JOC The Journal of Organic Chemistry

NOTE

pubs.acs.org/joc

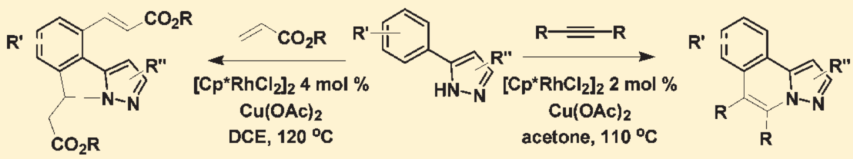
Rhodium(III)-Catalyzed Oxidative Coupling of 5-Aryl-1*H*-pyrazoles with Alkynes and Acrylates

Xingwei Li* and Miao Zhao

Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, People's Republic of China

Supporting Information

ABSTRACT:



$[RhCp^*Cl_2]_2$-catalyzed oxidative coupling of 5-aryl-1*H*-pyrazoles with alkynes and acrylates has been achieved using $Cu(OAc)_2$ as an oxidant. Coupling with alkynes afforded six-membered azacycles as a result of C−C and C−N coupling. Coupling with acrylates followed a process of diolefination and a subsequent aza-Michael cyclization.

Metal-catalyzed C−H activation has become a powerful strategy for the synthesis of complex structures, and it has received increasing attention.[1] This is an advantageous process in that no prefunctionalization of C−H bonds is necessary. Given the abundance of C−H bonds, versatile, selective, and efficient C−H functionalization under mild conditions should allow the construction of complex molecules in an energy-efficient and step-economic fashion.[2] Heterocycles such as pyrazoles are widely present in important natural products, synthetic drugs, and materials.[3] They have also been employed as precursors to N-heterocyclic carbenes, which play an important role in organometallic chemistry and in catalysis.[4] Thus efficient synthesis of heterocycles from readily available starting materials has been long sought.

Rhodium complexes have stood out as highly efficient catalysts in the functionalization of C−H bonds using unsaturated molecules via a C−H activation pathway, and rhodium catalysis has allowed for the synthesis of a broad spectrum of useful heterocycles with wide substrate scopes, high efficiency, and high functional group tolerance under relatively mild conditions.[5] In this context, Rh(III)-catalyzed synthesis of heterocycles via oxidative coupling of C−H bonds (especially in arenes) with alkynes has recently been increasingly explored.[6] A number of research groups, including ours,[7] have applied this method to the synthesis of heterocycles such as isoquinolines,[8] isoquinolones,[7c,9] indoles,[10] isocoumarins,[11] indenols,[12] pyrroles,[13] and pyridones[7d,14] under chelation-assisted C−H activation (Figure 1). These systems can be complementary to palladium-catalyzed oxidative coupling in terms of substrate scope, selectivity, and reactivity.[15] Despite this success, it is still necessary to explore substrates bearing readily installed directing groups in order to expand the versatility and the synthetic utility. We now report the oxidative C−C and C−N coupling of 5-arylpyrazoles with alkynes and alkenes catalyzed by $[RhCp^*Cl_2]_2$, leading to the facile construction of C−C and C−N bonds.

Given the availability of pyrazoles and their significance in organic synthesis and in material studies,[16] we have chosen NH pyrazoles as a directing group to facilitate C−H bond activation.[17] We commenced our studies with the screening of the conditions in the coupling of pyrazole **1a** with PhC≡CPh (**2a**). With the $[RhCp^*Cl_2]_2$ catalyst at a fixed loading of 2 mol %, this reaction proceeded in various solvents such as MeCN, DMF, acetone, dioxane, and toluene and with different oxidants (Table 1). In contrast, a combination of $Cu(OAc)_2$ and air (1 atm) in *o*-xylene at 150 °C gave a poor result (entry 10). Given the low cost of $Cu(OAc)_2$, it is designated as a preferred oxidant. Although the reaction conducted in DMF afforded the product in high yield, the workup is more tedious due to its high boiling point. The optimal yield was obtained when acetone was used as a solvent (110 °C, sealed tube, entry 9). Under these conditions, the coupled product **3aa** was isolated in 94% yield.

The scope and limitations of this coupling reaction have been explored under the optimized conditions (Scheme 1). Pyrazoles bearing different ortho, meta, and para substituents on the phenyl ring have been successfully applied. Both electron-donating (**3ea**, **3ha**, and **3ja**) and -withdrawing groups, including esters and nitrile groups, in the phenyl ring can be tolerated (see **3fa**, **3ga**, **3ka**, **3la**, **3ma**, **3sa**, and **3ta**). The steric hindrance caused by the introduction of an *o*-Me or *o*-Cl or by fusing a phenyl ring is well tolerated, and the corresponding products **3ea**, **3fa**, and **3oa** were isolated in high yield. Halogen substituents at the *o* and *p* positions of the phenyl ring are retained in most cases during this coupling process (**3fa**, **3ga**, **3ka**, **3la**, and **3ma**). The presence of C−halogen bonds in the coupled products should allow further elaboration. However, the debrominative coupled product **3aa** was isolated (32%) for an *o*-bromo-substituted starting

Received: July 23, 2011
Published: September 13, 2011

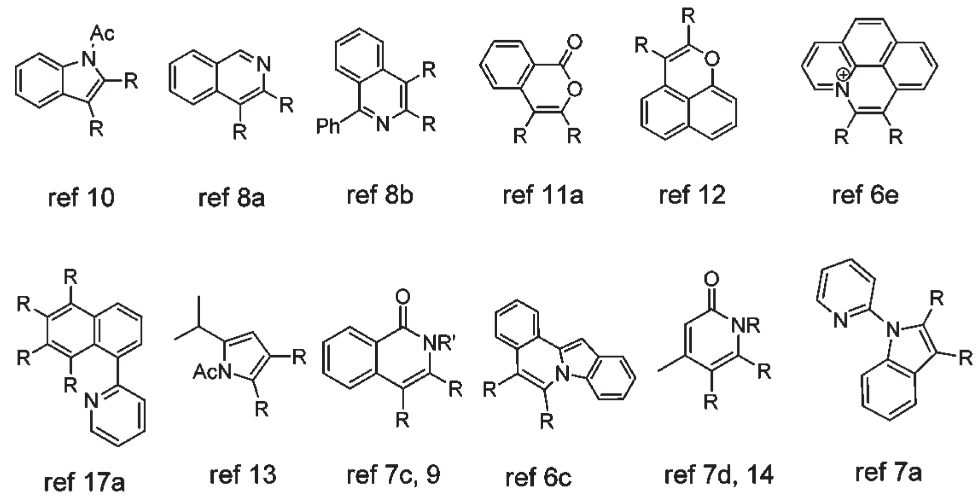
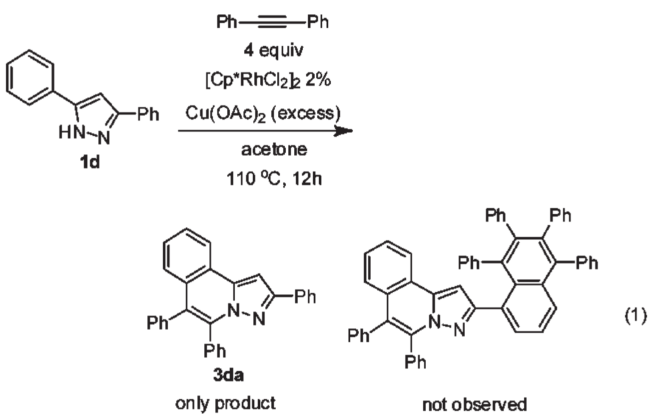


Figure 1. Chelation-assisted Rh(III)-catalyzed C−H functionalization with alkynes.

material in addition to the expected product **3ga** (39% yield). However, dehalogenation is limited to the reactive ortho C−Br bonds, and it essentially does not bother the reaction of the *o*-chloro-substituted pyrazole substrate (see **3fa**). Activation of the phenyl C−H bond is also readily achievable by attaching substituents (Me, Ph, and CF_3) to the pyrazole ring (**3ba**, **3ca**, **3da**, and **3pa**), although the introduction of highly withdrawing groups such as CF_3 retarded this coupling (**3pa**). In the case of different possible sites of C−H activation, regioselectivity can be an issue. However, regioselective C−H functionalization has been achieved in the synthesis of **3ha** and **3na**, which were isolated as the only products, and the C−H bond at the less hindered position was functionalized. Attempts to activate heteroaryl C−H bonds met with difficulty, and the coupled products **3qa** and **3ra** were isolated in rather low yields.

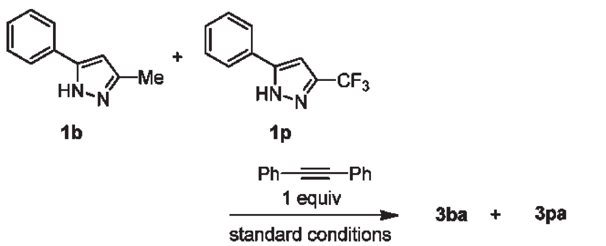
To probe if the pyrazole ring nitrogen can act as an effective directing group for further ortho C−H activation in the product **3da**,[7f,17] an excess of PhC≡CPh and $Cu(OAc)_2$ was provided for the coupling of **1d** that bears two phenyl groups in the pyrazole ring. In fact, only **3da** was obtained (90% yield), suggesting that the nitrogen atom is sterically inaccessible (eq 1).



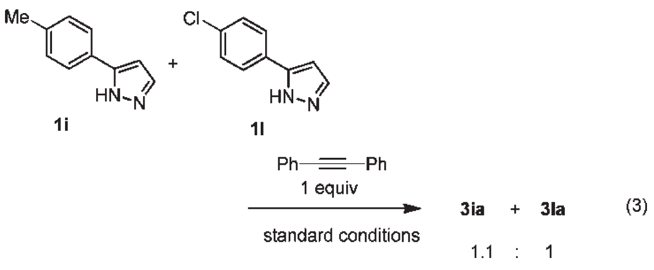
(1)

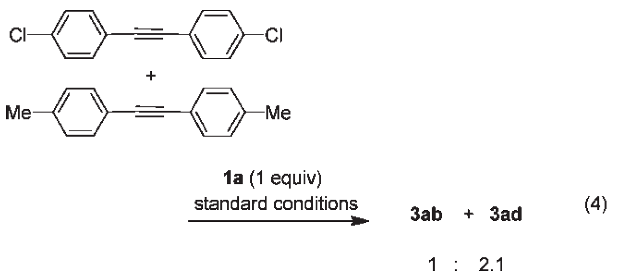
The scope of internal alkynes has been explored in their coupling with pyrazole **1a** (Scheme 2). Coupling with other symmetrical diarylacetylenes gave somewhat lower yields (62−67%). In addition, bis(2-thiophenyl)acetylene underwent slow conversion, and the product **3af** was isolated in only 25% yield. When PhC≡CMe was used, **3ae** was isolated as the only regioisomer (61%). NMR analysis (NOESY) indicated that the methyl group is placed distal to the nitrogen group. This observed regioselectivity agrees with that in related Rh(III)-catalyzed oxidative coupling reactions.[10,13] In contrast, only traces of product were formed for other unsymmetrical alkynes such as PhC≡CCH_2OMe and PhC≡$CSiMe_3$.

Competition reactions have been carried out to probe the mechanism of this coupling reaction. The competition between **1b** and **1p** revealed that substrates bearing a donating group in the pyrazole ring showed higher reactivity (eq 2). The same trend was observed for substrates with a para substituent in the phenyl ring (eq 3). These observations are in sharp contrast to those in the oxidative coupling between *N*-aryl benzamides and alkynes.[7c,9] In this current study, the observed higher reactivity for pyrazoles bearing donating groups parallels that in the oxidative coupling between *N*-aryl-(2-amino)pyridines and alkynes, where chelation assistance is believed to be offered by the neutral pyridine ring nitrogen. Indeed, in this current system facile NH to NH tautomerization of the pyrazole ring should readily occur, and it is the neutral nitrogen that likely serves as a directing group for C−H activation. Competition of two diarylalkynes in their coupling with **1a** indicated that a donating group tends to give higher reactivity (eq 4). These data suggest a mechanistic dichotomy between this system and Rh(III)-catalyzed coupling between benzamides and alkynes leading to isoquinolones.[9a] A plausible catalytic cycle is given in Scheme 3. Cyclometalation of **1a** afforded a chelating Rh(III) intermediate, which is proposed to undergo insertion of an incoming alkyne to afford a seven-membered metallacyclic species, and the release of a HX coproduct may occur at this stage of prior to the alkyne insertion. C−N reductive elimination is then proposed to extrude the coupled product, and the resulting Rh(I) species is reoxidized to regenerate the active Rh(III) catalyst.



(2)





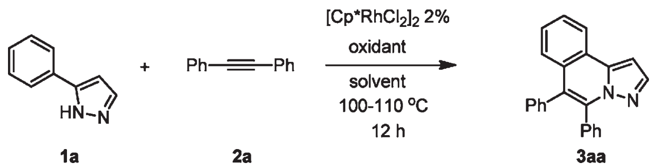
The unsaturated coupling partner is not limited to an alkyne. Activated olefins such as acrylates can be incorporated, but under modified conditions. Using a loading of 4 mol % of the catalyst, 5-aryl-1*H*-pyrazoles and ethyl arylate are oxidatively coupled (dichloroethane, 120 °C). Interestingly, 2 equiv of the olefin was incorporated to afford **4a**, even though only 1 equiv was provided. Optimization of the conditions by simply providing an excess of ethyl arylate afforded **4a** in 68% yield. NMR spectroscopy revealed that this product contains an olefin unit and a five-membered azacycle. The olefin unit has an *E* geometry on the basis of ^{1}H NMR analysis. This process likely proceeds via chelation-assisted diolefination at both ortho positions, followed by an aza-Michael addition process. Formation of five-membered heterocycles via oxidative olefination and NH or OH addition has been observed in many Pd- and Rh-catalyzed oxidative olefinations of amides, benzoic acids, and NH isoquinolones.[7b,f,11,18] The products here are reminiscent of those obtained from $[RhCp^*Cl_2]_2$-catalyzed oxidative coupling of benzoic acids with acrylates.[11] Under the standard conditions, several acrylates and pyrazoles are smoothly coupled to give products in 51−80% isolated yield (Scheme 4). When one of the ortho positions was blocked by an *o*-Cl group, this coupling occurred to give the mono-olefination product (**4f**) in 46% isolated yield. The *o*-Cl group should be removable under further transformations, leading to a simple mono-olefination product. In contrast, other olefins such as styrene, $CH_2{=}CHCN$, and $CH_2{=}CHC(O)NMe_2$ failed to give any isolable product under the same conditions.

In summary, we have developed a protocol of Rh(III)-catalyzed oxidative coupling of 5-aryl-functionalized NH pyrazoles with alkynes and acrylates. This reaction occurred via pyrazole-directed C−H activation. The coupling with alkynes yielded new six-membered azacycles, and a broad scope of substrates has been defined. The oxidative coupling with arylate esters leads to the incorporation of 2 equiv of such olefins as a result of diolefination−aza-Michael cyclization. Given the importance of pyrazoles as organic intermediates and materials, the current reactions are likely to find synthetic utility.

■ EXPERIMENTAL SECTION

General Considerations. All rhodium-catalyzed reactions were carried out using standard Schlenk techniques or in a nitrogen-filled

Table 1. Screening of the Conditions for the C−C and C−N Coupling[a]



entry	oxidant	solvent	temp (°C)	yield (%)[b]
1	AgOAc	DMF	100	92
2	Ag_2CO_3	DMF	100	86
3	$Cu(OAc)_2$	DMF	100	92
4	O_2	DMF	100	trace
5	$Cu(OAc)_2$	CH_3CN	100	86
6	$Cu(OAc)_2$	dioxane	100	88
7	$Cu(OAc)_2$	toluene	100	78
8	$Cu(OAc)_2$	acetone	100	93
9	$Cu(OAc)_2$	acetone	110	96 (94[c])
10	$Cu(OAc)_2$[d]	*o*-xylene	150	42

[a] Conditions: **1a** (0.3 mmol), **2a** (1.5 equiv), oxidant (1.5 equiv of Ag_2CO_3, 2.2 equiv of $Cu(OAc)_2$ or AgOAc), solvent (3 mL), sealed tube under nitrogen, 12 h. [b] GC yields with 1,3,5-trimethoxybenzene as an internal standard. [c] Isolated yield. [d] With $Cu(OAc)_2$ (10 mol %) and air (1 atm).

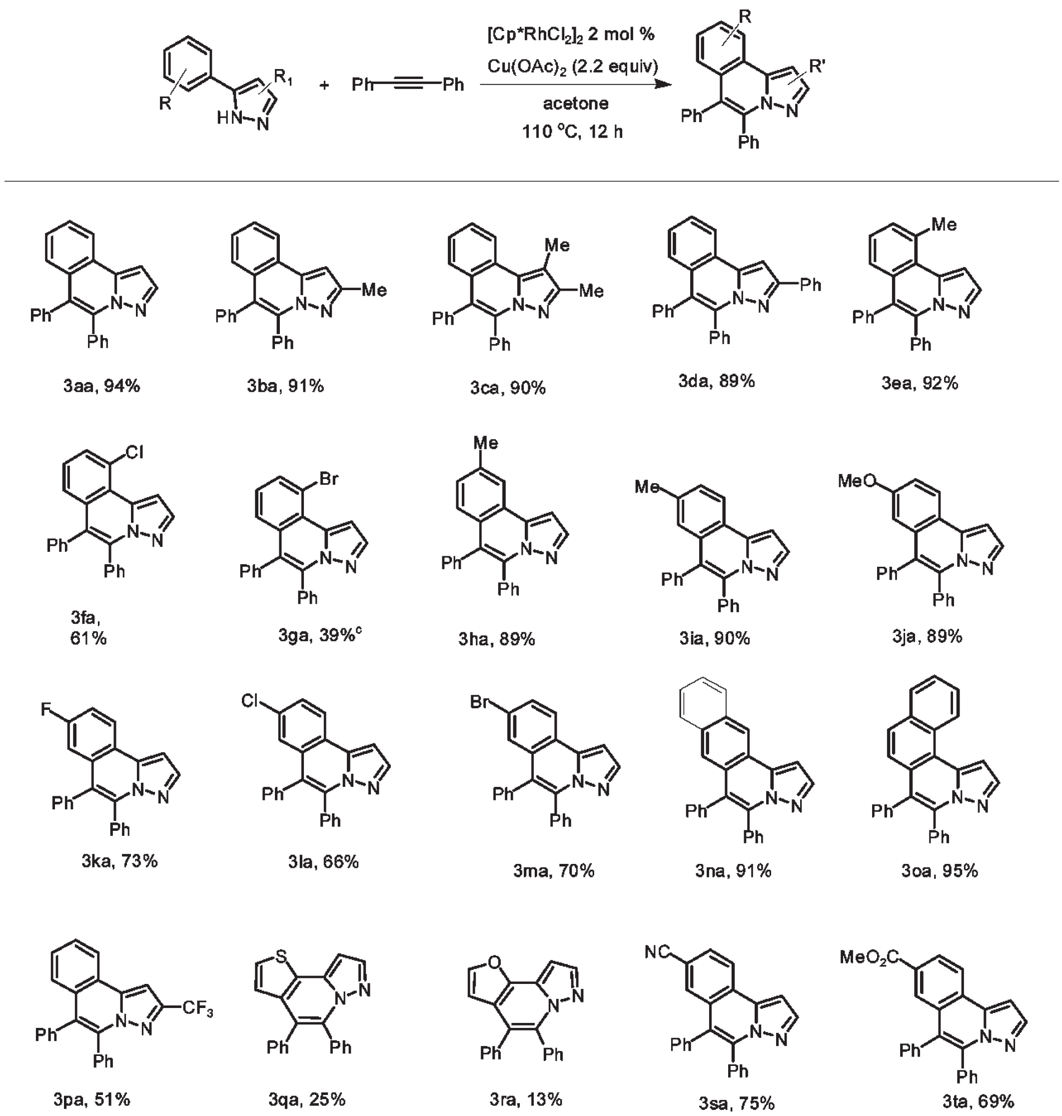
drybox. All solvents were distilled under N_2 prior to use. ^{1}H and ^{13}C NMR spectra were recorded using $CDCl_3$ as a solvent on a 400 or 500 MHz spectrometer at 298 K. Chemical shifts are given in dimensionless δ values and are referenced relative to $SiMe_4$ in ^{1}H and ^{13}C NMR spectroscopy. All other reagents were obtained from commercial sources. Anhydrous $Cu(OAc)_2$ was used throughout this work. 5-Aryl-1*H*-pyrazoles were synthesized according to a literature report.[19]

Representative Procedure of the Syntheses of 3aa−3ta and 3ab−3af. A sealed tube was charged with $Cu(OAc)_2$ (199 mg, 1.1 mmol, 2.2 equiv), $[RhCp^*Cl_2]_2$ (6.2 mg, 0.01 mmol, 2 mol %), 5-phenyl-1*H*-pyrazole (**1a**; 72 mg, 0.5 mmol, 1 equiv), and diphenylacetylene (133.5 mg, 0.75 mmol, 1.5 equiv). After the tube was purged with nitrogen, acetone (5 mL) was added. The mixture was stirred at 110 °C for 12 h. The mixture was diluted with CH_2Cl_2 and filtered through Celite. All volatiles were removed under reduced pressure. Purification was performed by flash column chromatography on silica gel with EtOAc in hexanes as an eluent to give **3aa** as a white solid: yield 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.21 (d, J = 8.0 Hz, 1H), 7.98 (d, J = 2.4 Hz 1H), 7.57−7.61 (m, 1H), 7.40−7.47 (m, 2H), 7.27−7.35 (m, 8H), 7.19−7.23 (m, 2H), 7.13 (d, J = 2.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.0, 138.5, 136.4, 136.2, 133.2, 131.6, 130.9, 129.9, 128.3, 128.0, 127.9, 127.7, 127.3, 127.2, 126.7, 124.1, 124.0, 123.5, 97.6; HRMS (ESI) calcd for $[C_{23}H_{16}N_2 + H]^+$ 321.1394 found 321.1392.

Compound ***3ba***: white solid; yield 91%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (d, J = 7.6 Hz, 1H), 7.52−7.56 (m, 1H), 7.37−7.43 (m, 2H), 7.32−7.34 (m, 2H), 7.25−7.29 (m, 6H), 7.16−7.18 (m, 2H), 6.90 (s, 1H), 2.47 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.6, 139.4, 136.5, 136.2, 133.2, 131.7, 131.1, 130.0, 128.1, 127.9, 127.7, 127.4, 127.0, 126.9, 126.5, 123.7, 123.4, 122.9, 97.3, 14.4; HRMS (ESI) calcd for $[C_{24}H_{18}N_2 + H]^+$ 335.1548, found 335.1552.

Compound ***3ca***: white solid; yield 90%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.38 (d, J = 8.4 Hz, 1H), 7.54−7.58 (m, 1H), 7.37−7.41 (m, 2H), 7.29−7.31 (m, 2H), 7.21−7.28 (m, 6H), 7.15−7.17 (m, 2H), 2.61 (s, 3H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.6, 136.8, 136.3, 134.9, 133.5, 131.8, 131.0, 130.4, 128.0, 127.9, 127.7, 126.9, 126.7,

Scheme 1. Rh(III)-Catalyzed C−C and C−N Coupling between 5-Aryl-1*H*-pyrazoles and PhC≡CPh [a,b]



[a] Conditions: pyrazole (0.5 mmol), PhC≡CPh (0.75 mmol), $[RhCp^*Cl_2]_2$ (0.01 mmol), $Cu(OAc)_2$ (1.1 mmol), acetone (5 mL), sealed tube, 110 °C, 12 h. [b] Isolated yield. [c] **3aa** (32%) was isolated as a byproduct.

126.6, 126.5, 125.4, 123.0, 122.3, 107.6, 12.4, 10.9; HRMS (ESI) calcd for $[C_{25}H_{20}N_2 + H]^+$ 349.1705, found 349.1711.

Compound ***3da***: white solid; yield 89%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.23 (d, *J* = 8.0 Hz, 1 H), 7.91−7.93 (m, 2 H), 7.56−7.60 (m, 1 H), 7.37−7.44 (m, 7H), 7.26−7.32 (m, 7H), 7.21−7.23 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 152.2, 139.9, 136.5, 136.4, 133.5, 133.0, 131.7, 131.4, 130.0, 128.5, 128.2, 128.1, 128.0, 127.7, 127.5, 127.3, 127.1, 126.8, 126.4, 124.0, 123.8, 123.5, 94.6; HRMS (ESI) calcd for $[C_{29}H_{20}N_2 + H]^+$ 397.1703, found 397.1705.

Compound ***3ea***: white solid; yield 92%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.02 (d, *J* = 2.5 Hz, 1H), 7.44 (d, *J* = 7.0 Hz, 1H), 7.26−7.36 (m, 8H), 7.19−7.25 (m, 5H), 2.94 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.7, 137.7, 136.8, 136.4, 134.5, 133.6, 131.6, 131.2, 130.8, 129.7, 128.2, 128.0, 127.9, 127.1, 127.0, 124.9, 124.4, 123.8, 102.3, 24.0; HRMS (ESI): calcd for $[C_{24}H_{18}N_2 + H]^+$ 335.1548, found 335.1550.

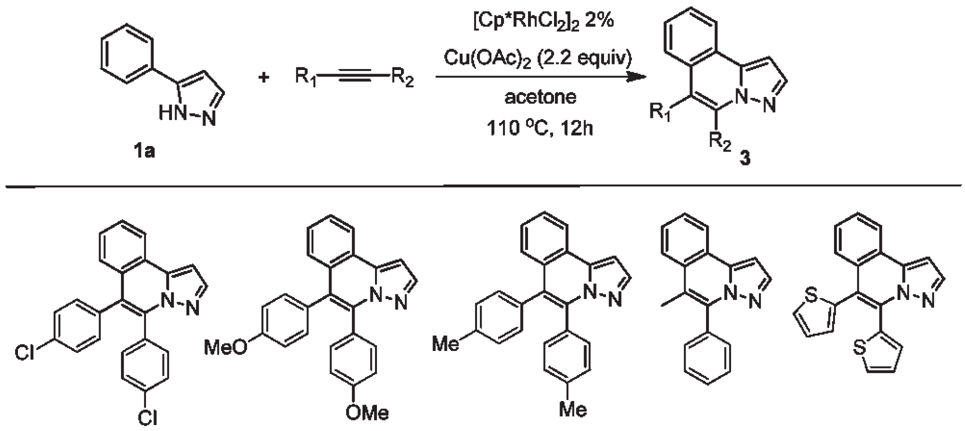
Compound ***3fa***: light yellow solid; yield 61%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.03 (d, *J* = 2.0 Hz, 1H), 7.88 (d, *J* = 2.5 Hz, 1H), 7.64−7.66 (m, 1H), 7.27−7.33 (m, 8H), 7.24−7.26 (m, 2H), 7.17−7.19 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.9, 137.4, 136.2, 135.8, 133.1, 132.7, 131.5, 130.6, 129.2, 128.4, 128.1, 128.0, 127.4, 127.3, 125.6, 123.7, 122.5, 119.6, 103.8; HRMS (ESI): calcd for $[C_{23}H_{15}ClN_2 + H]^+$ 355.1002, found 355.1010.

Compound ***3ga***: pale yellow solid; yield 39%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.13 (d, *J* = 2.0 Hz, 1H), 8.02 (d, *J* = 2.5 Hz, 1H), 7.87−7.88 (m, 1H), 7.37−7.39 (m, 1H), 7.27−7.30 (m, 6H), 7.21−7.26 (m, 3H), 7.16−7.18 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.5, 137.4, 136.7, 136.2, 133.3, 133.2, 133.0, 131.6, 130.6, 128.4, 128.2, 128.0, 127.5, 127.4, 126.4, 123.9, 123.8, 119.6, 103.6; HRMS (ESI) calcd for $[C_{23}H_{15}BrN_2 + H]^+$ 399.0501, found 399.0497.

Compound ***3ha***: white solid; yield 89%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.00 (s, 1H), 7.95 (d, *J* = 2.5 Hz, 1H), 7.23−7.34 (m, 10H), 7.20 (d, *J* = 2.0 Hz, 1H), 7.18−7.19 (m, 1H), 7.09 (d, *J* = 3.0 Hz, 1H), 2.55 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.9, 138.4, 137.4, 136.3, 135.6, 133.3, 131.6, 130.9, 129.3, 128.2, 128.0, 127.9, 127.7, 127.1, 126.6, 124.1, 123.9, 123.3, 97.3, 21.6; HRMS (ESI) calcd for $[C_{24}H_{18}N_2 + H]^+$ 335.1548, found 335.1541.

Compound ***3ia***: white solid; yield 90%; ^1H NMR (500 MHz, $CDCl_3$) δ 8.10 (d, *J* = 8.0 Hz, 1H), 7.95 (d, *J* = 2.5 Hz, 1H), 7.39−7.42 (m, 1H),

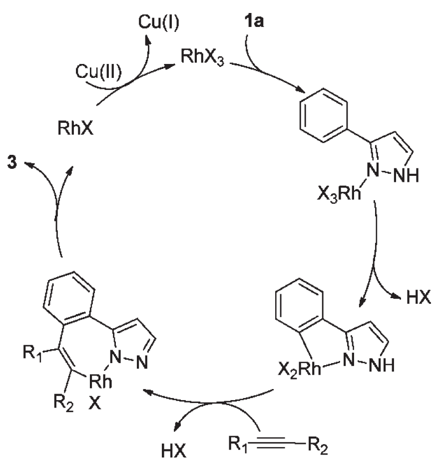
Scheme 2. Coupling of Pyrazole 1a with Different Alkynes[a,b]



3ab, 62% **3ac**, 65% **3ad**, 67% **3ae**, 61% **3af**, 25%

[a] Conditions: pyrazoles (0.5 mmol), alkynes (0.75 mmol), $[RhCp^*Cl_2]_2$ (0.01 mmol), $Cu(OAc)_2$ (1.1 mmol), acetone (5 mL), sealed tube, 110 °C, 12 h. [b] Isolated yield.

Scheme 3. Proposed Catalytic Cycle for the Coupling with an Alkyne



7.31–7.33 (m, 2H), 7.26–7.30 (m, 6H), 7.18–7.20 (m, 3H), 7.06 (d, J = 2.0 Hz, 1H), 2.39 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.0, 138.6, 137.7, 136.4, 136.3, 133.3, 131.6, 130.8, 130.0, 128.9, 128.4, 128.3, 128.0, 127.9, 127.1, 126.3, 123.8, 123.5, 97.0, 21.8; HRMS (ESI) calcd for $[C_{24}H_{18}N_2 + H]^+$ 335.1548; found 335.1551.

Compound ***3ja***: white solid; yield 89%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, J = 8.5 Hz, 1H), 7.93 (d, J = 2.0 Hz, 1H), 7.26–7.33 (m, 7H), 7.19–7.25 (m, 4 H), 7.41 (d, J = 2.0 Hz 1H), 6.82 (d, J = 2.5 Hz, 1H), 3.72 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 159.2, 141.2, 138.6, 136.8, 136.2, 133.3, 131.7, 131.5, 130.8, 128.4, 128.1, 128.0, 127.2, 125.2, 123.6, 118.4, 116.5, 108.7, 96.4, 55.3; HRMS (ESI) calcd for $[C_{24}H_{18}N_2O + H]^+$ 351.1499, found 351.1491.

Compound ***3ka***: light yellow solid; yield 73%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.16–8.19 (m, 1H), 7.99 (d, J = 2.0 Hz, 1H), 7.25–7.36 (m, 9H), 7.19–7.21 (m, 2H), 7.06–7.10 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.1 (d, J_{F-C} = 250 Hz), 141.4, 138.2, 137.5, 135.7, 132.9, 132.0 (d, J_{F-C} = 8.5 Hz), 131.5, 130.8, 128.6, 128.3, 128.0, 127.5, 125.9 (d, J_{F-C} = 9.0 Hz), 123.4 (d, J_{F-C} = 3.8 Hz), 120.8 (d, J_{F-C} = 2.1 Hz), 116.1 (d, J_{F-C} = 24 Hz), 112.0 (d, J_{F-C} = 23 Hz), 97.4; HRMS (ESI) calcd for $[C_{23}H_{15}FN_2 + H]^+$ 339.1299, found 339.1304.

Compound ***3la***: yellow solid; yield 66%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.16 (d, J = 8.5 Hz, 1H), 8.01 (d, J = 2.0 Hz, 1H), 7.55–7.57 (m, 1H), 7.41 (d, J = 2.0 Hz, 1H), 7.29–7.36 (m, 8H), 7.20–7.22 (m, 2H), 7.13 (d, J = 2.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.3, 138.0, 137.5, 135.4, 133.7, 132.8, 131.5, 131.3, 130.7, 128.6, 128.2, 128.0, 127.8, 127.5, 126.0, 125.0, 123.1, 122.5, 97.8; HRMS (ESI) calcd for $[C_{23}H_{15}ClN_2 + H]^+$ 355.1002, found 355.1006.

Compound ***3ma***: pale yellow solid; yield 70%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.06 (d, J = 8.0 Hz, 1H), 7.97 (d, J = 2.5 Hz, 1H), 7.66–7.68 (m, 1H), 7.54 (d, J = 1.5 Hz, 1H), 7.26–7.33 (m, 8 H), 7.16–7.18 (m, 2H), 7.10 (d, J = 2.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.3, 138.0, 137.5, 135.3, 132.8, 131.6, 131.5, 130.7, 130.5, 129.1, 128.5, 128.2, 128.0, 127.5, 125.2, 123.0, 122.8, 121.9, 97.9; HRMS (ESI) calcd for $[C_{23}H_{15}BrN_2 + H]^+$ 399.0501, found 399.0506.

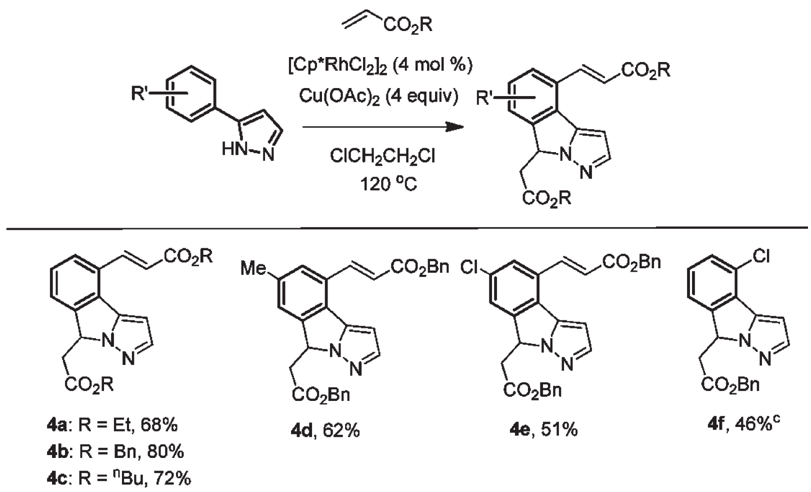
Compound ***3na***: white solid; yield 91%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.68 (s, 1 H), 8.04 (d, J = 8.0 Hz, 1H), 7.97 (d, J = 2.0 Hz, 1 H), 7.86 (s, 1H), 7.79 (d, J = 8.0 Hz, 1H), 7.52–7.56 (m, 1H), 7.46–7.49 (m, 1H), 7.26–7.38 (m, 11H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.8, 138.4, 136.3, 136.1, 133.2, 132.6, 132.1, 131.7, 131.0, 128.6, 128.5, 128.3, 128.1, 127.9, 127.7, 127.3, 126.6, 126.2, 126.0, 123.8, 122.6, 122.2, 99.2; HRMS (ESI) calcd for $[C_{27}H_{18}N_2 + H]^+$ 371.1549, found 371.1547.

Compound ***3oa***: white solid; yield 95%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.10 (d, J = 8.5 Hz, 1H), 8.17 (d, J = 2.5 Hz, 1H), 7.98–1.80 (m, 1H), 7.80–7.84 (m, 2H), 7.66–7.70 (m, 2H), 7.49 (d, J = 8.5 Hz, 1H), 7.36–7.38 (m, 2H), 7.23–7.34 (m, 8H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.8, 137.4, 137.3, 136.7, 133.6, 132.6, 131.8, 130.8, 129.4, 129.1, 129.0, 128.5, 128.4, 128.1, 128.0, 127.5, 127.2, 126.5, 125.3, 124.7, 124.5, 120.6, 101.1; HRMS (ESI) calcd for $[C_{27}H_{18}N_2 + H]^+$ 371.1549, found 371.1543.

Compound ***3pa***: yellow solid; yield 51%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.21 (d, J = 8.0 Hz, 1H), 7.62–7.66 (m, 1H), 7.44–7.53 (m, 2H), 7.37 (s, 1H), 7.31–7.34 (m, 2H), 7.26–7.30 (m, 6H), 7.18–7.20 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 143.3 (q, J_{C-F} = 37.5 Hz), 139.4, 136.4, 135.7, 132.1, 131.4, 131.2, 130.1, 128.6, 128.5, 128.2, 128.0, 127.8, 127.5, 127.1, 126.2, 123.8, 123.6, 122.6 (q, J_{C-F} = 37.5 Hz), 96.1; HRMS (ESI) calcd for $[C_{24}H_{15}F_3N_2 + H]^+$ 389.1267, found 389.1260.

Compound ***3qa***. pale yellow solid; yield 25%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97 (d, J = 2.0 Hz, 1H), 7.43 (d, J = 5.0 Hz, 1H), 7.29–7.37 (m, 5H), 7.20–7.27 (m, 5H), 7.07 (d, J = 5.5 Hz, 1H), 6.78 (d, J = 2.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.6, 136.9, 136.1, 135.8, 135.2, 132.9, 131.1, 130.9, 128.4 (two overlapping signals), 128.0, 127.2,

Scheme 4. Coupling of Pyrazoles with Acrylates[a,b]



[a] Conditions: pyrazoles (0.5 mmol), acrylate esters (1.1 mmol), $[RhCp^*Cl_2]_2$ (0.02 mmol), $Cu(OAc)_2$ (2 mmol), 1,2-dichloroethane (5 mL), sealed tube, 120 °C, 12 h. [b] Isolated yield. [c] 1.2 equiv benzyl acrylate was used.

127.1, 125.7, 125.1, 121.8, 95.6; HRMS (ESI) calcd for $[C_{21}H_{14}N_2S + H]^+$ 327.0958, found 327.0964.

Compound ***3ra***: pale yellow solid; yield 13%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.96 (d, *J* = 2.0 Hz, 1H), 7.71 (d, *J* = 1.5 Hz, 1H), 7.32−7.38 (m, 5H), 7.20−7.26 (m, 5H), 6.84 (d, *J* = 2.0 Hz, 1H), 6.67 (d, *J* = 1.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 144.5, 143.6, 141.4, 136.2, 134.3, 133.0, 131.4, 130.5, 128.5, 128.1, 128.0, 127.1, 122.0, 119.5, 110.0, 107.7, 93.3; HRMS (ESI) calcd for $[C_{21}H_{14}N_2O + H]^+$ 311.1184, found 311.1192.

Compound ***3sa***: light yellow solid; yield 75%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.28 (d, *J* = 8.5 Hz, 1H), 8.04 (d, *J* = 2.0 Hz, 1H), 7.79−7.75 (m, 2H), 7.33−7.30 (m, 8H), 7.30 (d, *J* = 2.5 Hz, 1H), 7.18−7.17 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.7, 138.3, 137.5, 134.8, 132.4, 131.7, 131.4, 130.7, 130.1, 129.2, 128.9, 128.5, 128.1, 128.0, 126.6, 124.5, 123.2, 118.9, 111.2, 99.6; HRMS (ESI) calcd for $[C_{24}H_{15}N_3 + H]^+$; 346.1466, found 346.1470.

Compound ***3ta***: white solid; yield 69%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.25−8.20 (m, 2H), 8.16 (d, *J* = 1.5 Hz, 1H), 8.02 (d, *J* = 2.5 Hz, 1H), 7.35−7.28 (m, 8H), 7.22−7.20 (m, 3H), 3.88 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 166.7, 141.4, 138.0, 137.3, 135.5, 132.9, 131.6, 130.9, 129.7, 129.2, 128.8, 128.6, 128.3, 128.0, 127.7, 127.6, 127.1, 124.2, 123.8, 99.0, 52.4; HRMS (ESI) calcd for $[C_{25}H_{18}N_2O_2 + H]^+$ 379.1448, found 379.1444.

Compound ***3ab***: white solid; yield 62%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.20 (d, *J* = 7.6 Hz, 1H), 7.97 (d, *J* = 1.6 Hz, 1H), 7.60 (t, *J* = 7.4 Hz, 1H), 7.46 (t, *J* = 7.6 Hz, 1H), 7.36 (d, *J* = 8.0 Hz, 1H), 7.25−7.31 (m, 6H), 7.12−7.14 (m, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.2, 138.6, 135.3, 134.7, 134.4, 133.6, 132.8, 132.2, 131.3, 129.5, 128.6, 128.5, 128.0, 127.8, 126.5, 124.2, 123.7, 123.0, 97.9; HRMS (ESI) calcd for $[C_{23}H_{14}Cl_2N_2 + H]^+$ 389.0612, found 389.0619.

Compound ***3ac***: white solid; yield 65%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.18 (d, *J* = 8.0 Hz, 1H), 7.96 (d, *J* = 1.6 Hz, 1H), 7.54−7.58 (m 1H), 7.43 (d, *J* = 3.6 Hz, 2H), 7.26 (d, *J* = 8.4 Hz, 2H), 7.11 (d, *J* = 8.0 Hz, 3H), 6.83 (d, *J* = 8.8 Hz, 4H), 3.80 (s, 3H), 3.78 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 159.2, 158.5, 140.8, 138.5, 136.4, 132.6, 132.2, 130.4, 128.5, 127.6, 127.1, 126.7, 125.6, 124.0, 123.6, 123.5, 113.6, 113.5, 97.5, 55.2, 55.1; HRMS (ESI) calcd for $[C_{25}H_{20}N_2O_2 + H]^+$ 381.1603, found 381.1599.

Compound ***3ad***: white solid; yield 67%; ^{1}H NMR (500 MHz, $CDCl_3$) δ. 8.18 (d, *J* = 7.5 Hz, 1H), 7.95 (d, *J* = 2.5 Hz, 1H), 7.54−7.57 (m, 1H), 7.47−7.50 (m, 1H), 7.41−7.42 (m, 2H), 7.21−7.23 (m, 2H), 7.09−7.11 (m, 6H), 2.34 (s, 3H), 2.31(s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ. 140.9, 138.5, 138.0, 136.6, 136.5, 133.2, 131.4, 130.7, 130.3, 130.2, 128.7, 128.7, 127.6, 127.1, 126.8, 124.0, 123.8, 123.5, 97.4, 21.4, 21.2; HRMS (ESI) calcd for $[C_{25}H_{20}N_2 + H]^+$ 349.1708, found 349.1699.

Compound ***3ae***. light yellow solid; yield 61%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15−8.17 (m, 1H), 7.88−7.92 (m, 2H), 7.47−7.61 (m, 7H), 7.03 (d, *J* = 2.0 Hz, 1H), 2.35 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ. 140.4, 138.0, 135.9, 133.9, 130.4, 129.8, 128.8, 128.7, 127.8, 127.2, 124.4, 124.2, 123.8, 116.2, 97.3, 15.0; HRMS (ESI) calcd for $[C_{18}H_{14}N_2 + H]^+$ 259.1235, found 259.1240.

Compound ***3af***. yellow solid; yield 25%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.16 (d, *J* = 7.5 Hz, 1H), 8.02 (d, *J* = 1.5 Hz, 1H), 7.57−7.62 (m, 2H), 7.47−7.50 (m, 1H), 7.43−7.45 (m, 1H), 7.37−7.39 (m, 1H), 7.24−7.25 (m, 1H), 7.11 (d, *J* = 2.5 Hz, 1H), 7.06−7.07 (m, 1H), 7.02−7.03 (m, 1H), 6.99−7.01 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.3, 138.9, 136.9, 132.6, 131.9, 131.4, 130.3, 130.1, 128.2, 128.0, 127.9, 127.0, 126.8, 126.8, 126.3, 123.8, 123.4, 118.3, 98.1; HRMS (ESI) calcd for $[C_{19}H_{12}N_2S_2 + H]^+$ 333.0520, found 333.0516.

Typical Procedure for Rh(III)-Catalyzed Oxidation of 5-Aryl-1*H*-pyrazoles with Acrylates (Scheme 3). 5-Phenyl-1*H*-pyrazole (**1a**; 72 mg, 0.5 mmol, 1 equiv), $Cu(OAc)_2$ (362 mg, 2 mmol, 4 equiv), and $[RhCp^*Cl_2]_2$ (12.4 mg, 4 mol %) were charged into a pressure tube. After purging with nitrogen, ethyl acrylate (110 mg, 1.1 mmol, 2.2 equiv) and 1,2-dichloroethane (5 mL) were added, and the mixture was stirred at 120 °C for 12 h. The mixture was then diluted with CH_2Cl_2 and filtered through Celite. All volatiles were removed under reduced pressure. The purification was performed by flash column chromatography on silica gel with EtOAc in hexanes to give light yellow solid **4a**: yield 68%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, *J* = 16 Hz, 1H), 7.69 (d, *J* = 2.0 Hz, 1H), 7.62 (d, *J* = 8.0 Hz, 1H), 7.48 (d, *J* = 8.0 Hz, 1H), 7.32 (t, *J* = 7.5 Hz, 1 H), 6.54 (d, *J* = 16 Hz, 2H), 5.55−5.58 (m, 1H), 4.28−4.32 (m, 2H), 4.18−4.23 (m, 2H), 3.26 (dd, *J* = 16.5, 5.0 Hz, 1H), 2.84 (dd, *J* = 16.5, 8.0 Hz, 1H), 1.37 (t, *J* = 7.0 Hz, 3H), 1.23 (t, *J* = 7.0 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.8, 166.4, 145.0, 144.2, 143.5, 140.0, 130.5, 128.0, 127.8, 125.7, 124.7, 120.5, 99.4, 61.1, 60.7, 58.8, 38.8, 14.3, 14.1; HRMS (ESI) calcd for $[C_{19}H_{20}N_2O_4 + H]^+$ 341.1501, found 341.1497.

Compound ***4b***: yellow solid; yield 80%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, *J* = 15.5 Hz, 1H), 7.67 (d, *J* = 2.0 Hz, 1H), 7.61 (d, *J* = 7.5 Hz, 1H), 7.25−7.46 (m, 12H), 6.58 (d, *J* = 16 Hz, 1H), 6.47 (d, *J* = 2.0 Hz, 1H), 5.56−5.59 (m, 1H), 5.30 (s, 2H), 5.16−5.21 (m, 2H), 3.32 (dd, J = 16.5, 5.0 Hz, 1H), 2.91 (dd, J = 16.5, 8.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.6, 166.2, 144.8, 144.3, 143.5, 140.6, 136.0, 135.3, 130.6, 128.6, 128.5, 128.43, 128.41, 128.3, 128.2, 127.8, 127.7, 125.7, 124.8, 120.1, 99.5, 67.0, 66.5, 58.8, 38.8; HRMS (ESI) calcd for $[C_{29}H_{24}N_2O_4 + H]^+$ 465.1811, found 465.1814.

Compound ***4c***: yellow solid; yield 72%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (d, J = 16.0 Hz, 1H), 7.68 (d, J = 2.0 Hz, 1H), 7.63 (d, J = 8.0 Hz, 1H), 7.48 (d, J = 7.5 Hz, 1H), 7.32 (t, J = 7.5 Hz, 1H), 6.54 (d, J = 16.0 Hz, 1H), 6.50 (d, J = 1.5 Hz, 1H), 5.55−5.57 (m, 1H), 4.25 (t, J = 6.5 Hz, 2H), 4.14 (t, J = 6.5 Hz, 2H), 3.28 (dd, J = 16.5, 5.0 Hz, 1H), 2.84 (dd, J = 16.5, 8.0 Hz, 1H), 1.69−1.75 (m, 2H), 1.54−1.60 (m, 2H), 1.43−1.50 (m, 2H), 1.29−1.36 (m, 2H), 0.98 (t, J = 7.5 Hz, 3H), 0.90 (t, J = 7.5 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.9, 166.5, 145.0, 144.2, 143.5, 140.0, 130.5, 128.0, 127.8, 125.7, 124.7, 120.5, 99.4, 65.0, 64.6, 58.8, 38.8, 30.8, 30.5, 19.2, 19.0, 13.7, 13.6; HRMS (ESI) calcd for $[C_{23}H_{28}N_2O_4 + H]^+$ 397.2127, found 397.2122.

Compound ***4d***: yellow solid; yield 62%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, J = 16 Hz, 1H), 7.66 (d, J = 2.0 Hz, 1H), 7.32−7.46 (m, 11H), 7.19 (s, 1H), 6.57 (d, J = 16 Hz, 1H), 6.42 (d, J = 2.0 Hz, 1H),5.52−5.55 (m, 1H), 5.30 (s, 2H), 5.20 (s, 2H), 3.32 (dd, J = 16.5, 5.0 Hz, 1H), 2.89 (dd, J = 16.5, 8.0 Hz, 1H), 2.35 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.7, 166.3, 145.1, 144.1, 143.6, 140.8, 138.0, 136.0, 135.4, 128.7, 128.6, 128.5, 128.4, 128.3, 128.2, 128.1, 127.5, 126.2, 125.8, 119.8, 98.9, 66.9, 66.5, 58.6, 38.9, 21.5; HRMS (ESI) calcd for $[C_{30}H_{26}N_2O_4 + H]^+$ 479.1971, found 479.1964.

Compound ***4e***: yellow solid; yield 51%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.00 (d, J = 16 Hz, 1H), 7.67 (d, J = 2.0 Hz, 1H), 7.58, (d, J = 1.5 Hz, 1H), 7.28−7.45 (m, 11H), 6.57 (d, J = 16 Hz, 1H), 6.46 (d, J = 2.0 Hz, 1H), 5.54−5.56 (m, 1H), 5.30 (s, 2H), 5.20 (s, 2H), 3.35 (dd, J = 17.5, 5.0 Hz, 1 H), 2.90 (dd, J = 17, 8.0 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.4, 165.9, 146.4, 144.4, 142.6, 139.3, 135.8, 135.2, 133.8, 129.0, 128.8, 128.6, 128.53, 128.50, 128.4, 128.3, 128.2, 125.7, 125.3, 121.3, 99.6, 67.1, 66.7, 58.6, 38.5; HRMS (ESI) calcd for $[C_{29}H_{23}ClN_2O_4 + H]^+$ 499.1424, found 499.1418.

Compound ***4f***: light yellow solid; yield 51%; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75 (s, 1H), 7.44−7.33 (m, 7H), 7.28−7.24 (m, 1H), 6.62, (s, 1H), 5.67 (dd, J = 9.5, 7.0 Hz, 1 H), 5.27 (s, 2H), 3.40 (dd, J = 20.5, 6.5 Hz, 1 H), 2.95 (dd, J = 20.5, 10 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.6, 145.6, 144.0, 135.3, 130.9, 129.3, 129.1, 128.8, 128.6, 128.52, 128.50, 128.4, 127.0, 99.4, 67.0, 59.2, 38.8; HRMS (ESI) calcd for $[C_{19}H_{15}ClN_2O_2 + H]^+$ 339.0901, found 339.0908.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Figures giving NMR spectra and characterization data for new products. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: xwli@dicp.ac.cn.

■ ACKNOWLEDGMENT

This work was supported by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences. We thank Dr. Guoyong Song for helpful discussions.

■ REFERENCES

(1) (a) Yeung, C. S.; Dong, V. M. *Chem. Rev.* **2011**, *111*, 1215. (b) Lyons, T. W.; Sanford, M. S. *Chem. Rev.* **2010**, *110*, 1147. (c) Xu, L.-M.; Li, B.-J.; Yang, Z.; Shi, Z.-J. *Chem. Soc. Rev.* **2010**, *39*, 712. (d) Chen, X.; Engle, K. M; Wang, D.-H.; Yu, J.-Q *Angew. Chem., Int. Ed.* **2009**, *48*, 5094.

(2) (a) Sun, C.-L.; Li, B.-J.; Shi, Z.-J. *Chem. Commun.* **2010**, *46*, 677. (b) Ackermann, L.; Vicente, R.; Kapdi, A. R. *Angew. Chem., Int. Ed.* **2009**, *48*, 9792.

(3) (a) Elguero, J.; Goya, P.; Jagerovic, N.; Silva, A. M. S. In *Targets in Heterocyclic Systems*; Attanasi, O. A., Spinelli, D., Eds.; Italian Society of Chemistry: Roma, 2002; Vol. 6, p 52. (b) Zhang, J.; Didierlaurent, S.; Fortin, M.; Lefrancois, D.; Uridat, E.; Vevert, J. P. *Bioorg. Med. Chem. Lett.* **2000**, *10*, 1351.

(4) (a) Jothibasu, R.; Huynh, H. V. *Chem. Commun.* **2010**, *46*, 2986. For a recent review, see: (b) Schuster, O.; Yang, L. R.; Raubenheimer, H. G.; Albrecht, M. *Chem. Rev.* **2009**, *109*, 3445.

(5) For recent reviews see: (a) Colby, D. A.; Bergman, R. G.; Ellman, J. A. *Chem. Rev.* **2010**, *110*, 624. (b) Satoh, T.; Miura, M. *Chem. Eur. J.* **2010**, *37*, 11212. For individual reports, see: (c) Rakshit, S.; Grohmann, C.; Besset, T.; Glorius, F. *J. Am. Chem. Soc.* **2011**, *133*, 2350. (d) Patureau, F. W.; Besset, T.; Glorius, F. *Angew. Chem., Int. Ed.* **2011**, *50*, 1064. (e) Li, Y.; Li, B.-J.; Wang, W.-H.; Huang, W.-P.; Zhang, X.-S.; Chen, K.; Shi, Z.-J. *Angew. Chem., Int. Ed.* **2011**, *50*, 2115. (f) Mochida, S.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2010**, *12*, 5776.

(6) (a) Patureau, F. W.; Besset, T.; Kuhl, N.; Glorius, F. *J. Am. Chem. Soc.* **2011**, *133*, 2154. (b) Stuart, D. R.; Alsabeh, P.; Kuhn, M.; Fagnou, K. *J. Am. Chem. Soc.* **2010**, *132*, 18326. (c) Morimoto, K.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2010**, *12*, 2068. (d) Fukutani, T.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2009**, *11*, 5198. (e) Li, L.; Brennessel, W. W.; Jones, W. D. *J. Am. Chem. Soc.* **2008**, *130*, 12414.

(7) (a) Chen, J.; Song, G.; Pan, C.-L.; Li, X. *Org. Lett.* **2010**, *12*, 5426. (b) Wang, F.; Song, G.; Li, X. *Org. Lett.* **2010**, *12*, 5430. (c) Song, G.; Chen, D.; Pan, C.-L.; Crabtree, R. H.; Li, X. *J. Org. Chem.* **2010**, *75*, 7487. (d) Su, Y.; Zhao, M.; Han, K.; Song, G.; Li, X. *Org. Lett.* **2010**, *12*, 5462. (e) Zhang, X. P.; Chen, D.; Zhao, M.; Zhao, J.; Jia, A. Q.; Li, X. *Adv. Synth. Catal.* **2011**, *353*, 719. (f) Wang, F.; Song, G.; Du, Z.; Li, X. *J. Org. Chem.* **2011**, *76*, 2926.

(8) (a) Guimond, N.; Fagnou, K. *J. Am. Chem. Soc.* **2009**, *131*, 12050. (b) Fukutani, T.; Umeda, N.; Hirano, K.; Satoh, T.; Miura, M. *Chem. Commun.* **2009**, *44*, 5141.

(9) (a) Hyster, T. K.; Rovis, T. *J. Am. Chem. Soc.* **2010**, *132*, 10565. (b) Mochida, S.; Umeda, N.; Hirano, K.; Satoh, T.; Miura, M. *Chem. Lett.* **2010**, *39*, 744.

(10) Stuart, D. R.; Bertrand-Laperle, M.; Burgess, K. M. N.; Fagnou, K. *J. Am. Chem. Soc.* **2008**, *130*, 16474.

(11) (a) Ueura, K.; Satoh, T.; Miura, M. *Org. Lett.* **2007**, *9*, 1407. (b) Ueura, K.; Satoh, T.; Miura, M. *J. Org. Chem.* **2007**, *72*, 5362.

(12) Mochida, S.; Shimizu, M.; Hirano, K.; Satoh, T.; Miura, M. *Chem. Asian J.* **2010**, *5*, 847.

(13) Rakshit, S.; Patureau, F. W.; Glorius, F. *J. Am. Chem. Soc.* **2010**, *132*, 9585.

(14) Hyster, T. K.; Rovis, T. *Chem. Sci.* **2011**, *2*, 1606.

(15) (a) Chen, J.; Pang, Q.; Sun, Y.; Li, X. *J. Org. Chem.* **2011**, *76*, 3523. (b) Gong, T. J.; Xiao, B.; Liu, Z. J.; Wan, J.; Xu, J.; Luo, D. F.; Fu, Y.; Liu, L. *Org. Lett.* **2011**, *13*, 3235.

(16) Abunada, N. M.; Hassaneen, H. H.; Kandile, N. G.; Miqdad, O. A. *Molecules* **2008**, *13*, 1501.

(17) (a) Umeda, N.; Hirano, K.; Satoh, T.; Shibata, N.; Sato, H.; Miura, M. *J. Org. Chem.* **2011**, *76*, 13. (b) Umeda, N.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem.* **2009**, *74*, 7094. (c) Umeda, N.; Tsurugi, H.; Satoh, T.; Miura, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4019.

(18) (a) Wasa, M.; Engle, K. M.; Yu, J.-Q. *J. Am. Chem. Soc.* **2010**, *132*, 3680. (b) Mochida, S.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem.* **2009**, *74*, 6295.

(19) (a) Pleier, A.-K.; Glas, H.; Grosche, M.; Sirsch, P.; Thiel, W. R. *Synthesis* **2001**, 55. (b) Mitkidou, S.; Stephanidou-Stephanatou, J. *Tetrahedron Lett.* **1990**, *31*, 5197.