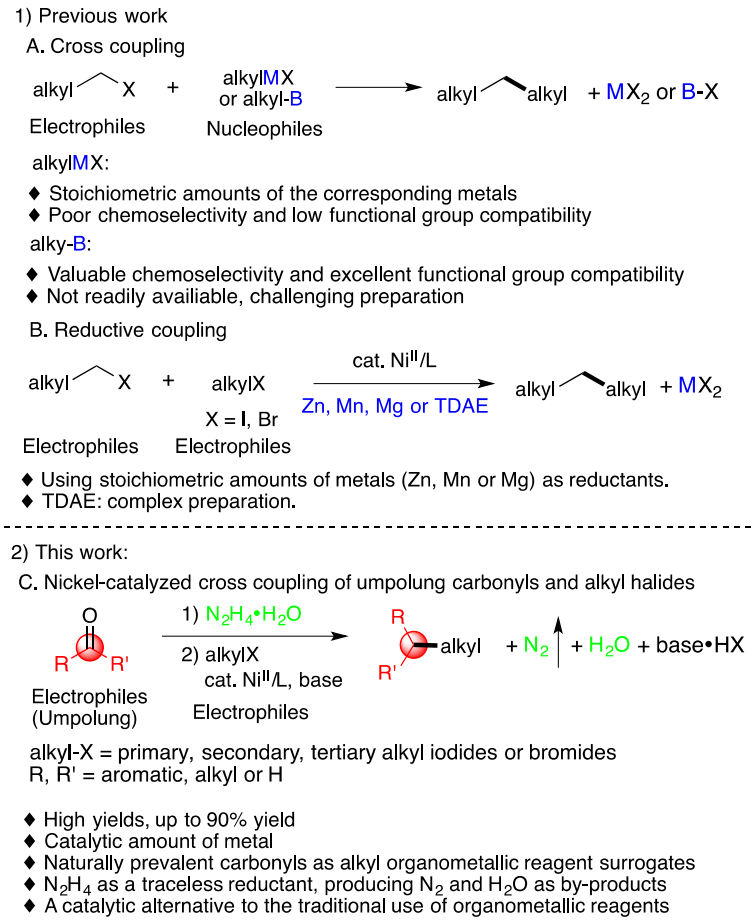
INTRODUCTION

Over the past decades, transition metal-catalyzed cross-coupling reactions have been among the most powerful and straightforward tools for constructing carbon-carbon bonds and have widespread applications in organic synthesis.[1] While traditional processes mainly focus on the construction of Csp^2-Csp^2 bonds, there has been a recent increase in developing effective and challenging cross-coupling to generate Csp^3-Csp^3 bonds with alkyl halides.[2]

Traditional processes typically involve the palladium-catalyzed couplings of alkyl halides with alkyl organometallic reagents (such as organomagnesium or zinc reagents, etc.) or alkyl boron reagents (Scheme 1A).[3] For the alkyl halide partner, slow oxidative addition of alkyl electrophiles to the palladium and facile β-hydride elimination from the intermediate are two likely causes for this comparatively less success.[4] Fu made the systematic

investigations and determined that Pd/PR_3 (PR_3 = PCy_3 or $P(t\text{-}Bu)_2Me$) can inhibit the β-hydride elimination and serve as an efficient catalyst system for Suzuki reactions of primary alkyl halides with trialkylboranes.[5] Alternatively, a variety of alkyl-alkyl couplings catalyzed by nickel,[6] copper,[7] iron[8] or cobalt,[9] have emerged to make the oxidative addition of alkyl electrophile to the metal center much easier via oxidative radical addition process. However for the alkyl nucleophile partner, the alkyl organometallic reagents are generally air/moisture sensitive and requires stoichiometric amounts of metals for its preparation. Moreover, the reactions of alkyl organometallic reagents often result in poor chemoselectivity and low functional group compatibility due to their strong basicity and high nucleophilicity. To avoid the use of alkyl organometallic reagents, metal-catalyzed reductive couplings of two alkyl electrophiles under the metal or organic reductants (such as Zn, Mn, Mg or TDAE, etc.) represented a major step forward (Scheme 1B), as reported by Weix, Gong, Liu and others.[10] Nevertheless, stoichiometric amounts of metal reductants will produce extra metal wastes, which complicate the synthetic operations and raise environmental concerns. Moreover, the complex preparation of TDAE may also inhibit its synthetic applications. Notably, MacMillan, Vanucci, Lei and others also developed photoredox/ electrochemical[11] or transition metal-free[12] methods for the Csp^3–Csp^3 cross-coupling under mild conditions.

In 2018, our group reported Ni$(COD)_2$-catalyzed Csp^2-Csp^3 cross couplings with aryl halides and hydrazones.[13e] Inspired by hydrazones serving as alkyl carbanion equivalents in the catalytic nucleophilic additions and cross couplings,[13] herein, we wish to report a nickel(II)-catalyzed alkyl-alkyl coupling with umpolung carbonyls with alkyl halides (Scheme 1C). In this strategy, simple carbonyls act as alkyl carbanion equivalents instead of alkyl organometallic reagents to couple with alkyl halides, with N_2H_4 serving as a formal traceless reductant.



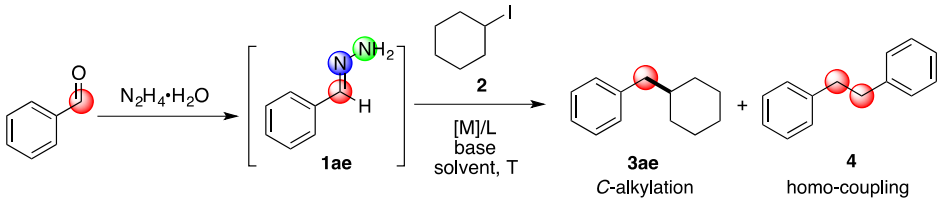
Scheme 1. Alkyl-Alkyl Couplings with Alkyl Halides.

RESULTS AND DISCUSSION

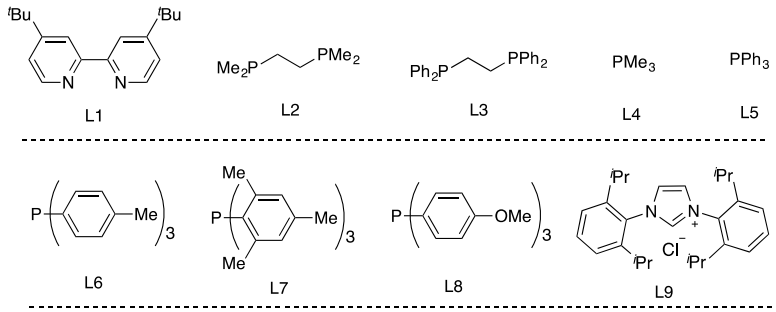
We began our studies by evaluating the coupling of benzaldehyde hydrazone **1ae** (generated *in situ* from benzaldehyde and hydrazine) with iodocyclohexane (Table 1). The base-free or catalyst/ligand-free reaction did not lead to any *C*-alkylated product (**3ae**, (cyclohexylmethyl)benzene), suggesting that catalyst/ligand and base are indispensable for the alkylation of aldehydes in this system (entries 1-2). Later reaction optimizations showed that *C*-alkylated product **3ae** and homo-coupling product **4** were observed while *N*-alkylated product was not detected. We think that alkyl halide (iodocyclohexane) may serve as the oxidant to form the oxidative coupling product **4**. In such a context, the key challenge is to control the cross-coupling over the homo-coupling to deliver the high yield of *C*-alkylated products. Surprisingly, reaction in the presence of 2.0 equiv of ^{t}BuOK using a simple $NiCl_2(Py)_4$[14] /PPh_3 catalytic system in 1,4-dioxane at 60 °C for 24 h provided the *C*-alkylated product **3ae** in high yield (88%), along

with a trace amount of homo-coupling product **4** (dibenzyl, 15%) (entry 9). With $Ni(COD)_2$ (COD: 1,5-cyclooctadiene) as catalyst, the reaction still successfully afforded 82% yield of the corresponding product (entry 8). Other nickel (II) catalysts including $NiCl_2$, $NiCl_2$•glyme, $NiCl_2$•diglyme, $NiBr_2$•DME and $NiCl_2(PPh_3)_2$ gave lower yields of **3ae** (entries 3-7). Parallel experiments showed that dinitrogen ligand (4 4'-di-tert-butyl-2 2'-bipyridine) and many other monodentate or bidentate phosphine ligands proceeded to afford 62%-78% yields of *C*-alkylated product **3ae** (entries 10-16), while the reaction delivered 28% yield of **3ae** when NHC ligand such as IPr was used (entriy 17). The choice of base was found to be crucial to the de-nitrogenation: weak bases cannot deprotonate the hydrazones, while relatively strong bases could deliver satisfactory yields of *C*-alkylated product **3ae** (entries 9, 18-20). For example, high yield of **3ae** was observed with ^{t}BuOK, K_3PO_4 could not give any of this product. Moreover, other solvents such as 2-methyltetrahydrofuran, cyclopentyl methyl ether or tetrahydrofuran were also effective to deliver lower yields of *C*-alkylated products (entries 21-23). The reaction could be performed at 45 ^{o}C with a decreased yield for the expected product (69%) (entry 24). Finally, lower loading of $NiCl_2(Py)_4/PPh_3$ led to unsatisfied yield (entry 26).

Table 1. Optimization of Reaction Conditions[a,b]



Entry[a]	Catalyst	Ligand	Base	Solvent	Tem (°C)	3ae:4 (yield, %)[b]
1	$NiCl_2(Py)_4$	L5	—	1,4-dioxane	60	—
2	—	—	^{t}BuOK	1,4-dioxane	60	—
3	$NiCl_2$	L5	^{t}BuOK	1,4-dioxane	60	52/20
4	$NiCl_2$•glyme	L5	^{t}BuOK	1,4-dioxane	60	66/21
5	$NiCl_2$•diglyme	L5	^{t}BuOK	1,4-dioxane	60	69/23
6	$NiBr_2$•DME	L5	^{t}BuOK	1,4-dioxane	60	82/20
7	$NiCl_2(PPh)_2$	L5	^{t}BuOK	1,4-dioxane	60	68/15
8	$Ni(COD)_2$	L5	^{t}BuOK	1,4-dioxane	60	82/18
9	**$NiCl_2(Py)_4$**	**L5**	**^{t}BuOK**	**1,4-dioxane**	**60**	**88/15**
10	$NiCl_2(Py)_4$	L1	^{t}BuOK	1,4-dioxane	60	62/12
11	$NiCl_2(Py)_4$	L2	^{t}BuOK	1,4-dioxane	60	62/21
12	$NiCl_2(Py)_4$	L3	^{t}BuOK	1,4-dioxane	60	68/13
13	$NiCl_2(Py)_4$	L4	^{t}BuOK	1,4-dioxane	60	78/25
14	$NiCl_2(Py)_4$	L6	^{t}BuOK	1,4-dioxane	60	62/23
15	$NiCl_2(Py)_4$	L7	^{t}BuOK	1,4-dioxane	60	78/22
16	$NiCl_2(Py)_4$	L8	^{t}BuOK	1,4-dioxane	60	64/20
17	$NiCl_2(Py)_4$	L9	^{t}BuOK	1,4-dioxane	60	28/25
18	$NiCl_2(Py)_4$	L5	^{t}BuONa	1,4-dioxane	60	68/23
19	$NiCl_2(Py)_4$	L5	^{t}BuOLi	1,4-dioxane	60	17/17
20	$NiCl_2(Py)_4$	L5	K_3PO_4	1,4-dioxane	60	—
21	$NiCl_2(Py)_4$	L5	^{t}BuOK	2-MeTHF	60	78/22
22	$NiCl_2(Py)_4$	L5	^{t}BuOK	Cyclopentyl methyl ether	60	64/18
23	$NiCl_2(Py)_4$	L5	^{t}BuOK	THF	60	62/13
24	$NiCl_2(Py)_4$	L5	^{t}BuOK	1,4-dioxane	45	69/12
25	$NiCl_2(Py)_4$	L5	^{t}BuOK	1,4-dioxane	80	64/15
26[c]	$NiCl_2(Py)_4$	L5	^{t}BuOK	1,4-dioxane	60	62/13

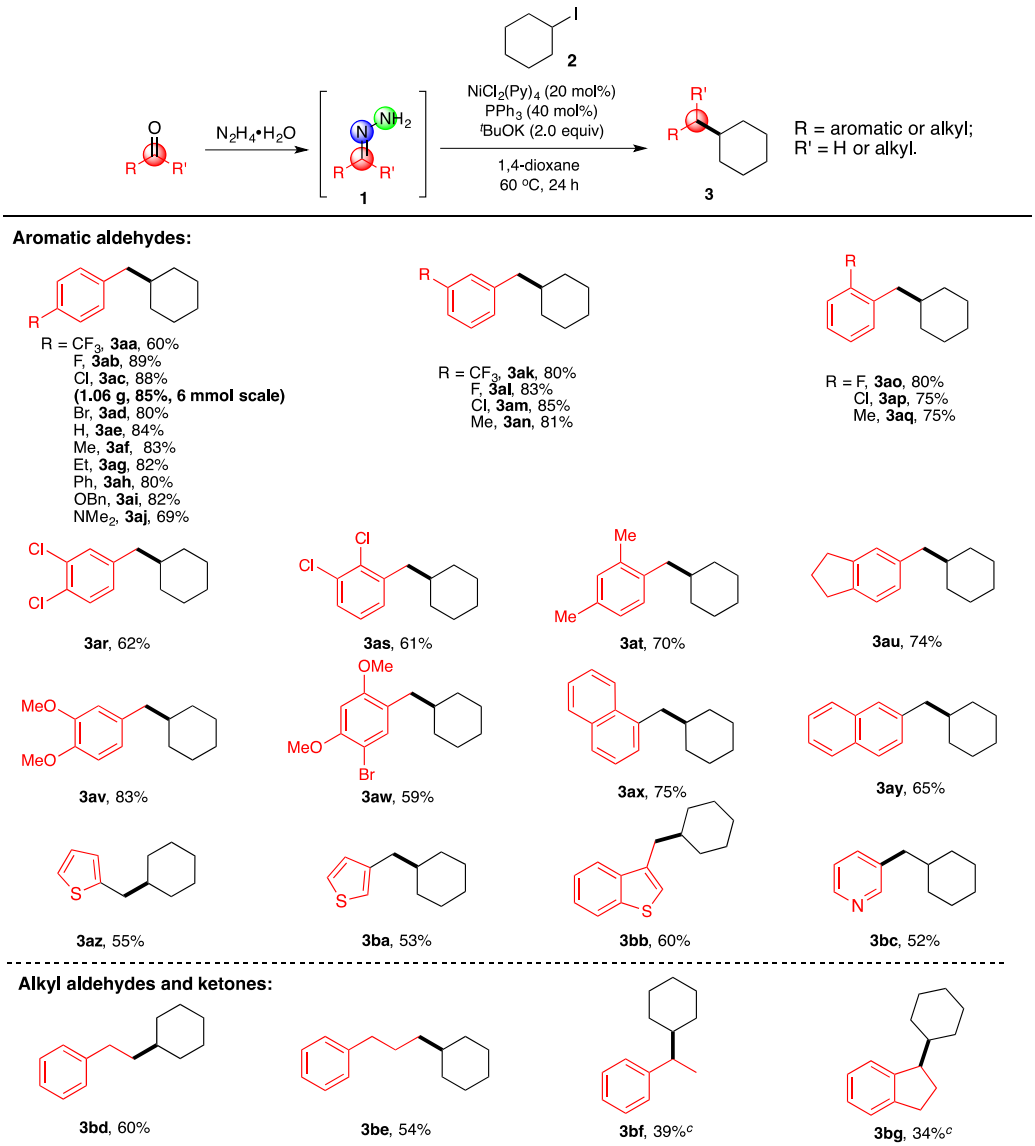


[a] General reaction conditions: hydrazones (0.40 mmol, 1.25 M generated *in situ* from benzaldehyde and hydrazine), iodocyclohexane (0.20 mmol), catalyst (20 mol%), ligand (monodentate phosphine ligand 40 mol%, bidentate

phosphine ligand 20 mol%) and base (2.0 equiv) in 1.0 mL solvent for 24 h. [b] GC yields. [c] $NiCl_2(Py)_4$ (10 mol%), PPh_3 (20 mol%) used instead.

With the optimized conditions in hand, the scope of carbonyls for cross coupling was investigated in Table 2. In general, carbonyls bearing both electron-withdrawing and electron-donating substituents gave good to high yields. The reaction showed certain functional group compatibility, as trifluoromethyl, fluoro, chloro, methyl, ethyl, phenyl, amino, methoxy and alkoxy substituents were all tolerated to give the corresponding products in high yields (**3aa-3ac**, **3ae-3aw**). Bromo group, which was not compatible with the traditional alkylations of alkyl organometallic reagents, also worked well with our conditions (**3ad**). In addition to the good functional-group compatibility, *para*-, *meta*-, *ortho*-, or multi-substituted aromatic aldehydes were all effective under standard conditions (**3aa-3ay**). Then hydrazones generated from heterocyclic aldehydes were investigated in this system. Hydrazones prepared from thiophene-2-carbaldehyde, thiophene-3-carbaldehyde, benzo[*b*]thiophene-3-carbaldehyde and nicotinaldehyde, were all compatible with this system, affording the *C*-alkylated products in 52%-60% yields (**3az-3bc**). To our delight, aliphatic aldehydes such as 2-phenylacetaldehyde and 3-phenylpropanal, which are challenging substrates in the most cases of previous reports related to the umpolung hydrazone strategy, were also applicable in this cross-coupling reaction (**3bd-3be**). Moreover, the attempt to apply ketones as highly active alkyl nucleophiles to couple with iodocyclohexane in this transformation also proved feasible (**3bf-3bg**).

Table 2. Scope of Carbonyls[a,b]



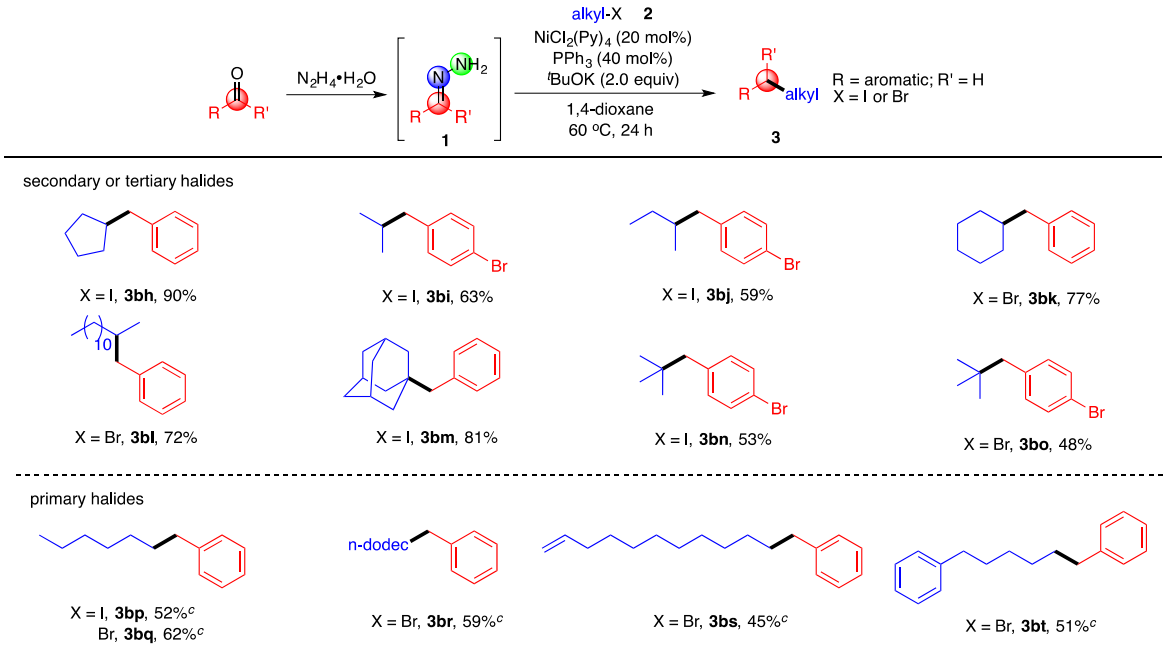
[a] Reaction conditions: hydrazones (1.20 mmol, 1.25 M generated *in situ* from carbonyls and hydrazine), iodocyclohexane (0.60 mmol), $NiCl_2(Py)_4$ (20 mol%), PPh_3 (40 mol%), ^{t}BuOK (2.0 equiv) in 3.0 mL 1,4-dioxane at 60 °C for 24 h. [b] Isolated yield. [c] $NiCl_2(Py)_4$ (10 mol%), IPr·HCl (10 mol%) used instead.

To emphasize the synthetic potential of our methodology, a gram scale alkyl cross-coupling of carbonyls was performed, giving product **3ac** in 85% yields (1.06 g). Later, the transformation of natural aldehydes and their derivatives were tested, to show the great potential of this alkyl cross-coupling reaction. Hydrazones originated from 4-hydroxyaldehyde derivative (benzyl 4-hydroxyaldehyde) gave *C*-alkylated products in 82% yields under the

standard conditions (**3ai**). Besides, veratraldehyde (methyl vanillin) could efficiently afford the desired product (4-(cyclohexylmethyl)-1,2-dimethoxybenzene) in 83% yield (**3av**).

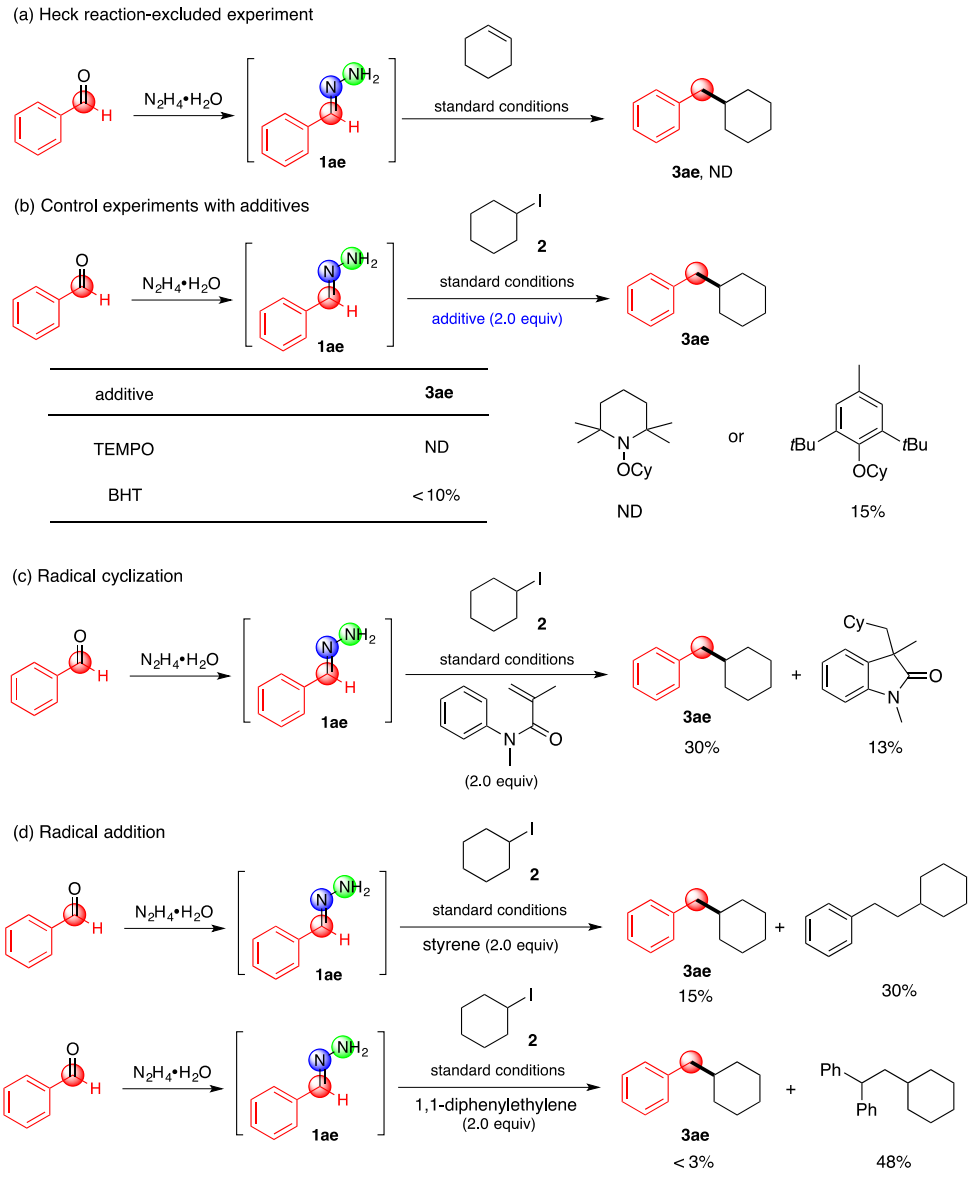
Subsequently, the alkyl halide substrate scope was investigated in Table 3. This method can be applied to an array of unactivated secondary alkyl iodides or bromides, generating the desired Csp^3–Csp^3 bonds in moderate to high yields. Thus, 2-iodopropane, 2-iodobutane and 2-bromododecane are all suitable substrates (**3bi-3bj**, **3bl**). Besides, secondary cyclic iodides or bromides such as iodocyclopentane and bromocyclohexane can be cross-coupled (**3bh**, **3bk**). Furthermore, unactivated tertiary alkyl halides, which are significantly more hindered, such as 1-iodoadamantane, *tert*-butyl iodide or bromide were also effective in this system, generating the corresponding alkylated products (**3bm-3bo**). Importantly, the primary alkyl bromides and iodides, which are challenging substrate in alkyl-alkyl coupling, are also compatible in current cross-coupling using a $NiBr_2$•DME/PMe_3 system. As illustrated in Table 3, 1-bromohexane, 1-iodohexane, 1-bromododecane, 11-bromoundec-1-ene and (5-bromopentyl)benzene can successfully couple with umpolung benzaldehyde (**3bp-3bt**).

Table 3. Scope of Alkyl Halides[a,b]



[a] Reaction conditions: hydrazones (1.20 mmol, 1.25 M generated *in situ* from aldehydes and hydrazine), alkyl halides (0.60 mmol), $NiCl_2(Py)_4$ (20 mol%), PPh_3 (40 mol%), ^{t}BuOK (2.0 equiv) in 3.0 mL 1,4-dioxane at 60 ^{o}C for 24 h. [b] Isolated yield. [c] hydrazones (1.20 mmol), alkyl halides (0.60 mmol), $NiBr_2$**.**DME (10 mol%), PMe_3 (40 mol%), ^{t}BuOLi (3.5 equiv) in 3.0 mL 2-Me THF at 60 ^{o}C for 24 h.

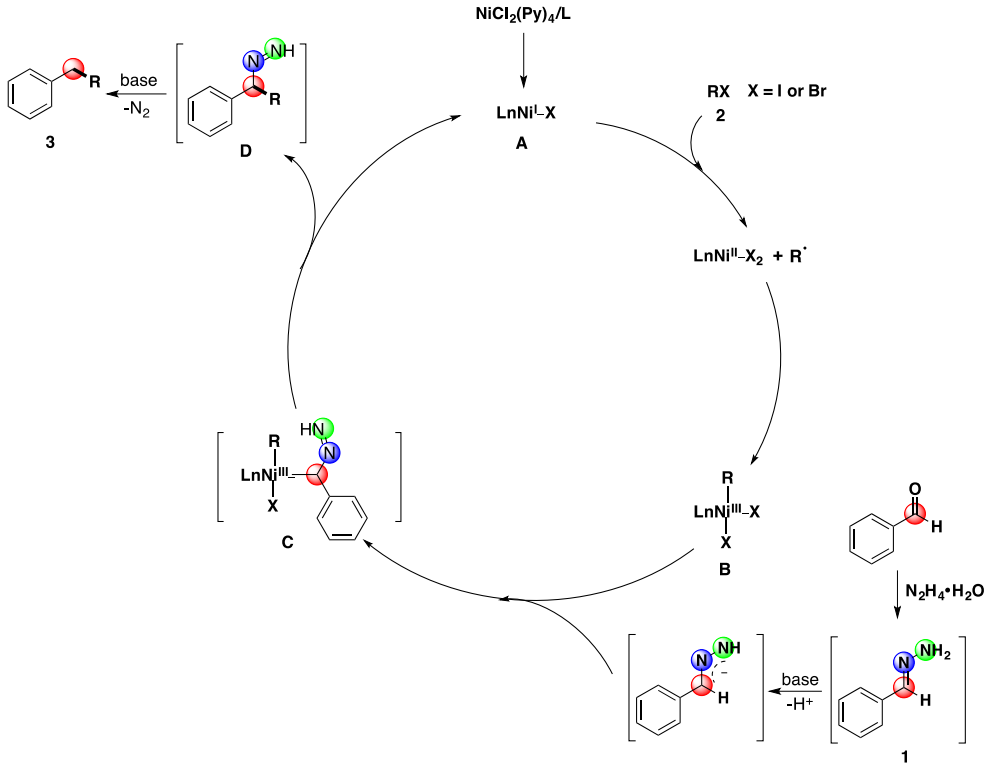
To gain preliminary insights into the cross-coupling of umpolung carbonyls and alkyl halides, several control experiments were subsequently carried out (Scheme 2). First, the reaction of cyclohexene and benzaldehyde did not afford the desired product, (cyclohexylmethyl)benzene, which excluded the Heck reaction intermediate. Then, the radical inhibiting experiments were performed. It was found that the reaction was completely or nearly suppressed by the addition of 2,2,6,6-tetramethylpiperidin-1-oxyl (TEMPO) or 2, 6-ditertbutyl-4-methylphenol (BHT). The radical cyclization experiment employing *N*-methyl-*N*-phenylmethacrylamide as a substrate produced cyclized product in 13% yield. The radical additions of styrene or 1,1-diphenylethlene successfully delivered addition products in 30% and 48% yields, respectively. These results suggest that the reaction might involve a free radical process.



Scheme 2. Preliminary Mechanism Investigations

Although the exact mechanism of the reaction remains elusive at this moment, on the basis of preliminary mechanism investigations and the reported literatures, [15] a tentative mechanism of the nickel-catalyzed cross-coupling of umpolung carbonyls and alkyl halides is proposed in Scheme 3. The catalytic cycle commences with the formation of Ni^{I} species **A**, which is generated from the Ni(II) precatalyst. Electron transfer between the catalytically active nickel species **A** and alkyl halides affords Ni^{II} species and alkyl radical **B**, which then form the alkyl nickel species **B** (Ni^{III}). Later **B** undergoes transmetalation with carbon nucleophile derived from deprotonation of

hydrazone **1** to form the intermediate **C**. Then subsequent reductive elimination delivers the *C*-alkyl product **3** by de-nitrogenation assisted with the base and renders Ni^{I} species **A** for the next cycle.



Scheme 3. A Tentative Mechanism.

CONCLUSION

In summary, we have developed an efficient cross-coupling of umpolung carbonyls and alkyl halides enabled by nickel(II) catalyst. Highlighted features of this methodology are: (a) effective not only for secondary and tertiary alkyl iodides or bromides, but also for primary alkyl iodides and bromides, (b) umpolung of naturally rich carbonyls as environmentally benign alkyl nucleophiles, (c) N_2H_4 as a traceless reductant, generating N_2 and H_2O as the innocuous side products, (d) using cheap nickel(II) and PPh_3 as the catalyst/ligand and the requirement of only a catalytic amounts of both metal and ligand, (e) moderate to high yields and ease to scale up, (f) tolerating certain functional groups. With all those characteristics, this umpolung reaction is expected to complement the present cross-coupling and reductive coupling of Csp^3-Csp^3 bonds and provide with a novel catalytic alternative to the traditional

use of highly reactive alkyl organometallic reagents. During the preparation for submitting our manuscript, Zhang and co-workers just reported a $Ni(COD)_2$-catalyzed alkyl-alkyl couplings of aldehydes and secondary alkyl bromides.[16] Detailed studies of the mechanism and applications of this reaction are underway and more strategies using carbonyls as alkyl carbanion equivalents for cross coupling are likely to emerge in the future.

Experimental Section

General Information. ^1H NMR spectra were recorded on 500 MHz spectrometer and the chemical shifts were reported in parts per million (δ) relative to internal solvent signal (7.28 ppm in $CDCl_3$). The peak patterns are indicated as follows: s, singlet; d, doublet; dd, doublet of doublet; t, triplet; q, quartet; m, multiplet. The coupling constants, *J*, are reported in Hertz (Hz). ^{13}C NMR spectra were obtained at 125 MHz and referenced to the internal solvent signal (central peak is 77.0 ppm in $CDCl_3$). ^{19}F NMR spectra were obtained at 470 MHz. $CDCl_3$ was used as the NMR solvent. Flash column chromatography was performed over silica gel 200-300. All reagents were purchased from commercial source and used without further purification. The $NiCl_2(Py)_4$ and hydrazone solutions (*in situ*) were synthesized according to the reported literatures. [13i, 14] The HRMS measurements were recorded on a TOF analyzer using an ESI or APCI source in the positive mode.

General procedure and characterization data for products 3.

Method I (using $NiCl_2(Py)_4$/PPh_3 as the catalyst/ligand): 25 mL Schlenk tube was charged with $NiCl_2(Py)_4$ (54.0 mg, 20 mol%), PPh_3 (63.6 mg, 40 mol%) and 3 mL 1,4-dioxane under argon and stirred at room temperature for 1 h. Then secondary or tertiary alkyl halides (0.6 mmol) were added to the mixture before hydrazone solution (0.96 mL, 2.0 equiv, 1.25 M generated *in situ* from aldehydes and hydrazine) and ^{t}BuOK (136.8 mg, 2.0 equiv) were added. The resulting mixture was stirred in oil bath at 60 ^{o}C for 24 h. After the completion of the reaction, the solution was filtered in a short celite pad and washed with dichloromethane (20 mL×3). The solvent was removed under vacuum

and the residue was purified by flash column chromatography to give the desired product.

Method II (using $NiBr_2$•DME/PMe_3 as the catalyst/ligand): 25 mL Schlenk tube was charged with $NiBr_2$•DME (18.6 mg, 10 mol%), and then transferred into the glovebox before PMe_3 (21 μL, 40 mol%) was added. The reaction tube was then moved out of the glovebox, charged with 3 mL 2-methyltetrahydrofuran under argon and stirred at room temperature for 1 h. Then primary alkyl halide (0.6 mmol) was added to the mixture before hydrazone solution (0.96 mL, 2.0 equiv, 1.25 M generated *in situ* from aldehydes and hydrazine) and ^{t}BuOLi (168 mg, 3.5 equiv) were added. The resulting mixture was stirred in oil bath at 60 ^{o}C for 24 h. After the completion of the reaction, the solution was filtered in a short celite pad and washed with dichloromethane (20 mL×3). The solvent was removed under vacuum and the residue was purified by flash column chromatography to give the desired product.

Method III (using $NiCl_2(Py)_4$/IPr as the catalyst/ligand): 25 mL Schlenk tube was charged with $NiCl_2(Py)_4$ (27.0 mg, 10 mol%), IPr•HCl (25.5 mg, 10 mol%), ^{t}BuOK (15.0 mg, 22 mol%) and 3 mL 1,4-dioxane under argon and stirred at room temperature for 1 h. Then alkyl halide (0.6 mmol) was added to the mixture before hydrazone solution (0.96 mL, 2.0 equiv, 1.25 M generated *in situ* from ketones and hydrazine) and ^{t}BuOK (136.8 mg, 2.0 equiv) were added. The resulting mixture was stirred in oil bath at 60 ^{o}C for 24 h. After the completion of the reaction, the solution was filtered in a short celite pad and washed with dichloromethane (20 mL×3). The solvent was removed under vacuum and the residue was purified by flash column chromatography to give the desired product.

General procedure for gram scale synthesis of 3ac:

100 mL Schlenk tube was charged with $NiCl_2(Py)_4$ (540 mg, 20 mol%), PPh_3 (636 mg, 40 mol%) and 30 mL 1,4-dioxane under argon and stirred at room temperature for 1 h. Then iodocyclohexane (6 mmol) was added to the mixture before hydrazone solution (9.6 mL, 2.0 equiv, 1.25 M generated *in situ* from 4-chlorobenzaldehyde and hydrazine) and ^{t}BuOK (1.36 g, 2.0 equiv) were added. The resulting mixture was stirred in oil bath at 60 ^{o}C for 24 h. After the completion of the reaction, the solution was filtered in a short celite pad and washed with dichloromethane

(200 mL×3). The solvent was removed under vacuum and the residue was purified by flash column chromatography to give 1-chloro-4-(cyclohexylmethyl)benzene **3ac** (1.06 g, 85%).

1-(Cyclohexylmethyl)-4-(trifluoromethyl)benzene (3aa). Colorless liquid (87.2 mg, 60% (method I)). Eluent: petroleum ether (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.54 (d, *J* = 10.0 Hz, 2 H), 7.26 (d, *J* = 5.0 Hz, 2 H), 2.56 (d, *J* = 10.0 Hz, 2 H), 1.66-1.74 (m, 5 H), 1.53-1.59 (m, 1 H), 1.18-1.24 (m, 3 H), 0.96-1.01 (m, 2 H); ^{19}F NMR (470 MHz, $CDCl_3$) δ -62.3 (s, 3 F); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 145.5, 129.4, 127.9 (q, *J* = 31.3 Hz), 124.9 (q, *J* = 3.75 Hz), 124.4 (q, *J* = 270.0 Hz), 43.9, 39.6, 33.1, 26.5, 26.2 ppm. HRMS (APCI) for $C_{14}H_{17}F_2$ (M-HF+H^+): Calcd: 223.1298; Found: 223.1297.

1-(Cyclohexylmethyl)-4-fluorobenzene (3ab). Colorless liquid (102.6 mg, 89% (method I) [17]. Eluent: petroleum ether (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.10 (td, *J* = 10.0, 5.0 Hz, 2 H), 6.97 (tt, *J* = 10.0, 5.0 Hz, 2 H), 2.47 (d, *J* = 5.0 Hz, 2 H), 1.65-1.74 (m, 5 H), 1.46-1.54 (m, 1 H), 1.18-1.24 (m, 3 H), 0.91-0.98 (m, 2 H); ^{19}F NMR (470 MHz, $CDCl_3$) δ -118.3 (m, 1 F); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 161.2 (d, *J* = 241.3 Hz), 136.9 (d, *J* = 2.5 Hz), 130.4 (d, *J* = 3.75 Hz), 114.7 (d, *J* = 21.25 Hz), 43.3, 39.9, 33.1, 26.6, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}F$: 192.1, found: 192.1.

1-Chloro-4-(cyclohexylmethyl)benzene (3ac). Colorless liquid (110.0 mg, 88% (method I)) [18]. Eluent: n-pentane (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.26 (dd, *J* = 10.0, 5.0 Hz, 2 H), 7.09 (dd, *J* = 5.0, 2.0 Hz, 2 H), 2.48 (d, *J* = 10.0 Hz, 2 H), 1.66-1.74 (m, 5 H), 1.48-1.57 (m, 1 H), 1.17-1.24 (m, 3 H), 0.90-0.99 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 139.8, 131.3, 130.5, 128.1, 43.4, 39.8, 33.1, 26.5, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}Cl$: 208.1, found: 208.2.

1-Bromo-4-(cyclohexylmethyl)benzene (3ad). Colorless liquid (120.9 mg, 80% (method I)) [18]. Eluent: hexanes (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.40 (tt, *J* = 10.0, 5.0 Hz, 2 H), 7.03 (tt, *J* = 10.0, 5.0 Hz, 2 H), 2.46 (d, *J* = 10.0 Hz, 2 H), 1.66-1.73 (m, 5 H), 1.46-1.55 (m, 1 H), 1.18-1.24 (m, 3 H), 0.90-0.99 (m, 2 H);

$^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 140.3, 131.1, 130.9, 119.3, 43.5, 39.7, 33.1, 26.5, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}Br$: 252.1, found: 252.2.

(Cyclohexylmethyl)benzene (3ae). Colorless liquid (87.8 mg, 84% (method I)) [19]. Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.32 (td, *J* = 10.0, 5.0 Hz, 2 H), 7.23 (td, *J* = 10.0, 5.0 Hz, 1 H), 7.19 (dd, *J* = 10.0, 5.0 Hz, 2 H), 2.53 (d, *J* = 5.0 Hz, 2 H), 1.67-1.76 (m, 5 H), 1.53-1.61 (m, 1 H), 1.19-1.26 (m, 3 H), 0.96-1.04 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.4, 129.2, 128.0, 125.6, 44.2, 39.8, 33.2, 26.6, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{18}$: 174.1, found: 174.3.

1-(Cyclohexylmethyl)-4-methylbenzene (3af). Colorless liquid (93.7 mg, 83% (method I)) [18]. Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.13 (d, *J* = 5.0 Hz, 2 H), 7.08 (d, *J* = 5.0 Hz, 2 H), 2.50 (d, *J* = 10.0 Hz, 2 H), 2.37 (s, 3 H), 1.67-1.76 (m, 5 H), 1.51-1.59 (m, 1 H), 1.18-1.29 (m, 3 H), 0.92-1.03 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 138.3, 134.9, 129.1, 128.8, 43.7, 39.9, 33.2, 26.6, 26.4, 21.0 ppm. MS (EI) m/z (M^+) calcd for $C_{14}H_{20}$: 188.1, found: 188.1.

1-(Cyclohexylmethyl)-4-ethylbenzene (3ag). Colorless liquid (99.5 mg, 82% (method I)). Eluent: hexanes (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.16 (dd, *J* = 10.0, 5.0 Hz, 2 H), 7.10 (dd, *J* = 10.0, 5.0 Hz, 2 H), 2.68 (q, *J* = 10.0 Hz, 2 H), 2.50 (d, *J* = 5.0 Hz, 2 H), 1.69-1.76 (m, 5 H), 1.51-1.59 (m, 1 H), 1.28 (t, *J* = 10.0 Hz, 3 H), 1.18-1.24 (m, 3 H), 0.97-1.03 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.4, 138.5, 129.1, 127.5, 43.8, 39.9, 33.2, 28.5, 26.6, 26.4, 15.7 ppm. HRMS (APCI) for $C_{15}H_{22}$ (M^+): Calcd: 202.1722; Found: 202.1719.

4-(Cyclohexylmethyl)-1,1'-biphenyl (3ah). Colorless liquid (120.0 mg, 80% (method I)) [20]. Eluent: dichloromethane/hexanes (1:3, R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.64 (dd, *J* = 10.0, 5.0 Hz, 2 H), 7.56 (dd, *J* = 5.0, 2.0 Hz, 2 H), 7.47 (td, *J* = 5.0, 5.0 Hz, 2 H), 7.37 (tt, *J* = 10.0, 5.0 Hz, 1 H), 7.26 (dd, *J* = 10.0, 5.0 Hz, 2 H), 2.58 (d, *J* = 5.0 Hz, 2 H), 1.69-1.79 (m, 5 H), 1.56-1.65 (m, 1 H), 1.21-1.31 (m, 3 H), 0.98-1.06

(m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.2, 140.6, 138.5, 129.6, 128.7, 127.0, 126.9, 126.8, 43.8, 39.8, 33.2, 26.6, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{19}H_{22}$: 250.2, found: 250.3.

1-(Benzyloxy)-4-(cyclohexylmethyl)benzene (3ai). Colorless liquid (137.8 mg, 82% (method I)). Eluent: dichloromethane/hexanes (1:2, R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.47 (td, *J* = 10.0, 5.0 Hz, 2 H), 7.41 (tt, *J* = 10.0, 5.0 Hz, 2 H), 7.35 (tt, *J* = 10.0, 5.0 Hz, 1 H), 7.08 (dd, *J* = 5.0, 1.5 Hz, 2 H), 6.92 (dd, *J* = 5.0, 1.5 Hz, 2 H), 5.07 (s, 2 H), 2.45 (d, *J* = 5.0 Hz, 2 H), 1.65-1.73 (m, 5 H), 1.47-1.53 (m, 1 H), 1.18-1.24 (m, 3 H), 0.91-0.99 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 156.9, 137.3, 133.8, 130.0, 128.6, 127.9, 127.5, 114.4, 70.1, 43.2, 39.9, 33.1, 26.6, 26.4 ppm. HRMS (APCI) for $C_{20}H_{25}O$ ($M+H^+$): Calcd: 281.1905; Found: 281.1894.

4-(Cyclohexylmethyl)-N,N-dimethylaniline (3aj). Colorless liquid (89.9 mg, 69% (method I)) [21]. Eluent: dichloromethane/hexanes (1:3, R_f = 0.35, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.05 (dd, *J* = 5.0, 1.5 Hz, 2 H), 6.73 (dd, *J* = 10.0, 1.5 Hz, 2 H), 2.95 (s, 6 H), 2.42 (d, *J* = 5.0 Hz, 2 H), 1.65-1.74 (m, 5 H), 1.45-1.52 (m, 1 H), 1.18-1.24 (m, 3 H), 0.92-0.99 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 148.9, 129.8, 113.2, 112.8, 43.1, 41.0, 40.0, 33.2, 26.7, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{15}H_{23}N$: 217.2, found: 217.2.

1-(Cyclohexylmethyl)-3-(trifluoromethyl)benzene (3ak). Colorless liquid (116.0 mg, 80% (method I)). Eluent: petroleum ether (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.47 (d, *J* = 10.0 Hz, 1 H), 7.40 (dd, *J* = 15.0, 5.0 Hz, 2 H), 7.34 (d, *J* = 5.0 Hz, 1 H), 2.57 (d, *J* = 5.0 Hz, 2 H), 1.66-1.76 (m, 5 H), 1.53-1.60 (m, 1 H), 1.15-1.28 (m, 3 H), 0.95-1.03 (m, 2 H); ^{19}F NMR (470 MHz, $CDCl_3$) δ -62.5 (s, 3 F); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 142.2, 132.5, 130.4 (q, *J* = 32.5 Hz), 128.4, 125.7 (q, *J* = 3.75 Hz), 124.4 (q, *J* = 270.0 Hz), 122.5 (q, *J* = 3.75 Hz), 43.9, 39.7, 33.0, 26.5, 26.2 ppm. HRMS (APCI) for $C_{14}H_{17}F_2$ ($M-HF+H^+$): Calcd: 223.1298; Found: 223.1298.

1-(Cyclohexylmethyl)-3-fluorobenzene (3al). Colorless liquid (95.6 mg, 83% (method I)). Eluent: petroleum ether

(R_f = 0.70, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.22-7.27 (m, 1 H), 6.94 (td, *J* = 10.0, 5.0 Hz, 1 H), 6.86-6.90 (m, 2 H), 2.51 (d, *J* = 10.0 Hz, 2 H), 1.65-1.75 (m, 5 H), 1.52-1.58 (m, 1 H), 1.17-1.25 (m, 3 H), 0.91-1.02 (m, 2 H); ^{19}F NMR (470 MHz, $CDCl_3$) δ -114.4 (m, 1 F); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 162.8 (d, *J* = 243.7 Hz), 144.9 (d, *J* = 7.5 Hz), 129.3 (d, *J* = 7.5 Hz), 124.8 (d, *J* = 2.5 Hz), 115.8 (d, *J* = 21.25 Hz), 112.4 (d, *J* = 21.25 Hz), 43.8 (d, *J* = 1.25 Hz), 39.6, 33.1, 26.5, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}F$: 192.1, found: 192.3. HRMS (APCI) for $C_{13}H_{18}F$ ($M+H^+$): Calcd: 193.1393; Found: 193.1394.

1-Chloro-3-(cyclohexylmethyl)benzene (3am). Colorless liquid (106.1 mg, 85% (method I)) [18]. Eluent: petroleum ether (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.06-7.22 (m, 3 H), 7.05 (tt, *J* = 10.0, 5.0 Hz, 1 H), 2.49 (d, *J* = 10.0 Hz, 2 H), 1.66-1.75 (m, 5 H), 1.50-1.58 (m, 1 H), 1.17-1.25 (m, 3 H), 0.95-1.00 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.4, 133.8, 129.3, 129.2, 127.4, 125.8, 43.8, 39.6, 33.1, 26.5, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}Cl$: 208.1, found: 208.1.

1-(Cyclohexylmethyl)-3-methylbenzene (3an). Colorless liquid (91.4 mg, 81% (method I)) [18]. Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.21 (t, *J* = 10.0 Hz, 1 H), 7.04 (d, *J* = 5.0 Hz, 1 H), 7.00 (t, *J* = 5.0 Hz, 2 H), 2.50 (d, *J* = 10.0 Hz, 2 H), 2.38 (s, 3 H), 1.67-1.78 (m, 5 H), 1.53-1.60 (m, 1 H), 1.19-1.29 (m, 3 H), 0.98-1.03 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.3, 137.5, 130.0, 127.9, 126.3, 126.2, 44.1, 39.8, 33.3, 26.6, 26.4, 21.5 ppm. MS (EI) m/z (M^+) calcd for $C_{14}H_{20}$: 188.2, found: 188.2.

1-(Cyclohexylmethyl)-2-fluorobenzene (3ao). Colorless liquid (92.2 mg, 80% (method I)). Eluent: petroleum ether (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.15-7.21 (m, 2 H), 7.01-7.09 (m, 2 H), 2.56 (dd, *J* = 10.0, 5.0 Hz, 2 H), 1.66-1.75 (m, 5 H), 1.55-1.62 (m, 1 H), 1.19-1.25 (m, 3 H), 0.97-1.05 (m, 2 H); ^{19}F NMR (470 MHz, $CDCl_3$) δ -118.0 (m, 1 F); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 161.3 (d, *J* = 243.7 Hz), 131.5 (d, *J* = 5.0 Hz), 128.1 (d, *J* = 16.25 Hz), 127.3 (d, *J* = 8.75 Hz), 123.6 (d, *J* = 2.5 Hz), 115.1 (d, *J* = 22.5 Hz), 38.8, 36.8, 33.1, 26.5, 26.3 ppm. HRMS (APCI) for $C_{13}H_{18}F$ ($M+H^+$): Calcd: 193.1393; Found: 193.1396.

1-Chloro-2-(cyclohexylmethyl)benzene (3ap). Colorless liquid (93.6 mg, 75% (method I)) [18]. Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.37 (d, *J* = 10.0 Hz, 1 H), 7.19 (d, *J* = 5.0 Hz, 2 H), 7.13-7.17 (m, 1 H), 2.65 (d, *J* = 5.0 Hz, 2 H), 1.68-1.75 (m, 5 H), 1.64-1.68 (m, 1 H), 1.18-1.26 (m, 3 H), 1.01-1.08 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 139.0, 134.3, 131.4, 129.4, 127.1,126.3, 41.4, 38.2, 33.2, 26.6, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{17}Cl$: 208.1, found: 208.2.

1-(Cyclohexylmethyl)-2-methylbenzene (3aq). Colorless liquid (84.6 mg, 75% (method I)) [22]. Eluent: hexanes (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.18 (dd, *J* = 10.0, 5.0 Hz, 1 H), 7.11-7.16 (m, 3 H), 2.53 (d, *J* = 5.0 Hz, 2 H), 2.35 (s, 3 H), 1.68-1.77 (m, 5 H), 1.52-1.59 (m, 1 H), 1.20-1.26 (m, 3 H), 1.00-1.07 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 139.6, 136.2, 130.1, 130.0, 125.7, 125.4, 41.3, 38.8, 33.5, 26.6, 26.4, 19.6 ppm. MS (EI) m/z (M^+) calcd for $C_{14}H_{20}$: 188.2, found: 188.2.

1,2-Dichloro-4-(cyclohexylmethyl)benzene (3ar). Colorless liquid (90.1 mg, 62% (method I)) [23]. Eluent: petroleum ether (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.34 (d, *J* = 10.0 Hz, 1 H), 7.25 (d, *J* = 2.0 Hz, 1 H), 6.99 (dd, *J* = 10.0, 5.0 Hz, 1 H), 2.45 (d, *J* = 5.0 Hz, 2 H), 1.65-1.73 (m, 5 H), 1.47-1.55 (m, 1 H), 1.17-1.24 (m, 3 H), 0.89-0.99 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.6, 131.9, 131.0, 129.9, 129.5, 128.6, 43.2, 39.6, 33.0, 26.4, 26.2 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{16}Cl_2$: 242.0, found: 242.0.

1,2-Dichloro-3-(cyclohexylmethyl)benzene (3as). Colorless liquid (89.0 mg, 61% (method I)). Eluent: hexanes (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.32 (dd, *J* = 10.0, 5.0 Hz, 1 H), 7.12 (t, *J* = 10.0 Hz, 1 H), 7.08 (dd, *J* = 10.0, 5.0 Hz, 1 H), 2.67 (d, *J* = 5.0 Hz, 2 H), 1.67-1.75 (m, 5 H), 1.62-1.67 (m, 1 H), 1.17-1.24 (m, 3 H), 0.98-1.06 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.4, 133.1, 132.4, 129.5, 128.0, 126.6, 42.4, 37.9, 33.1, 26.5, 26.2 ppm. HRMS (APCI) for $C_{13}H_{16}Cl_2$ (M^+): Calcd: 242.0629; Found: 242.0629.

1-(Cyclohexylmethyl)-2,4-dimethylbenzene (3at). Colorless liquid (85.0 mg, 70% (method I)). Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.01 (d, *J* = 10.0 Hz, 2 H), 6.96 (dd, *J* = 10.0, 5.0 Hz, 1 H),

2.48 (d, *J* = 5.0 Hz, 2 H), 2.33 (s, 3 H), 2.30 (s, 3 H), 1.68-1.76 (m, 5 H), 1.48-1.55 (m, 1 H), 1.18-1.24 (m, 3 H), 0.97-1.05 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 136.5, 136.0, 135.1, 130.9, 130.0, 126.1, 40.9, 38.8, 33.5, 26.7, 26.4, 20.9, 19.5 ppm. HRMS (APCI) for $C_{15}H_{23}$ ($M+H^+$): Calcd: 203.1800; Found: 203.1800.

5-(Cyclohexylmethyl)-2,3-dihydro-1H-indene (3au). Colorless liquid (95.0 mg, 74% (method I)) [24]. Eluent: hexanes (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.17 (d, *J* = 10.0 Hz, 1 H), 7.06 (s, 1 H), 6.96 (dd, *J* = 10.0, 5.0 Hz, 1 H), 2.91-2.95 (m, 4 H), 2.49 (d, *J* = 5.0 Hz, 2 H), 2.08-2.14 (m, 2 H), 1.67-1.76 (m, 5 H), 1.51-1.58 (m, 1 H), 1.18-1.29 (m, 3 H), 0.95-1.03 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 144.1, 141.3, 139.2, 127.0, 125.2, 123.8, 44.0, 40.0, 33.3, 32.9, 32.5, 26.7, 26.4, 25.6 ppm. MS (EI) m/z (M^+) calcd for $C_{16}H_{22}$: 204.1, found: 204.1.

4-(Cyclohexylmethyl)-1,2-dimethoxybenzene (3av). Colorless liquid (116.6 mg, 83% (method I)) [25]. Eluent: ethyl acetate/hexanes (1:10, R_f = 0.4, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 6.79 (dd, *J* = 10.0, 5.0 Hz, 1 H), 6.69 (dd, *J* = 5.0, 1.5 Hz, 2 H), 3.89 (s, 3 H), 3.88 (s, 3 H), 2.44 (d, *J* = 5.0 Hz, 2 H), 1.63-1.74 (m, 5 H), 1.46-1.54 (m, 1 H), 1.17-1.24 (m, 3 H), 0.91-0.99 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 148.6, 147.0, 134.0, 121.0, 112.4, 110.9, 55.9, 55.8, 43.8, 39.9, 33.2, 26.6, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{15}H_{22}O_2$: 234.2, found: 234.2.

1-Bromo-5-(cyclohexylmethyl)-2,4-dimethoxybenzene (3aw). Colorless liquid (110.0 mg, 59% (method I)). Eluent: ethyl acetate/hexanes (1 :10, R_f = 0.5, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.22 (s, 1 H), 6.48 (s, 1 H), 3.91 (s, 3 H), 3.84 (s, 3 H), 2.41 (d, *J* = 10.0 Hz, 2 H), 1.64-1.71 (m, 5 H), 1.46-1.54 (m, 1 H), 1.15-1.22 (m, 3 H), 0.91-0.98 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 157.8, 154.6, 134.3, 123.7, 101.2, 96.7, 56.4, 55.7, 38.4, 37.0, 33.2, 26.6, 26.4 ppm. HRMS (ESI) for $C_{15}H_{21}O_2BrNa$ ($M+Na^+$): Calcd: 335.0623; Found: 335.0619.

1-(Cyclohexylmethyl)naphthalene (3ax). Colorless liquid (100.8 mg, 75% (method I)) [26]. Eluent: petroleum ether

(R_f = 0.65, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 8.08 (d, *J* = 10.0 Hz, 1 H), 7.89 (dd, *J* = 5.0, 1.5 Hz, 1 H), 7.75 (d, *J* = 5.0 Hz, 1 H), 7.49-7.56 (m, 2 H), 7.43 (dd, *J* = 10.0, 10.0 Hz, 1 H), 7.32 (d, *J* = 5.0 Hz, 1 H), 2.98 (d, *J* = 5.0 Hz, 2 H), 1.72-1.80 (m, 5 H), 1.67-1.70 (m, 1 H), 1.18-1.26 (m, 3 H), 1.08-1.14 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 137.4, 134.0, 132.3, 128.7, 127.2, 126.5, 125.5, 125.3, 125.2, 124.3, 41.3, 39.0, 33.7, 26.6, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{17}H_{20}$: 224.1, found: 224.1.

2-(Cyclohexylmethyl)naphthalene (3ay). Colorless liquid (87.4 mg, 65% (method I)) [27]. Eluent: hexanes (R_f = 0.5, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.77-7.84 (m, 3 H), 7.60 (s, 1 H), 7.42-7.49 (m, 2 H), 7.33 (dd, *J* = 10.0, 1.5 Hz, 1 H), 2.67 (d, *J* = 5.0 Hz, 2 H), 1.69-1.76 (m, 5 H), 1.62-1.69 (m, 1 H), 1.18-1.25 (m, 3 H), 0.98-1.06 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 138.9, 133.5, 131.9, 128.1, 127.6, 127.5, 127.4, 127.2, 125.8, 125.0, 44.3, 39.8, 33.2, 26.6, 26.3 ppm. MS (EI) m/z (M^+) calcd for $C_{17}H_{20}$: 224.1, found: 224.1.

2-(Cyclohexylmethyl)thiophene (3az). Colorless liquid (59.4 mg, 55% (method I)). Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.13 (dd, *J* = 5.0, 1.5 Hz, 1 H), 6.94 (dd, *J* = 5.0, 5.0 Hz, 1 H), 6.77 (dd, *J* = 5.0, 1.5 Hz, 1 H), 2.72 (d, *J* = 10.0 Hz, 2 H), 1.65-1.79 (m, 5 H), 1.53-1.60 (m, 1 H), 1.15-1.31 (m, 3 H), 0.93-1.01 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 144.1, 126.6, 124.9, 122.9, 40.2, 37.8, 33.0, 26.5, 26.2 ppm. HRMS (APCI) for $C_{11}H_{17}S$ ($M+H^+$): Calcd: 181.1051; Found: 181.1049.

3-(Cyclohexylmethyl)thiophene (3ba). Colorless liquid (57.2 mg, 53% (method I)). Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.25 (dd, *J* = 5.0, 5.0 Hz, 1 H), 6.93 (dd, *J* = 5.0, 1.5 Hz, 1 H), 6.91 (dd, *J* = 5.0, 1.5 Hz, 1 H), 2.53 (d, *J* = 10.0 Hz, 2 H), 1.64-1.74 (m, 5 H), 1.52-1.58 (m, 1 H), 1.16-1.28 (m, 3 H), 0.91-0.99 (m, 2 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.7, 128.8, 124.8, 120.6, 39.2, 38.2, 33.2, 26.6, 26.3 ppm. HRMS (APCI) for $C_{11}H_{17}S$ ($M+H^+$): Calcd: 181.1051; Found: 181.1049.

3-(Cyclohexylmethyl)benzo[*b*]thiophene (3bb). Colorless liquid (82.8 mg, 60% (method I)). Eluent: petroleum ether (R_f = 0.4, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.88 (dd, *J* = 5.0, 1.5 Hz, 1 H), 7.77 (dd, *J* = 5.0,

1.5 Hz, 1 H), 7.35-7.43 (m, 2 H), 7.08 (s, 1 H), 2.76 (d, J = 5.0 Hz, 2 H), 1.70-1.81 (m, 5 H), 1.67-1.70 (m, 1 H), 1.18-1.25 (m, 3 H), 1.00-1.08 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 140.5, 139.4, 135.7, 123.9, 123.7, 122.9, 122.0, 121.8, 38.0, 36.6, 33.6, 26.5, 26.3 ppm. HRMS (APCI) for $C_{15}H_{19}S$ ($M+H^+$): Calcd: 231.1207; Found: 231.1207.

3-(Cyclohexylmethyl)pyridine (3bc). Colorless liquid (54.6 mg, 52% (method I)). Eluent: ethyl acetate/hexanes (1:3, R_f = 0.25, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 8.46 (d, J = 10.0 Hz, 2 H), 7.53 (d, J = 10.0 Hz, 1 H), 7.28 (s, 1 H), 2.52 (d, J = 5.0 Hz, 2 H), 1.66-1.74 (m, 5 H), 1.50-1.58 (m, 1 H), 1.17-1.24 (m, 3 H), 0.93-1.01 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 149.7, 146.4, 137.2, 136.9, 123.4, 41.0, 39.5, 32.9, 26.4, 26.2 ppm. HRMS (ESI) for $C_{12}H_{18}N$ ($M+H^+$): Calcd: 176.1439; Found: 176.1436.

(2-Cyclohexylethyl)benzene (3bd). Colorless liquid (67.7 mg, 60% (method I)) [18]. Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.30 (t, J = 10.0 Hz, 2 H), 7.17-7.21 (m, 3 H), 2.63-2.66 (m, 2 H), 1.70-1.82 (m, 5 H), 1.66-1.70 (m, 1 H), 1.51-1.56 (m, 2 H), 1.20-1.29 (m, 3 H), 0.92-1.00 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.3, 128.4, 128.2, 125.5, 39.4, 37.3, 33.3, 33.2, 26.7, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{14}H_{20}$: 188.2, found: 188.2.

(3-Cyclohexylpropyl)benzene (3be). Colorless liquid (65.5 mg, 54% (method I)) [18]. Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.32 (m, 2 H), 7.19-7.22 (m, 3 H), 2.61 (t, J = 10.0 Hz, 2 H), 1.67-1.76 (m, 5 H), 1.62-1.67 (m, 1 H), 1.23-1.31 (m, 4 H), 1.14-1.23 (m, 3 H), 0.86-0.94 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.0, 128.4, 128.2, 125.5, 37.6, 37.2, 36.3, 33.4, 28.8, 26.8, 26.5 ppm. MS (EI) m/z (M^+) calcd for $C_{15}H_{22}$: 202.1, found: 202.1.

(1-Cyclohexylethyl)benzene (3bf). Colorless liquid (44.0 mg, 39% (method III), from iodocyclohexane) [28]. Eluent: petroleum ether (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.30 (td, J = 10.0, 5.0 Hz, 2 H), 7.20 (tt, J = 10.0, 5.0 Hz, 1 H), 7.17 (dd, J = 10.0, 5.0 Hz, 2 H), 2.44-2.50 (m, 1 H), 1.87-1.93 (m, 1 H), 1.74-1.80 (m, 1

H), 1.61-1.67 (m, 2 H), 1.39-1.48 (m, 2 H), 1.25 (d, J = 5.0 Hz, 3 H), 1.18-1.25 (m, 1 H), 1.08-1.17 (m, 2 H), 0.92-1.00 (m, 1 H), 0.80-0.88 (m, 1 H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 147.1, 128.0, 127.7, 125.6, 46.0, 44.2, 31.5, 30.6, 26.6, 18.8 ppm. MS (EI) m/z (M^+) calcd for $C_{14}H_{20}$: 188.1, found: 188.1.

1-Cyclohexyl-2,3-dihydro-1H-indene (3bg). Colorless liquid (40.8 mg, 34% (method III), from iodocyclohexane). Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^1H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.21-7.23 (m, 2 H), 7.15-7.17 (m, 2 H), 3.07-3.11 (m, 1 H), 2.89-2.96 (m, 2 H), 2.80-2.86 (m, 1 H), 2.08-2.13 (m, 1 H), 1.90-1.96 (m, 1 H), 1.67-1.81 (m, 6 H), 1.25-1.32 (m, 1 H), 1.13-1.22 (m, 2 H), 0.99-1.07 (m, 1 H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 146.2, 144.6, 126.1, 125.7, 124.5, 124.3, 50.7, 41.5, 31.8, 28.5, 27.6, 26.9, 26.7 ppm. HRMS (APCI) for $C_{15}H_{21}$ ($M+H^+$): Calcd: 201.1643; Found: 201.1643.

(Cyclopentylmethyl)benzene (3bh). Colorless liquid (86.5 mg, 90% (method I)) [29]. Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^1H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.32 (m, 2 H), 7.19-7.22 (m, 3 H), 2.64 (d, J = 5.0 Hz, 2 H), 2.08-2.15 (m, 1 H), 1.72-1.77 (m, 2 H), 1.65-1.70 (m, 2 H), 1.30-1.35 (m, 2 H), 1.21-1.29 (m, 2 H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 142.4, 128.8, 128.1, 125.5, 42.1, 42.0, 32.5, 31.6, 24.9, 22.7 ppm. MS (EI) m/z (M^+) calcd for $C_{12}H_{16}$: 160.1, found: 160.2.

1-Bromo-4-isobutylbenzene (3bi). Colorless liquid (80.0 mg, 63% (method I), from 2-iodopropane) [30]. Eluent: hexanes (R_f = 0.75, UV/I_2). ^1H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.41 (dd, J = 5.0, 1.5 Hz, 2 H), 7.04 (dd, J = 5.0, 1.5 Hz, 2 H), 2.45 (d, J = 5.0 Hz, 2 H), 1.82-1.90 (m, 1 H), 0.93 (s, 3 H), 0.92 (s, 3 H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 140.6, 131.1, 130.9, 119.4, 44.8, 30.2, 22.3 ppm. MS (EI) m/z (M^+) calcd for $C_{10}H_{13}Br$: 212.0, found: 212.0.

1-Bromo-4-(2-methylbutyl)benzene (3bj). Colorless liquid (80.2 mg, 59% (method I), from 2-iodobutane). Eluent: hexanes (R_f = 0.80, UV/I_2). ^1H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.41 (dd, J = 10.0, 5.0 Hz, 2 H), 7.04 (dd, J = 5.0, 1.5 Hz, 2 H), 2.61 (dd, J = 10.0, 5.0 Hz, 1 H), 2.34 (dd, J = 10.0, 5.0 Hz, 1 H), 1.60-1.67 (m, 1 H), 1.36-1.44 (m,

1 H), 1.16-1.24 (m, 1 H), 0.93 (t, *J* = 10.0 Hz, 3 H), 0.86 (d, *J* = 5.0 Hz, 3 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 140.6, 131.1, 130.9, 119.3, 42.7, 36.6, 29.1, 18.9, 11.5 ppm. HRMS (APCI) for $C_{11}H_{14}Br$ ($M\text{-}H^+$): Calcd: 225.0279; Found: 225.0279.

(Cyclohexylmethyl)benzene (3bk). Colorless liquid (80.5 mg, 77% (method I), from bromocyclohexane) [19]. Eluent: petroleum ether (R_f = 0.75, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.32 (td, *J* = 10.0, 5.0 Hz, 2 H), 7.23 (td, *J* = 10.0, 5.0 Hz, 1 H), 7.19 (dd, *J* = 10.0, 5.0 Hz, 2 H), 2.53 (d, *J* = 5.0 Hz, 2 H), 1.67-1.76 (m, 5 H), 1.53-1.61 (m, 1 H), 1.19-1.26 (m, 3 H), 0.96-1.04 (m, 2 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.4, 129.2, 128.0, 125.6, 44.2, 39.8, 33.2, 26.6, 26.4 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{18}$: 174.1, found: 174.3.

(2-Methyltridecyl)benzene (3bl). Colorless liquid (118.5 mg, 72% (method I), from 2-bromotridecane). Eluent: hexanes (R_f = 0.80, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.31 (td, *J* = 10.0, 5.0 Hz, 2 H), 7.21 (tt, *J* = 10.0, 5.0 Hz, 1 H), 7.18 (dd, *J* = 10.0, 5.0 Hz, 2 H), 2.68 (dd, *J* = 10.0, 5.0 Hz, 1 H), 2.38 (dd, *J* = 10.0, 5.0 Hz, 1 H), 1.37-1.44 (m, 1 H), 1.27-1.37 (m, 20 H), 0.93 (t, *J* = 5.0 Hz, 3 H), 0.88 (d, *J* = 5.0 Hz, 3 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 141.7, 129.2, 128.1, 125.6, 43.8, 36.8, 35.0, 32.0, 29.9, 29.8, 29.7, 29.6, 29.5, 29.4, 27.2, 22.7, 19.4, 14.2 ppm. HRMS (APCI) for $C_{20}H_{35}$ ($M+H^+$): Calcd: 275.2739; Found: 275.2739.

1-Benzyladamantane (3bm). Colorless liquid (110 mg, 81% (method I), from 1-iodoadamantane) [31]. Eluent: hexanes (R_f = 0.7, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.30 (tt, *J* = 10.0, 5.0 Hz, 2 H), 7.24 (tt, *J* = 10.0, 5.0 Hz, 1 H), 7.13 (dt, *J* = 10.0, 5.0 Hz, 2 H), 2.43 (s, 2 H), 1.98 (s, 3 H), 1.71 (d, *J* = 10.0 Hz, 3 H), 1.62 (d, *J* = 10.0 Hz, 3 H), 1.53 (d, *J* = 5.0 Hz, 6 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 138.3, 130.6, 127.5, 125.7, 51.3, 42.4, 37.0, 33.5, 28.8 ppm. MS (EI) m/z (M^+) calcd for $C_{17}H_{22}$: 226.1, found: 226.2.

1-Bromo-4-neopentylbenzene (3bn or 3bo). Colorless liquid (**3bq**, 71.5 mg, 53% (method I), from 2-iodo-2-methylpropane; **3br**, 65.0 mg, 48% (method I), from 2-bromo-2-methylpropane) [32]. Eluent: hexanes (R_f = 0.80, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.41 (td, *J* = 10.0, 5.0 Hz, 2 H), 7.02 (td, *J* = 10.0, 5.0 Hz, 2 H),

2.47 (s, 2 H), 0.92 (s, 9 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 138.7, 132.1, 130.7, 119.7, 49.6, 31.7, 29.3 ppm. MS (EI) m/z (M^+) calcd for $C_{11}H_{15}Br$: 226.0, found: 226.0.

Heptylbenzene (3bp or 3bq). Colorless liquid (**3bs**, 54.9 mg, 52% (method II), from 1-iodohexane; **3bt**, 65.5 mg, 62% (method II), from 1-bromohexane) [33]. Eluent: hexanes (R_f = 0.80, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.32 (m, 2 H), 7.18-7.21 (m, 3 H), 2.63 (t, *J* = 10.0 Hz, 2 H), 1.61-1.67 (m, 2 H), 1.28-1.37 (m, 8 H), 0.91 (t, *J* = 10.0 Hz, 3 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.0, 128.4, 128.2, 125.5, 36.0, 31.8, 31.6, 29.3, 29.2, 22.7, 14.1 ppm. MS (EI) m/z (M^+) calcd for $C_{13}H_{20}$: 176.1, found: 176.1.

Tridecylbenzene (3br). Colorless liquid (92.2 mg, 59% (method II), from 1-bromododecane) [34]. Eluent: hexanes (R_f = 0.8, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.31 (m, 2 H), 7.17-7.21 (m, 3 H), 2.62 (t, *J* = 10.0 Hz, 2 H), 1.60-1.65 (m, 4 H), 1.32-1.34 (m, 4 H), 1.28-1.32 (m, 14 H), 0.91 (t, *J* = 10.0 Hz, 3 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.0, 128.4, 128.2, 125.5, 36.0, 34.1, 32.9, 31.9, 31.5, 29.9, 29.8, 29.7, 29.6, 29.5, 29.4, 22.7, 14.1 ppm. MS (EI) m/z (M^+) calcd for $C_{19}H_{32}$: 260.2, found: 260.1.

Dodec-11-en-1-ylbenzene (3bs). Colorless liquid (65.9 mg, 45% (method I), from 11-bromoundec-1-ene) [35]. Eluent: hexanes (R_f = 0.80, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.31 (m, 2 H), 7.18-7.21 (m, 3 H), 5.80-5.88 (m, 1 H), 5.02 (qd, *J* = 15.0, 5.0 Hz, 1 H), 4.96 (qd, *J* = 10.0, 5.0 Hz, 1 H), 2.63 (t, *J* = 10.0 Hz, 2 H), 2.04-2.09 (m, 2 H), 1.61-1.67 (m, 2 H), 1.37-1.41 (m, 2 H), 1.28-1.36 (m, 12 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 143.0, 139.3, 128.4, 128.2, 125.5, 114.1, 36.0, 33.8, 31.5, 29.7, 29.6, 29.5, 29.4, 29.3, 29.2, 29.0 ppm. MS (EI) m/z (M^+) calcd for $C_{18}H_{28}$: 244.2, found: 244.2.

1,6-Diphenylhexane (3bt). Colorless liquid (72.8 mg, 51% (method I), from (5-bromopentyl)benzene) [36]. Eluent: hexanes (R_f = 0.50, UV/I_2). ^{1}H NMR (500 MHz, $CDCl_3$, 296 K, TMS) 7.28-7.32 (m, 4 H), 7.19-7.23 (m, 6 H), 2.62 (t, *J* = 10.0 Hz, 4 H), 1.59-1.67 (m, 4 H), 1.37-1.41 (m, 4 H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, 296 K, TMS) δ 142.8, 128.4, 128.2, 125.6, 36.0, 31.4, 29.2 ppm. MS (EI) m/z (M^+) calcd for $C_{18}H_{22}$: 238.1, found: 238.1.

ASSOCIATED CONTENT

Supporting Information

Copies of NMR spectra of all products of nickel-catalyzed cross-coupling of umpolung carbonyls and alkyl halides.

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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