JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

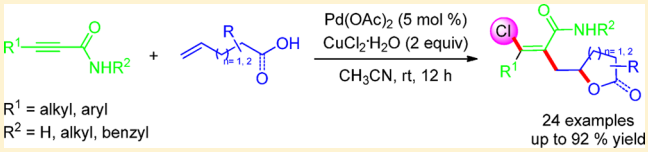
Nucleopalladation-Initiated Oxyalkenylation of Alkenes: A Strategy To Construct Functionalized Oxygenated Heterocycles

Liangbin Huang,† Qian Wang,† Wanqing Wu, and Huanfeng Jiang*

School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China

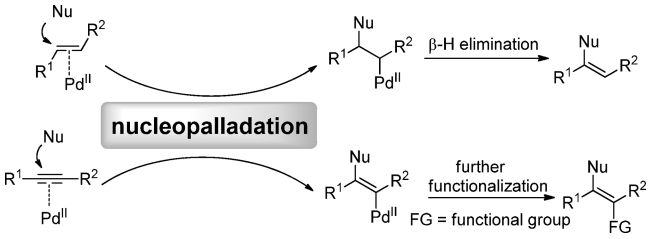
Supporting Information

ABSTRACT: A convenient and efficient approach to construct functionalized oxygen heterocycles, i.e., tetrahydrofurans, tetrahydropyrans, and γ-lactones, has been reported. This process successfully provides a route to construct derivatives of naturally occurring biologically active tetrahydrofurans, especially ones with spirocyclic structure. Highly regio- and stereoselective nucleopalladation of alkynes initiates the cross-coupling between alkynamides and alkenes to give the olefin oxyalkenylation products in good to excellent yields. The hydroxyl group in the olefins cooperates with the amide in alkynamides to promote the cyclization by suppressing the β-H elimination.



Palladium-catalyzed cross-coupling reaction to construct C−C bonds is of great importance in organic synthesis.[1] The palladium catalyst, as a Lewis-acidic transition metal, could also promote the C−C multiple bonds to undergo nucleophilic addition. Nucleopalladation of alkynes and alkenes, which affords the alkyl-Pd and vinyl-Pd species, respectively, (Scheme 1) has been proven to be a highly important route to generate

Scheme 1. Nucleopalladation of Alkenes and Alkynes



C−X (X = O, N, halogen) bonds.[2,3] In comparison to the obvious tendency to undergo β-H elimination in alkyl-Pd species, the vinyl-Pd intermediate could be captured by a variety of electrophiles. Also, the vinyl-Pd intermediate could undergo the oxidative cross-coupling reaction with nucleophiles.[1b,4]

In the traditional Heck and oxidative Heck processes, the aryl-Pd species was easily captured by activated olefins.[5] Similarly, the in situ formed vinyl-Pd intermediate coupled with a variety of activated olefins to give the conjugated diene derivatives via rapid β-H elimination (Scheme 2, path a).[6] Later we found that the nucleopalladation of alkyne triggered oxidative coupling between alkynoates and allylic alcohols affording the γ,σ-unsaturated carbonyl compounds via selective β-H elimination (Scheme 2, path b).[7] Very recently, a potentially bioactive α-methylene-γ-lactone skeleton was successfully constructed via palladium-catalyzed coupling between alkynamides and homoallylic alcohols, in which the remote hydroxyl group could cooperate with the amide to suppress the β-H elimination of alkyl-Pd intermediate (Scheme 2, path c).[8] On the basis of our previous work and inspired by Wolfe-type carbooxygenation of alkenes with aromatic electrophiles,[9] herein we disclose a Pd-catalyzed intermolecular oxyalkenylation of terminal alkenes (Scheme 2, path d). Various functionalized oxygenated heterocycles, such as tetrahydrofurans, tetrahydropyrans, and γ-lactones, were smoothly constructed in high yields. It also provides a route to construct derivatives of naturally occurring biologically active tetrahydrofurans, especially the spirocyclic compounds.

Our initial investigation concentrated on Pd-catalyzed coupling of 3-phenylpropiolamide (**1a**) with pent-4-en-1-ol (**2a**) in the presence of $PdCl_2$ (5 mol %), $CuCl_2·2H_2O$ (2 equiv) in CH_3CN at room temperature for 12 h, which efficiently gave the desired product in 83% GC yield. Further exploration of catalyst revealed that **3aa** could be obtained in 90% yield (Table 1, entry 3) when using $Pd(OAc)_2$ instead of $PdCl_2$. However, with the use of other oxidants, such as $Cu(OAc)_2$, O_2, BQ, and Ag_2CO_3, the yield of the desired product plummeted to less than 15%; no product could be observed when LiCl acted as the chloride source (Table 1, entries 4−7). Unfortunately, only trace target product was detected by GC−MS when the amount of $CuCl_2·2H_2O$ was dropped to 10 mol %, and O_2 played a co-oxidant role in this reaction (Table 1, entry 8). Two other solvents, DMF and toluene, had a slight effect on this reaction (Table 1, entries 9 and 10). By contrast, the blank experiment illustrated that no reaction occurred in the absence of palladium catalyst (Table 1, entry 11).

With the optimized conditions established, the scope of the terminal alkenes was first examined. Initially, 2-methylhex-5-en-2-ol and 5-butylnon-1-en-5-ol could be transformed to the

Received: June 12, 2014
Published: July 15, 2014

   dx.doi.org/10.1021/jo501317v | J. Org. Chem. 2014, 79, 7734−7739

Scheme 2. Pd-Catalyzed Cross-Coupling Reactions of Alkynes and Alkenes

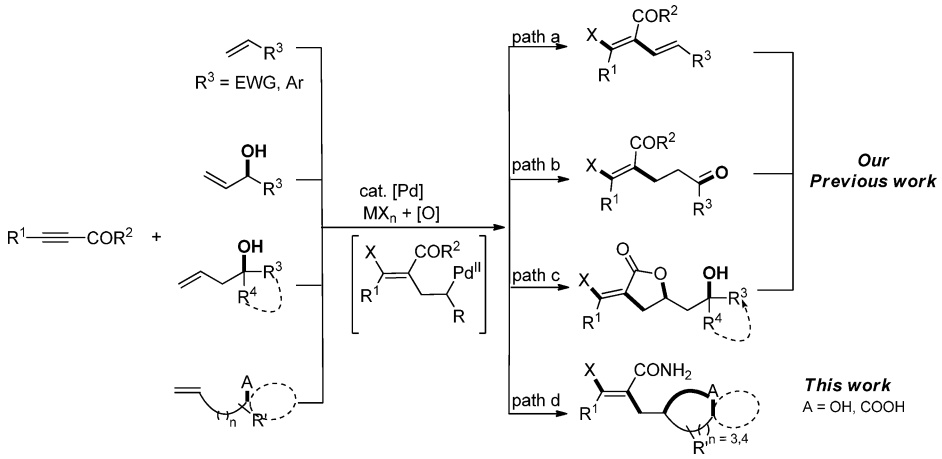
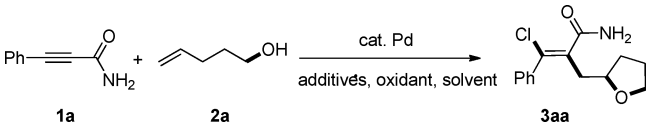


Table 1. Optimization of Reaction Conditions[a]

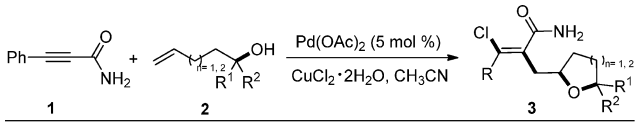


1a 2a 3aa

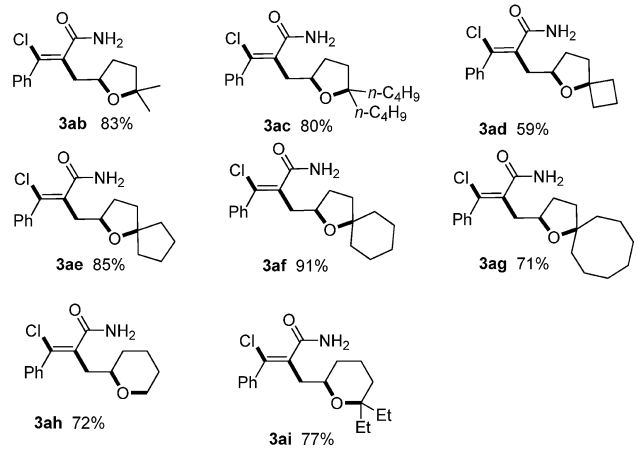
entry	Pd catalyst	additive/oxidant	solvent	yield[b] (%)
1	$PdCl_2$	$CuCl_2{\cdot}2H_2O$	CH_3CN	83
2	$Pd_2(dba)_3$	$CuCl_2{\cdot}2H_2O$	CH_3CN	86
3	$Pd(OAc)_2$	$CuCl_2{\cdot}2H_2O$	CH_3CN	92 (90)
4[c]	$Pd(OAc)_2$	$LiCl/Cu(OAc)_2$	CH_3CN	15
5[c]	$Pd(OAc)_2$	LiCl/1 atm O_2	CH_3CN	<5
6[c]	$Pd(OAc)_2$	$LiCl/Ag_2CO_3$	CH_3CN	nd
7[c]	$Pd(OAc)_2$	LiCl/BQ	CH_3CN	nd
8[d]	$Pd(OAc)_2$	$LiCl/CuCl_2{\cdot}2H_2O$	CH_3CN	<5
9	$Pd(OAc)_2$	$CuCl_2{\cdot}2H_2O$	DMF	83
10	$Pd(OAc)_2$	$CuCl_2{\cdot}2H_2O$	toluene	80
11		$CuCl_2{\cdot}2H_2O$	CH_3CN	nr

[a]Reaction conditions: **1a** (0.5 mmol), **2a** (0.6 mmol), Pd catalyst (5 mol %), oxidant (1.0 mmol) in CH_3CN (0.5 mL) at room temperature for 12 h. [b]Yield was determined by GC analysis using dodecane as the internal standard. Isolated yield product in parentheses. [c]LiCl (4 mmol), oxidant (1.0 mmol). [d]$CuCl_2{\cdot}2H_2O$ (10 mol %) at 1 atm O_2 for 12 h.

Table 2. Substrate Scope of Alkenes[a]



1 2 3



[a]Reaction conditions: **1** (0.5 mmol), **2** (0.6 mmol), $Pd(OAc)_2$ (5 mol %), $CuCl_2{\cdot}2H_2O$ (1.0 mmol) in CH_3CN (0.5 mL) at room temperature for 12 h.

desired products **3ab** in 83% yield and **3ac** in 80% yield, respectively (Table 2). Then, we explored whether four kinds of α-substituted cyclic olefinic alcohols were suitable for the reaction. To our delight, all of them generated the corresponding spirocyclic compounds (**3ad**–**3ag**) successfully, while **3ae** and **3af** could reach excellent yields. It is worth noting that increasing tension of the substituted rings led to a dramatic decline in yield (**3ad**). Subsequently, with the carbon chain of terminal olefins extended, the tetrahydro-2*H*-pyran derivatives **3ah** and **3ai** were successfully obtained in moderate yields.

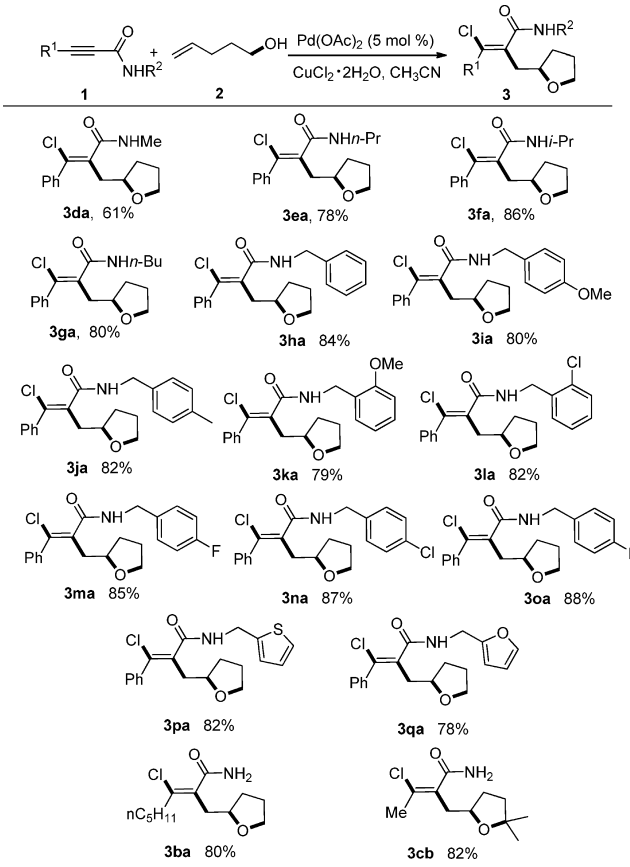
With the positive results above, we next explored the scope of carboetherification of *N*-substituted alkynamides with olefins, which showed high tolerance to the reactions. *N*-Substituted alkynamides with a series of alkyl groups, such as methyl, *n*-propyl, isopropyl, and *n*-butyl, could convert to the corresponding products (**3da**–**3ga**) in moderate yields (Table 3). Afterward, **3ia**–**3la** could be transformed efficiently, in which the substituted groups on benzene rings slightly affected the yields of products. Moreover, the halide functional groups, such as -F, -Cl, and -Br, could be tolerated in this transformation and gave good yields (**3ma**–**3oa**). Notably, thiophene- and furan-substituted alkynamides could still perform well under the standard reaction conditions (**3pa**–**3qa**). Then, but-2-ynamide and oct-2-ynamide were converted to the tetrahydrofuran derivatives **3ba**, and **3cb** in 80% and 82% yields, respectively.

The feasibility of conversion of **1a** provided us a possible route to the synthesis of γ-lactones. Under the standard conditions, it afforded γ-lactones (**4aa**) in 79% yield with the formation of C–O bond (Scheme 3). Notably, γ-lactones exist widely in a large number of natural products and drugs as an active moiety.[10]

On the basis of the above results, a plausible mechanism was proposed for Pd-catalyzed carboetherification of alkenes with alkynamides (Scheme 4). The process was initiated by the *trans*-halopalladation to triple bond, which resulted in vinyl-palladium intermediate **I**. Afterward, the insertion of a double bond experienced a Heck addition to produce the intermediate

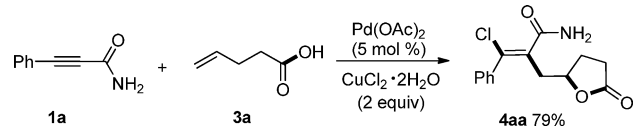
dx.doi.org/10.1021/jo501317v | J. Org. Chem. 2014, 79, 7734–7739

Table 3. Substrate Scope of Alkynamides[a]

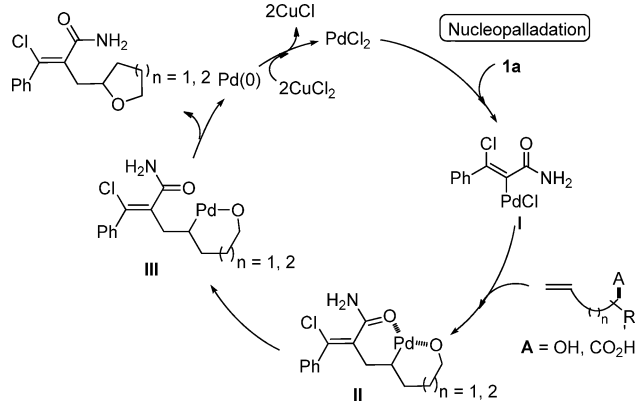


[a]Reaction conditions: **1** (0.5 mmol), **2** (0.6 mmol), $Pd(OAc)_2$ (5 mol %), $CuCl_2{\cdot}2H_2O$ (2 equiv) in CH_3CN (0.5 mL) at room temperature for 12 h.

Scheme 3. Synthesis of γ-Lactones



Scheme 4. Plausible Reaction Mechanism



II, and then Pd was captured by the hydroxyl group in the olefin, which could easily give access to form six- or seven-membered palladacycle intermediate **III**. Finally, the reductive elimination generated the corresponding product **IV** with C−O bond formation, and Pd^{II} active species was regenerated via oxidation by Cu^{II}.

In conclusion, we have developed a simple and efficient method for the synthesis of oxygenated heterocycles through Pd-catalyzed chelation-assisted carboetherification of alkynamides with olefins. With broad functional group tolerance, those oxygenated heterocycles that contain a halogen and amide group were easily modified. Moreover, this method provides a new route to suppress the β-H elimination and potentially synthesize biologically active compounds conveniently.

EXPERIMENTAL SECTION

General Methods. ^1H and ^{13}C NMR spectra were recorded on a 400 MHz spectrometer using $CDCl_3$ as solvent and TMS as an internal standard. High resolution mass spectra were obtained with Q-TOF analyzer equipment.

General Procedure for Synthesis of Tetrahydrofuran Derivatives. A mixture of alkynamides (0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 0.025 mmol,), olefin (0.6 mmol), and $CuCl_2{\cdot}2H_2O$ (207 mg, 1.0 mmol) in CH_3CN (0.5 mL) was stirred at room temperature for 12 h. The mixture was extracted with ethyl acetate (3 × 10 mL), and organic layer was dried by anhydrous $MgSO_4$ and concentrated in vacuum. The resulting residue was purified by flash silica gel chromatography to give the desired products.

(*Z*)-3-Chloro-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)-acrylamide (3aa). White solid (119.0 mg, 90%), mp 142−144 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.34−7.44 (m, 5H), 6.57 (s, 1H), 6.15 (s, 1H), 3.98−4.01 (m, 1H), 3.70−3.39 (m, 2H), 2.56 (dd, *J* = 14.2, 3.7 Hz, 1H), 2.40 (dd, *J* = 14.2, 9.8 Hz, 1H), 1.93 (dt, *J* = 13.1, 6.6 Hz, 1H), 1.77−1.84 (m, 2H), 1.37 (ddd, *J* = 15.0, 12.2, 7.5 Hz, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.5, 137.3, 133.7, 130.6, 128.9, 128.9, 128.4, 77.0, 67.8, 37.8, 31.4, 25.6. HRMS (ESI) *m*/*z*: calcd for $C_{14}H_{16}ClNNaO_2$ $[M + Na]^+$, 288.0762; found, 288.0763. IR (KBr pellet): 3183, 2990, 1764, 1664, 1378, 1243, 1056, 926, 850, 758, 700 cm^{-1}.

(*Z*)-3-Chloro-2-((5,5-dimethyltetrahydrofuran-2-yl)methyl)-3-phenylacrylamide (3ab). Pale yellow liquid (122.0 mg, 83%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.47 (dd, *J* = 7.5, 1.5 Hz, 2H), 7.30−7.38 (m, 3H), 6.85 (s, 1H), 6.57 (s, 1H), 4.09 (dd, *J* = 7.5, 5.3 Hz, 1H), 2.56 (dd, *J* = 14.1, 3.8 Hz, 1H), 2.42 (dd, *J* = 14.1, 9.5 Hz, 1H), 1.96 (dt, *J* = 12.5, 6.3 Hz, 1H), 1.66 (dd, *J* = 10.9, 5.0 Hz, 2H), 1.45−1.52 (m, 1H), 1.19 (s, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.9, 137.3, 133.9, 130.2, 129.0, 128.8, 128.2, 81.5, 76.4, 38.7, 38.3, 32.0, 29.0, 28.0. HRMS (ESI) *m*/*z*: calcd for $C_{16}H_{20}ClNNaO_2$ $[M + Na]^+$, 316.1075; found, 316.1069. IR (KBr pellet): 3298, 2990, 2877, 1764, 1663, 1376, 1243, 1056, 928, 849, 702 cm^{-1}.

(*Z*)-3-Chloro-2-((5,5-dibutyltetrahydrofuran-2-yl)methyl)-3-phenylacrylamide (3ac). Pale yellow solid (151.0 mg, 80%), mp 93−95 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.27−7.46 (m, 5H), 6.70 (s, 1H), 6.33 (s, 1H), 3.97−3.98 (m, 1H), 2.58 (d, *J* = 14.1 Hz, 1H), 2.40 (dd, *J* = 13.9, 9.7 Hz, 1H), 1.84−1.88 (m, 1H), 1.62−1.66 (m, 2H), 1.33−1.46 (m, 5H), 1.26−1.29 (m, 8H), 0.89−0.91 (m, 6H) $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.9, 137.3, 134.0, 130.3, 129.0, 128.8, 128.3, 86.0, 76.3, 39.3, 38.7, 38.1, 35.0, 32.3, 26.6, 26.5, 23.3, 23.3, 14.2, 14.1. HRMS (ESI) *m*/*z*: calcd for $C_{22}H_{32}ClNNaO_2$ $[M + Na]^+$, 400.2014; found, 400.2002. IR (KBr pellet): 2991, 2876, 1764, 1669, 1376, 1243, 1056, 928, 849 cm^{-1}.

(*Z*)-2-(5-Oxaspiro[3.4]octan-6-ylmethyl)-3-chloro-3-phenylacrylamide (3ad). Pale yellow liquid (90.0 mg, 59%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.42−7.47 (m, 2H), 7.31−7.38 (m, 3H), 6.80 (s, 1H), 6.73 (s, 1H), 4.05−4.08 (m, 1H), 2.58−2.47 (m, 1H), 2.33−2.40 (m, 1H), 2.15 (dd, *J* = 22.7, 10.6 Hz, 2H), 1.82−1.94 (m, 5H), 1.63 (dd, *J* = 13.8, 6.7 Hz, 1H), 1.43 (ddd, *J* = 15.3, 14.3, 7.8 Hz, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 171.0, 137.2, 133.7, 130.5, 128.9, 128.9, 128.3, 83.6, 76.7, 38.8, 36.2, 36.0, 36.0, 30.7, 12.7. HRMS (ESI) *m*/*z*: calcd for $C_{17}H_{20}ClNNaO_2$ $[M + Na]^+$, 328.1075; found,

dx.doi.org/10.1021/jo501317v | J. Org. Chem. 2014, 79, 7734−7739

328.1074. IR (KBr pellet): 2990, 1764, 1666, 1377, 1243, 1056, 929, 757, 699 cm^{-1}.

(*Z*)-2-(1-Oxaspiro[4.4]nonan-2-ylmethyl)-3-chloro-3-phenylacrylamide (3ae). Pale yellow liquid (136.0 mg, 85%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.45−7.47 (m, 2H), 7.32−7.39 (m, 3H), 6.91 (s, 1H), 6.13 (s, 1H), 3.48 (t, J = 10.4 Hz, 1H), 2.52 (dd, J = 14.3, 3.2 Hz, 1H), 2.28 (dd, J = 14.3, 9.7 Hz, 1H), 1.71 (dd, J = 14.5, 7.4 Hz, 1H), 1.52 (dd, J = 7.4, 6.0 Hz, 2H), 1.37−1.46 (m, 4H), 1.28 (dd, J = 12.4, 5.8 Hz, 2H), 0.89−0.98 (m, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 171.0, 137.6, 133.8, 131.2, 128.8, 128.8, 128.4, 76.6, 68.8, 38.6, 32.1, 31.6, 22.5, 19.1, 7.5, 7.3. HRMS (ESI) m/z: calcd for $C_{18}H_{22}ClNNaO_2$ $[M + Na]^+$, 342.1231; found, 342.1223. IR (KBr pellet): 3298, 2988, 1764, 1669, 1376, 1243, 1056, 928, 849, 700 cm^{-1}.

(*Z*)-2-(1-Oxaspiro[4.5]decan-2-ylmethyl)-3-chloro-3-phenylacrylamide (3af). Pale yellow liquid (152.0 mg, 91%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.47 (dd, J = 7.7, 1.6 Hz, 2H), 7.31−7.39 (m, 3H), 6.80 (s, 1H), 6.42 (s, 1H), 4.01−4.06 (m, 1H), 2.56 (dd, J = 14.1, 3.7 Hz, 1H), 2.40 (dd, J = 14.1, 9.6 Hz, 1H), 1.87−1.96 (m, 2H), 1.61−1.65 (m, 3H), 1.46−1.50 (m, 3H), 1.37−1.44 (m, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.9, 137.3, 134.0, 130.3, 129.0, 128.8, 128.3, 83.4, 75.9, 38.5, 38.4, 37.3, 35.9, 31.6, 25.6, 24.1, 23.7. HRMS (ESI) m/z: calcd for $C_{19}H_{24}ClNNaO_2$ $[M + Na]^+$, 356.1338; found, 356.1379. IR (KBr pellet): 3331, 3187, 2932, 2857, 1764, 1668, 1377, 1242, 1057, 757, 699 cm^{-1}.

(*Z*)-2-(1-Oxaspiro[4.7]dodecan-2-ylmethyl)-3-chloro-3-phenylacrylamide (3ag). Pale yellow solid (128.0 mg, 71%), mp 92−94 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.45−7.48 (m, 2H), 7.35−7.38 (m, 3H), 6.73 (s, 1H), 6.28 (s, 1H), 3.97−4.00 (m, 1H), 2.56 (dd, J = 14.1, 3.6 Hz, 1H), 2.39 (dd, J = 14.1, 9.7 Hz, 1H), 1.86−1.89 (m, 1H), 1.69−1.78 (m, 2H), 1.43−1.78 (m, 15H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.9, 137.3, 134.0, 130.3, 129.0, 128.8, 128.3, 86.8, 75.8, 38.3, 37.0, 36.9, 35.4, 31.8, 28.2, 28.2, 24.5, 22.9, 22.6. HRMS (ESI) m/z: calcd for $C_{21}H_{28}ClNNaO_2$ $[M + Na]^+$, 384.1701; found, 384.1694. IR (KBr pellet): 3298, 2990, 1764, 1665, 1376, 1242, 1056, 927, 759, 699 cm^{-1}.

(*Z*)-3-Chloro-3-phenyl-2-((tetrahydro-2*H*-pyran-2-yl)methyl)acrylamide (3ah). Pale yellow solid (100.0 mg, 72%), mp 163−165 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, J = 6.6 Hz, 2H), 7.34−7.41 (m, 3H), 6.48 (s, 1H), 6.17 (s, 1H), 3.96−3.98 (m, 1H), 3.32−3.42 (m, 2H), 2.43−2.46 (m, 2H), 1.76 (d, J = 11.0 Hz, 1H), 1.40−1.54 (m, 4H), 1.13 (dt, J = 12.1, 10.5 Hz, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.7, 137.2, 133.6, 130.3, 129.0, 128.9, 128.4, 75.8, 68.5, 38.4, 31.8, 25.7, 23.3. HRMS (ESI) m/z: calcd for $C_{15}H_{18}ClNNaO_2$ $[M + Na]^+$, 302.0918; found,302.0913. IR (KBr pellet): 2991, 2896, 1764, 1376, 1243, 1056, 930, 850 cm^{-1}.

(*Z*)-3-Chloro-2-((6,6-diethyltetrahydro-2*H*-pyran-2-yl)methyl)-3-phenylacrylamide (3ai). Pale yellow liquid (137.0 mg, 77%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.45−7.47 (m, 2H), 7.34−7.40 (m, 3H), 6.92 (s, 1H), 6.37 (s, 1H), 3.48 (dd, J = 14.9, 5.9 Hz, 1H), 2.52 (dd, J = 14.3, 3.2 Hz, 1H), 2.29 (dd, J = 14.3, 9.6 Hz, 1H), 1.66−1.74 (m, 1H), 1.50−1.53 (m, 2H), 1.39−1.46 (m, 4H), 1.25−1.30 (m, 2H), 0.91−1.01 (m, 1H), 0.81−0.86 (m, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 171.2, 137.6, 133.7, 131.2, 128.8, 128.7, 128.4, 76.6, 68.8, 38.6, 32.1, 31.7, 31.6, 22.5, 19.1, 7.5, 7.3. HRMS (ESI) m/z: calcd for $C_{19}H_{26}ClNNaO_2$ $[M + Na]^+$, 358.1544; found, 358.1540. IR (KBr pellet): 3297, 2990, 2890, 1764, 1653, 1376, 1243, 1056, 927, 848, 703 cm^{-1}.

(*Z*)-3-Chloro-*N*-methyl-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3da). Pale yellow liquid (85.0 mg, 61%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.41−7.43 (m, 2H), 7.33−7.33 (m, 3H), 6.60 (d, J = 4.2 Hz, 1H), 3.94 (ddd, J = 10.6, 6.5, 3.3 Hz, 1H), 3.67−3.78 (m, 2H), 2.94 (d, J = 4.9 Hz, 3H), 2.53 (dd, J = 14.2, 4.0 Hz, 1H), 2.39 (dd, J = 14.2, 9.6 Hz, 1H), 1.93 (dt, J = 19.0, 6.6 Hz, 1H)., 1.73−1.84 (m, 2H), 1.35 (tt, J = 14.9, 7.4 Hz, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 169.0, 137.3, 134.5, 130.1, 128.9, 128.8, 128.3, 76.8, 67.8, 37.9, 31.3, 26.2, 25.5. HRMS (ESI) m/z: calcd for $C_{15}H_{18}ClNNaO_2$ $[M + Na]^+$, 302.0918; found, 302.0926. IR (KBr pellet): 3298, 3060, 2987, 1764, 1648, 1543, 1376, 1243, 1058, 852, 764, 704 cm^{-1}.

(*Z*)-3-Chloro-3-phenyl-*N*-propyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ea). White solid (120.0 mg, 78%), mp 72−74 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 7.3 Hz, 2H), 7.33−7.38 (m, 3H), 6.57 (t, J = 5.0 Hz, 1H), 3.94 (td, J = 6.5, 3.2 Hz, 1H), 3.76 (dd, J = 14.5, 7.3 Hz, 1H), 3.69 (dd, J = 14.7, 7.3 Hz, 1H), 3.36 (qd, J = 13.3, 6.5 Hz, 2H), 2.54 (dd, J = 14.2, 3.9 Hz, 1H), 2.38 (dd, J = 14.2, 9.7 Hz, 1H), 1.91 (dt, J = 12.9, 6.6 Hz, 1H), 1.76−1.80 (m, 2H), 1.63 (dd, J = 14.5, 7.3 Hz, 2H), 1.34 (dd, J = 12.1, 7.5 Hz, 1H), 0.99 (t, J = 7.4 Hz, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.2, 137.3, 134.6, 129.8, 128.9, 128.8, 128.3, 76.8, 67.7, 41.3, 37.9, 31.3, 25.5, 22.6, 11.5. HRMS (ESI) m/z: calcd for $C_{17}H_{22}ClNNaO_2$ $[M + Na]^+$, 330.1231; found, 330.1238. IR (KBr pellet): 3298, 2976, 2874, 1764, 1643, 1540, 1376, 1243, 1057, 850, 764, 703 cm^{-1}.

(*Z*)-3-Chloro-*N*-isopropyl-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3fa). Pale yellow solid (132.0 mg, 86%), mp 89−91 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 7.3 Hz, 2H), 7.31−7.38 (m, 3H), 6.25 (d, J = 7.9 Hz, 1H), 4.23 (dd, J = 13.8, 6.9 Hz, 1H), 3.90−3.93 (m, 1H), 3.77 (dd, J = 14.5, 7.2 Hz, 1H), 3.68 (dd, J = 14.8, 7.3 Hz, 1H), 2.53 (dd, J = 14.2, 3.9 Hz, 1H), 2.37 (dd, J = 14.1, 9.7 Hz, 1H), 1.92 (dt, J = 13.0, 6.6 Hz, 1H), 1.75−1.80 (m, 2H), 1.35 (dd, J = 12.1, 7.5 Hz, 1H), 1.22−1.26 (m, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 167.2, 137.3, 134.7, 129.8, 128.9, 128.8, 128.3, 76.8, 67.6, 41.5, 37.8, 31.3, 25.5, 22.6, 22.4. HRMS (ESI) m/z: calcd for $C_{17}H_{22}ClNNaO_2$ $[M + Na]^+$, 330.1231; found, 330.1238. IR (KBr pellet): 3297, 3060, 2979, 1764, 1638, 1538, 1376, 1242, 1057, 764, 703 cm^{-1}.

(*Z*)-*N*-Butyl-3-chloro-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ga). Pale yellow liquid (128.0 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.41−7.44 (m, 2H), 7.35−7.39 (m, 3H), 6.38 (s, 1H), 3.91−3.95 (m, 1H), 3.77 (dd, J = 14.4, 7.3 Hz, 1H), 3.69 (dd, J = 14.7, 7.4 Hz, 1H), 3.34−3.44 (m, 2H), 2.55 (dd, J = 14.2, 3.8 Hz, 1H), 2.36 (dd, J = 14.2, 9.9 Hz, 1H), 1.93 (dt, J = 18.7, 6.6 Hz, 1H), 1.76−1.82 (m, 2H), 1.60 (dd, J = 14.6, 7.4 Hz, 2H), 1.33−1.45 (m, 3H), 0.96 (t, J = 7.3 Hz, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.2, 137.4, 134.7, 129.9, 128.9, 128.8, 128.3, 76.9, 67.8, 39.3, 37.9, 31.4, 31.3, 25.6, 20.1, 13.8. HRMS (ESI) m/z: calcd for $C_{18}H_{24}ClNNaO_2$ $[M + Na]^+$, 344.1388; found, 344.1389. IR (KBr pellet): 3298, 2990, 1764, 1645, 1376, 1242, 1057, 927, 850, 765, 703 cm^{-1}.

(*Z*)-*N*-Benzyl-3-chloro-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ha). Pale yellow liquid (149.0 mg, 84%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.33−7.42 (m, 9H), 7.29 (d, J = 7.0 Hz, 1H), 6.70 (s, 1H), 4.64 (dd, J = 14.8, 5.9 Hz, 1H), 4.55 (dd, J = 14.8, 5.6 Hz, 1H), 3.90 (ddd, J = 9.7, 6.5, 2.9 Hz, 1H), 3.70 (dd, J = 14.8, 6.9 Hz, 1H), 3.60 (dd, J = 15.0, 7.1 Hz, 1H), 2.57 (dd, J = 14.2, 3.7 Hz, 1H), 2.38 (dd, J = 14.2, 9.9 Hz, 1H), 1.89 (dd, J = 12.2, 6.6 Hz, 1H), 1.73−1.80 (m, 2H), 1.31−1.37 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.3, 138.0, 137.3, 134.4, 130.4, 128.9, 128.9, 128.7, 128.4, 128.0, 127.5, 76.9, 67.7, 43.7, 37.9, 31.4, 25.5. HRMS (ESI) m/z: calcd for $C_{21}H_{22}ClNNaO_2$ $[M + Na]^+$, 378.1231; found, 378.1233. IR (KBr pellet): 3298, 2990, 2876, 1760, 1650, 1373, 1243, 1056, 928, 848, 761, 700 cm^{-1}.

(*Z*)-3-Chloro-*N*-(4-methoxybenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ia). White solid (154.0 mg, 80%), mp 114−116 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.39 (d, J = 7.3 Hz, 2H), 7.28−7.36 (m, 5H), 6.86 (d, J = 8.4 Hz, 2H), 6.80 (t, J = 5.3 Hz, 1H), 4.51 (ddd, J = 34.0, 14.6, 5.7 Hz, 2H), 3.88−3.91 (m, 1H), 3.76 (s, 3H), 3.68 (dd, J = 14.5, 7.2 Hz, 1H), 3.59 (dd, J = 14.4, J = 7.3 Hz, 1H), 2.54 (dd, J = 14.2, 3.9 Hz, 1H), 2.38 (dd, J = 14.1, 9.6 Hz, 1H), 1.87 (dt, J = 12.9, 6.6 Hz, 1H), 1.70−1.77 (m, 2H), 1.26−1.33 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.1, 159.0, 137.3, 134.4, 130.2, 130.1, 129.3, 128.9, 128.9, 128.4, 114.0, 76.9, 67.7, 55.3, 43.1, 37.9, 31.3, 25.5. HRMS (ESI) m/z: calcd for $C_{22}H_{24}ClNNaO_3$ $[M + Na]^+$, 408.1337; found, 408.1337. IR (KBr pellet): 3299, 2991, 2878, 1764, 1649, 1513, 1377, 1243, 1056, 843, 763, 702 cm^{-1}.

(*Z*)-3-Chloro-*N*-(4-methylbenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ja). Pale yellow liquid (151.0 mg, 82%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.40 (d, J = 7.3 Hz, 2H), 7.30−7.37 (m, 3H), 7.26 (d, J = 7.9 Hz, 2H), 7.13 (d, J = 7.8 Hz, 2H), 6.79 (t, J = 5.0 Hz, 1H), 4.53 (qd, J = 14.7, 5.7 Hz, 2H), 3.88−3.92 (m,

dx.doi.org/10.1021/jo501317v | J. Org. Chem. 2014, 79, 7734−7739

1H), 3.68 (dd, J = 14.4, 7.2 Hz, 1H), 3.59 (dd, J = 14.4, J = 7.3 Hz, 1H), 3.64 (dq, J = 37.3, 7.5 Hz, 2H), 2.55 (dd, J = 14.2, 3.9 Hz, 1H), 2.44−2.37 (m, 1H), 2.32 (s, 3H), 1.87 (dt, J = 13.1, 6.6 Hz, 1H), 1.71−1.78 (m, 2H), 1.28−1.34 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.2, 137.4, 137.1, 135.0, 134.4, 130.3, 129.3, 128.9, 128.9, 128.4, 128.0, 76.9, 67.7, 43.5, 37.9, 31.3, 25.5, 21.1. HRMS (ESI) m/z: calcd for $C_{22}H_{24}ClNNaO_2$ $[M + Na]^+$, 392.1388; found, 392.1391. IR (KBr pellet): 3298, 2989, 1764, 1647, 1520, 1376, 1242, 1057, 848, 762, 702 cm^{-1}.

(*Z*)-3-Chloro-*N*-(2-methoxybenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ka). Pale yellow liquid (152.0 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.40 (t, J = 8.7 Hz, 3H), 7.31−7.34 (m, 3H), 7.26 (t, J = 7.8 Hz, 1H), 6.83−6.94 (m, 3H), 4.60 (d, J = 5.9 Hz, 2H), 3.85−3.89 (m, 1H), 3.83 (s, 3H), 3.69 (dd, J = 14.5, 7.2 Hz, 1H), 3.58 (dd, J = 14.8, 7.2 Hz, 1H), 2.54 (dd, J = 14.2, 4.0 Hz, 1H), 2.39 (dd, J = 14.1, 9.5 Hz, 1H), 1.86 (td, J = 13.1, 6.6 Hz, 1H), 1.69−1.76 (m, 2H), 1.23−1.34 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.1, 157.5, 137.4, 134.5, 130.0, 129.7, 128.9, 128.9, 128.8, 128.3, 126.0, 120.6, 110.2, 76.8, 67.6, 55.3, 39.3, 37.9, 31.3, 25.5. HRMS (ESI) m/z: calcd for $C_{22}H_{24}ClNNaO_3$ $[M + Na]^+$, 408.1337; found,408.1334. IR (KBr pellet): 3297, 2990, 2879, 1764, 1653, 1375, 1243, 1056, 757, 702 cm^{-1}.

(*Z*)-3-Chloro-*N*-(2-chlorobenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3la). White solid (159.0 mg, 82%), mp 125−127 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.53−7.56 (m, 1H), 7.41 (d, J = 7.1 Hz, 2H), 7.32−7.37 (m, 4H), 7.21−7.26 (m, 2H), 6.93 (t, J = 5.6 Hz, 1H), 4.67 (d, J = 6.0 Hz, 2H), 3.85 (dt, J = 9.5, 3.2 Hz, 1H), 3.71 (dd, J = 14.7, 7.0 Hz, 1H), 3.61 (dd, J = 14.9, 7.2 Hz, 1H), 2.55 (dd, J = 14.2, 3.8 Hz, 1H), 2.37 (dd, J = 14.2, 9.8 Hz, 1H), 1.86 (td, J = 12.9, 6.5 Hz, 1H), 1.71−1.78 (m, 2H), 1.26−1.33 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.4, 137.3, 135.5, 134.2, 133.6, 130.6, 130.3, 129.4, 128.9, 128.9, 128.4, 127.1, 77.0, 67.7, 41.5, 37.9, 31.4, 25.5. HRMS (ESI) m/z: calcd for $C_{21}H_{21}Cl_2NNaO_2$ $[M + Na]^+$, 412.0842; found, 412.0837. IR (KBr pellet): 2991, 2882, 1764, 1376, 1243, 1056, 928, 850, 756 cm^{-1}.

(*Z*)-3-Chloro-*N*-(4-fluorobenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3ma). White solid (158 mg, 85%), mp 133−135 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.41−7.34 (m, 7H), 7.01 (t, J = 8.5 Hz, 2H), 6.88−6.85 (m, 1H), 4.54 (ddd, J = 38.0, 14.8, 5.9 Hz, 2H), 3.92−3.84 (m, 1H), 3.69 (dd, J = 14.5, 7.2 Hz, 1H), 3.60 (dd, J = 14.5, 7.2 Hz, 1H), 2.57−2.53 (m, 1H), 2.41−2.35 (m, 1H), 1.92−1.84 (m, 1H), 1.75 (td, J = 13.0, 6.6 Hz, 2H), 1.36−1.30 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.1, 162.0 (d, J = 245.4 Hz), 137.1, 134.1, 133.7 (d, J = 3.2 Hz), 130.3, 129.5 (d, J = 8.1 Hz), 128.8, 128.7, 128.2, 115.2 (d, J = 21.4 Hz), 76.8, 67.6, 42.7, 37.8, 31.2, 25.4. HRMS (ESI) m/z: calcd for $C_{21}H_{22}ClFNO_2$ $[M + H]^+$, 374.1318; found, 374.1319. IR (KBr pellet): 3292, 2978, 1764, 1647, 1439, 1376, 1241, 1058, 915, 826, 751, 701 cm^{-1}.

(*Z*)-3-Chloro-*N*-(4-chlorobenzyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3na). White solid (169.0 mg, 87%), mp 118−120 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.40−7.27 (m, 9H), 6.95 (t, J = 5.4 Hz, 1H), 4.54 (ddd, J = 38.0, 15.0, 5.9 Hz, 2H), 3.92−3.92 (m,1H), 3.70 (dd, J = 14.4, J = 7.2 Hz, 1H), 3.61 (dd, J = 14.4, J = 7.3 Hz, 1H), 2.57−2.52 (m, 1H), 2.41−2.35 (m, 1H), 1.92−1.84 (m, 1H), 1.75 (td, J = 13.0, 6.7 Hz, 2H), 1.36−1.27 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.2, 137.0, 136.5, 134.1, 133.0, 130.3, 129.1, 128.7, 128.7, 128.5, 128.2, 76.8, 67.6, 42.7, 37.7, 31.2, 25.3. HRMS (ESI) m/z: calcd for $C_{21}H_{21}Cl_2NNaO_2$ $[M + Na]^+$, 412.0842; found, 412.0849. IR (KBr pellet): 3289, 3060, 2973, 1763, 1647, 1528, 1443, 1243, 1054, 899, 762, 702 cm^{-1}.

(*Z*)-*N*-(4-Bromobenzyl)-3-chloro-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3oa). White solid (191.0 mg, 88%), mp 126−128 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 7.45−7.34 (m, 7H), 7.28−7.24 (m, 2H), 6.96 (t, J = 5.2 Hz, 1H), 4.52 (ddd, J = 37.5, 15.0, 5.9 Hz, 2H), 3.91−3.85 (m, 1H), 3.69 (dd, J = 14.5, 7.3 Hz, 1H), 3.61 (dd, J = 14.4, 7.2 Hz, 1H), 2.56−2.52 (m, 1H), 2.41−2.35 (m, 1H), 1.94−1.82 (m, 1H), 1.75 (td, J = 13.0, 6.7 Hz, 2H), 1.36−1.27 (m,1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.2, 137.0, 134.0, 131.4, 130.3, 129.4, 128.7, 128.7, 128.2, 121.1, 76.8, 67.6, 42.8, 37.7, 31.2, 25.3. HRMS (ESI) m/z: calcd for $C_{21}H_{21}BrClNNaO_2$ $[M + Na]^+$, 456.0336; found, 456.0341. IR (KBr pellet): 3282, 3059, 2975, 2870, 1764, 1649, 1525, 1369, 1243, 1056, 900, 761, 702 cm^{-1}.

(*Z*)-3-Chloro-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)-*N*-(thiophen-2-ylmethyl)acrylamide (3pa). White solid (148.0 mg, 82%), mp 126−128 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.41−7.32 (m, 5H), 7.22 (d, J = 5.1 Hz, 1H), 7.04 (s, 1H), 6.95 (t, J = 3.9 Hz, 1H), 6.89 (s, 1H), 4.75 (d, J = 5.7 Hz, 2H), 3.93−3.86 (m, 1H), 3.69 (q, J = 7.2 Hz, 1H), 3.61 (q, J = 7.3 Hz, 1H), 2.57−2.53 (m, 1H), 2.40−2.34 (m, 1H), 1.92−1.79 (m, 1H), 1.75 (td, J = 13.0, 6.7 Hz, 2H), 1.36−1.26 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 167.9, 140.3, 137.1, 133.9, 130.5, 128.7, 128.2, 126.7, 126.1, 125.1, 76.7, 67.6, 38.2, 37.7, 31.2, 25.4. HRMS (ESI) m/z: calcd for $C_{19}H_{21}ClNO_2S$ $[M + H]^+$, 362.0976; found, 362.0977. IR (KBr pellet): 3289, 3061, 2966, 2868, 1650, 1649, 1520, 1441, 1295, 897, 762, 700 cm^{-1}.

(*Z*)-3-Chloro-*N*-(furan-2-ylmethyl)-3-phenyl-2-((tetrahydrofuran-2-yl)methyl)acrylamide (3qa). Pale yellow liquid (134.0 mg, 78%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.42−7.32 (m, 6H), 6.94 (s, 1H), 6.31 (d, J = 5.2 Hz, 2H), 4.57 (d, J = 5.6 Hz, 2H), 3.91−3.85 (m, 1H), 3.71 (q, J = 7.2 Hz, 1H), 3.62 (q, J = 7.3 Hz, 1H), 2.56−2.52 (m, 1H), 2.40−2.34 (m,1H), 1.94−1.82 (m, 1H), 1.75 (td, J = 13.0, 6.7 Hz, 2H), 1.36−1.27 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.0, 151.0, 141.9, 137.1, 133.9, 130.3, 128.7, 128.2, 76.7, 67.5, 37.6, 36.4, 31.1, 25.3. HRMS (ESI) m/z: calcd for $C_{19}H_{20}ClNNaO_3$ $[M + Na]^+$, 368.1024; found, 368.1028. IR (KBr pellet): 3291, 3060, 2973, 2871, 1764, 1653, 1370, 1242, 1057, 920, 741, 702 cm^{-1}.

(*Z*)-3-Chloro-2-((tetrahydrofuran-2-yl)methyl)oct-2-enamide (3ba). Pale yellow liquid (75.0 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$): δ 6.48 (s, 1H), 6.23 (s, 1H), 4.02−3.95 (m, 1H), 3.85 (dd, J = 14.5, 7.3 Hz, 1H), 3.73 (dd, J = 14.7, 7.4 Hz, 1H), 2.61−2.56 (m, 1H), 2.49−2.45 (m, 1H), 2.41 (dd, J = 14.2, 6.8 Hz, 2H), 2.09−2.01 (m, 1H), 1.95−1.85 (m, 2H), 1.65−1.50 (m, 3H), 1.32 (s, 4H), 0.90 (t, J = 6.4 Hz, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 170.9, 134.8, 131.1, 77.7, 67.7, 36.7, 35.3, 31.4, 31.0, 27.0, 25.5, 22.4, 13.8. HRMS (ESI) m/z: calcd for $C_{13}H_{22}ClNNaO_2$ $[M + Na]^+$, 282.1231; found, 282.1235. IR (KBr pellet): 3289, 3060, 2966, 2868, 1747, 1650, 1520, 1440, 1295, 1056, 897, 762, 702 cm^{-1}.

(*Z*)-3-Chloro-2-((5,5-dimethyltetrahydrofuran-2-yl)methyl)-but-2-enamide (3cb). Pale yellow liquid (95.0 mg, 82%). ^1H NMR (400 MHz, $CDCl_3$): δ 6.75 (s, 1H), 6.24 (s, 1H), 4.01−4.08 (m, 1H), 2.51 (dd, J = 14.3, 4.0 Hz, 1H), 2.37 (dd, J = 14.3, 8.8 Hz, 1H), 2.08 (s, 3H), 2.01 (dd, J = 12.1, 6.5 Hz, 1H), 1.66−1.71 (m, 2H), 1.56−1.63 (m, 1H), 1.20 (s, 3H), 1.14 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 171.1, 131.4, 130.2, 81.6, 76.8, 38.2, 38.0, 31.9, 29.1, 28.0, 22.9. HRMS (ESI) m/z: calcd for $C_{11}H_{19}ClNO_2$ $[M + H]^+$, 232.1098; found, 232.1102. IR (KBr pellet): 3290, 3060, 2965, 2870, 1750, 1653, 1520, 1368, 1293, 1054, 900, 761, 700 cm^{-1}.

(*Z*)-3-Chloro-2-((5-oxotetrahydrofuran-2-yl)methyl)-3-phenylacrylamide (4aa). Pale yellow liquid (110.0 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.35−7.43 (m, 5H), 6.47 (s, 2H), 4.63−4.70 (m, 1H), 2.73 (dd, J = 14.6, 4.0 Hz, 1H), 2.57 (dd, J = 14.6, 9.6 Hz, 1H), 2.38−2.50 (m, 2H), 2.28−2.30 (m, 1H), 1.70−1.79 (m, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 176.7, 169.5, 136.8, 132.3, 131.3, 129.3, 128.7, 128.6, 78.1, 37.8, 28.4, 27.6. HRMS (ESI) m/z: calcd for $C_{14}H_{14}ClNNaO_3$ $[M + Na]^+$, 302.0554; found, 302.0549. IR (KBr pellet): 2988, 1770, 1726, 1373, 1242, 1054, 902, 765, 703 cm^{-1}.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^1H and ^{13}C NMR spectra of all synthesized compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: jianghf@scut.edu.cn.

Author Contributions

†These authors contributed equally to this work.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful to the National Natural Science Foundation of China (21172076 and 21202046), the National Basic Research Program of China (973 Program) (2011CB808600), the Guangdong Natural Science Foundation (10351064101000000 and S2012040007088), and the Fundamental Research Funds for the Central Universities (2014ZP0004 and 2014ZZ0046).

■ REFERENCES

(1) (a) Zhang, Q.; Lu, X. *J. Am. Chem. Soc.* **2000**, *122*, 7604−7605. (b) Zhao, L.; Lu, X. *Angew. Chem., Int. Ed.* **2002**, *41*, 4343−4345. (c) Welbes, L. L.; Lyons, T. W.; Cychosz, K. A.; Sanford, M. S. *J. Am. Chem. Soc.* **2007**, *129*, 5836−5837. (d) Tong, X.; Beller, M.; Tse, M. K. *J. Am. Chem. Soc.* **2007**, *129*, 4906−4907. (e) Huang, J.; Zhou, L.; Jiang, H. *Angew. Chem., Int. Ed.* **2006**, *45*, 1945−1949. (f) Gagnier, S. V.; Larock, R. C. *J. Org. Chem.* **2000**, *65*, 1525−1529. (g) Xie, X.; Lu, X.; Liu, Y.; Xu, W. *J. Org. Chem.* **2001**, *66*, 6545−6550. (h) Aubert, C.; Buisine, O.; Malacria, M. *Chem. Rev.* **2002**, *102*, 813−834.

(2) (a) Zeni, G.; Larock, R. C. *Chem. Rev.* **2006**, *106*, 4644−4680. (b) Patil, N. P.; Yamamoto, Y. *Chem. Rev.* **2008**, *108*, 3395−3442. (c) Cacchi, S.; Fabrizi, G. *Chem. Rev.* **2011**, *111*, 215−283. (d) Yin, G.; Liu, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 5442−5445. (e) Liu, R.; Zhang, J. *Chem.—Eur. J.* **2009**, *15*, 9303−9306. (f) Li, W.; Zhang, J. *Chem. Commun.* **2010**, *46*, 8839−8841. (g) Zhang, X.; Lu, Z.; Fu, C.; Ma, S. *J. Org. Chem.* **2010**, *75*, 2589−2598.

(3) (a) McDonald, R. I.; Liu, G.; Stahl, S. S. *Chem. Rev.* **2011**, *111*, 2981−3019. (b) Ma, S.; Lu, X. *J. Org. Chem.* **1991**, *56*, 5120−5125. (c) Huang, L.; Wang, Q.; Liu, X.; Jiang, H. *Angew. Chem., Int. Ed.* **2012**, *51*, 5696−5700. (d) Feng, C.; Loh, T.-P. *J. Am. Chem. Soc.* **2010**, *132*, 17710−17712. (e) Jiang, H.; Qiao, C.; Liu, W. *Chem.—Eur. J.* **2010**, *16*, 10968−10970. (f) Chen, D.; Cao, Y.; Yuan, Z.; Cai, H.; Zheng, R.; Kong, L.; Zhu, G. *J. Org. Chem.* **2011**, *76*, 4071−4074.

(4) (a) Jia, X.; Petrone, D. A.; Lautens, M. *Angew. Chem., Int. Ed.* **2012**, *51*, 9870−9872. (b) Jiang, H.; Liu, X.; Zhou, L. *Chem.—Eur. J.* **2008**, *14*, 11305−11309. (c) Zhou, P.; Zheng, M.; Jiang, H.; Li, X.; Qi, C. *J. Org. Chem.* **2011**, *76*, 4759−4763. (d) Gabriele, B.; Salerno, G.; Pascali, F.; Costa, M.; Chiusoli, G. P. *J. Org. Chem.* **1999**, *64*, 7693−7699. (e) Kato, K.; Motodate, S.; Mochida, T.; Kobayashi, T.; Akita, H. *Angew. Chem., Int. Ed.* **2009**, *48*, 3326−3328. (f) Gabriele, B.; Veltri, L.; Mancuso, R.; Salerno, G.; Maggi, S.; Maria Aresta, B. *J. Org. Chem.* **2012**, *77*, 4005−4016.

(5) (a) Bras, J. L.; Muzart, J. *Chem. Rev.* **2011**, *111*, 1170−1214. (b) Su, Y.; Jiao, N. *Org. Lett.* **2009**, *11*, 2980−2983. (c) Yoo, K. S.; Park, C. P.; Yoon, C. H.; Sakaguchi, S.; O'Neill, J.; Jung, K. W. *Org. Lett.* **2007**, *9*, 3933−3935. (d) Xiong, D.; Zhang, L.; Ye, X. *Org. Lett.* **2009**, *11*, 1709−1712. (e) Thirunavukkarasu, V. S.; Parthasarathy, K.; Cheng, C. *Angew. Chem., Int. Ed.* **2008**, *47*, 9462−9465. (f) Yoo, K. S.; Yoon, C. H.; Jung, K. W. *J. Am. Chem. Soc.* **2006**, *128*, 16384−16393.

(6) (a) Huang, J.; Dong, Y.; Wang, X.; Luo, H. *Chem. Commun.* **2010**, *46*, 1035−1037. (b) Zhou, P.; Jiang, H.; Huang, L.; Li, X. *Chem. Commun.* **2011**, *47*, 1003−1005. (c) Zhou, P.; Huang, L.; Jiang, H.; Wang, A.; Li, X. *J. Org. Chem.* **2010**, *75*, 8279−8282. (d) Silva, F.; Reiter, M.; Mills-Webb, R.; Sawicki, M.; Klär, D.; Bensel, N.; Wagner, A.; Gouverneur, V. *J. Org. Chem.* **2006**, *71*, 8390−8394.

(7) Wen, Y.; Huang, L.; Jiang, H.; Chen, H. *J. Org. Chem.* **2012**, *77*, 2029−2034.

(8) Huang, L.; Wang, Q.; Wu, W.; Jiang, H. *ChemCatChem.* **2014**, *6*, 561−566.

(9) (a) Zhu, C.; Falck, J. R. *Angew. Chem., Int. Ed.* **2011**, *50*, 6626−6629. (b) Wolfe, J. P.; Rossi, M. A. *J. Am. Chem. Soc.* **2004**, *126*, 1620−1621. (c) Aranyos, A.; Old, D. W.; Kiyomori, A.; Wolfe, J. P.; Sadighi, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 4369−4378. (d) Ward, A. F.; Wolfe, J. P. *Org. Lett.* **2010**, *12*, 1268−1271. (e) Hanley, P. S.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2013**, *52*, 8510−8525.

(10) (a) Montgomery, T. P.; Hassan, A.; Park, B. Y.; Krische, M. J. *J. Am. Chem. Soc.* **2012**, *134*, 11100−11103. (b) Reynolds, A. J.; Scott, A. J.; Turner, C. I.; Sherburn, M. S. *J. Am. Chem. Soc.* **2003**, *125*, 12108−12109.