Decarboxylative Hydroamination of 3-Arylpropiolic Acids with N-Heterocycles under Transition-Metal-Free Conditions

Xixian Pan,[a] Xiaolong Wan,[b,c] Xin Yu,[a] Hui Zhang,*[a] Weiqing Xie*[c]

[a] Department of Chemistry, School of Science & Instrumental Analysis and Research Center, Shanghai University, No. 99, Shangda Road, Shanghai 200444, P. R. of China
Fax +86(21)66134856; E-mail: yehao7171@shu.edu.cn

[b] School of Materials Science and Engineering, Shanghai University, No. 99, Shangda Road, Shanghai 200444, P. R. of China

[c] State Key Laboratory of Bioorganic & Natural Products Chemistry, Shanghai Institute of Organic Chemistry Chinese Academy of Sciences, 354 Fenglin Lu, Shanghai 200032, P. R. of China
Fax +86(21)64166128; E-mail: xiewq@mail.sioc.ac.cn

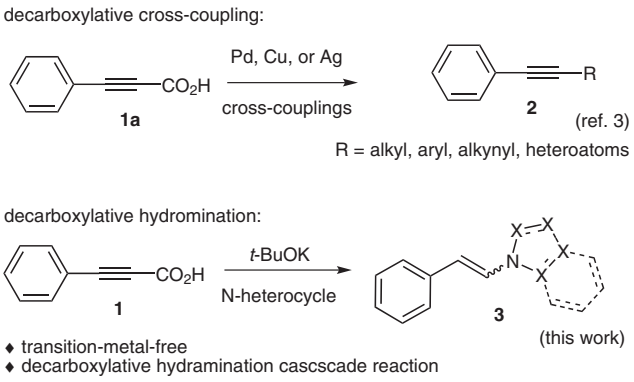
Received: 28.02.2014; Accepted after revision: 25.03.2014

Abstract: A decarboxylative hydroamination cascade reaction of 3-arylpropiolic acids with N-heterocycles under transition-metal-free conditions was developed. 3-Arylpropiolic acids were found to react smoothly with a range of N-heterocycles under the effect of *t*-BuOK to afford *N*-vinyl heterocycles in moderate to excellent yields. This reaction represents the first decarboxylative hydroamination of 3-arylpropiolic acids without the aid of a transition-metal catalyst.

Key words: alkynes, decarboxylation, hydroamination, *N*-vinyl heterocycle, potassium *tert*-butoxide

In recent years, tremendous achievements have been made by using carboxylic acids as nucleophiles or electrophiles in C–C bond formation reactions by decarbonylative or decarboxylative processes.[1] Compared with traditional organometallic reagents, carboxylic acids have several advantages such as easy availability and stability to air and moisture. Therefore, transition-metal-catalyzed cross-coupling through decarboxylative processes involving carboxylic acids holds an important position in C–C formation reactions.[1] As the equivalent of aryl acetylene metal species, propiolic acids could participate in various decarboxylative cross-coupling reactions including sp–sp^3, sp–sp^2, and sp–sp C–C and C–heteroatom bond-formation reactions (Scheme 1).[2] In most cases, propiolic acid is used as an equivalent of alkynyl organometallic species to participate in various cross-coupling reactions, and the alkyne moiety remains intact at the end of reaction. Little attention has been paid to decarboxylative cascade reactions involving transformations of the alkyne functionality.[2] To the best of our knowledge, only one example has described the decarboxylative hydrosulfination reaction of 3-arylpropiolic acid with thiol in the presence of a Cu catalyst.[2s]

Although it has long been known that decarboxylation of 3-arylpropiolic acid could be effected by heating in aniline at high temperature (over 160 °C), its application is hampered by the harsh reaction conditions.[3] With the advent of transition-metal catalysts, decarboxylative transformations of propiolic acid witnessed significant development not only because of its milder reaction conditions but also because of the diverse range of subsequent cascade reactions that can involve the transition-metal catalyst.[1,2] Despite these tremendous advances, transition metals (Pd, Cu or Ag) have, in all cases, been required to facilitate the decarboxylation and cross-coupling reaction. However, the use of transition-metal catalysts also has several disadvantages. High catalyst loading in the decarboxylation reaction usually leads to high economic cost, and further purification procedures are often required to remove metallic contaminants from the product. Therefore, decarboxylative cross-coupling of propiolic acid without the need for a transition-metal catalyst remains highly desirable. In this work, we disclosed the first decarboxylative hydroamination of 3-arylpropiolic acids under transition-metal-free conditions,[4] which represents the first example of decarboxylation hydroamination of 3-arylpropiolic acid to take place only in the presence of *t*-BuOK (Scheme 1).



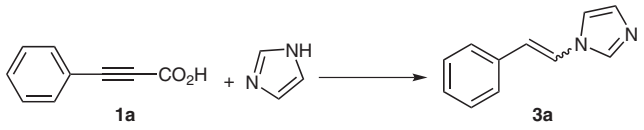
Scheme 1 Decarboxylative cross-coupling and decarboxylative hydroamination of 3-arylpropiolic acid

This reaction provides a new entry to *N*-vinyl heterocycles, which are valuable synthetic intermediates.[5] For example, *N*-vinylimidazole is a common scaffold found in various antifungal reagents and exhibits excellent antifungal and antiparasitic activities.[5a–c] *N*-Vinylimidazole has also found wide application in the synthesis of metal com-

SYNTHESIS 2014, 46, 2057–2064
Advanced online publication: 23.04.2014
DOI: 10.1055/s-0033-1338622; Art ID: SS-2014-H0142-OP

plexes, various heterocycles, and poly(*N*-vinylimidazole).[5d–h]

Table 1 Optimization of the Decarboxylative Hydroamination of 2-Phenylpropiolic Acid with Imidazole[a]



1a **3a**

Entry	Metal	Base (equiv)	Solvent	Temp (°C)	Yield (%)[c]	*Z*/*E*[d]
1	CuI[b]	*t*-BuOK (1.5)	DMF	120	24	n.d.
2	CuI[b]	Cs_2CO_3 (1.5)	DMSO	120	56	n.d.
3	CuI[b]	*t*-BuOK (1.5)	DMSO	120	73	n.d.
4	Ag_2SO_4	*t*-BuOK (1.5)	DMSO	120	35	n.d.
5	Ag_2SO_4[b]	Cs_2CO_3 (1.5)	DMSO	120	53	n.d.
6	Ag_2SO_4[b]	*t*-BuOK (2.0)	DMSO	120	99	2.7:1
7	–	*t*-BuOK (2.0)	DMSO	120	90	2.0:1
8	–	–	DMSO	120	n.r.	
9	–	*t*-BuOK (2.0)[e]	DMSO	120	89	1.6:1
10	–	*t*-BuOLi (2.0)	DMSO	120	trace	
11	–	*t*-BuONa (2.0)	DMSO	120	5	n.d.
12	–	Cs_2CO_3 (2.0)	DMSO	120	80	4:1
13	–	KOH (2.0)	DMSO	120	21	12:1
14	–	LiHMDS (2.0)	DMSO	120	49	1:1.6
15	–	NaHMDS (2.0)	DMSO	120	trace	
16	–	KHMDS (2.0)	DMSO	120	21	n.d.
17	–	*t*-BuOK (3.0)	DMSO	120	32	1.4:1
18	–	*t*-BuOK (1.2)	DMSO	120	13	10:1
19	–	*t*-BuOK (2.0)	DMSO	130	57	2:1
20	–	*t*-BuOK (2.0)	DMSO	100	64	4:1

[a] Reaction conditions: **1a** (0.6 mmol), imidazole (0.5 mmol), base, solvent (2 mL), 24 h.
[b] Using (±)-*N*,*N*′-dimethyl-1,2-cyclohexanediamine (0.1 equiv) as ligand.
[c] Isolated yield.
[d] Ratio was determined by ^{1}H NMR spectroscopic analysis.
[e] Using 99.99% *t*-BuOK as base

In the initial study, we were interested in the decarboxylative cross-coupling of 2-phenylpropiolic acid (**1a**) with imidazole under the effect of copper catalyst to prepare *N*-alkynyl imidazole. To our surprise, we only obtained *N*-vinyl imidazole **3a** instead of the desired *N*-alkynyl imidazole (Table 1, entries 1–3 and the Supporting Information). Further screening of the reaction conditions revealed that Ag_2SO_4 was the best catalyst for this reaction (Table 1, entries 4–6 and the Supporting Information), affording **3a** in 99% yield, albeit with poor stereoselectivity (*Z*/*E*, 2.7:1). Interestingly, when the reaction was carried out in the absence of any transition metal, **3a** could also be obtained in 90% yield with almost the same stereoselectivity (Table 1, entry 7). Omitting the base from the reaction only resulted in recovery of starting materials (Table 1, entry 8), and the use of extra pure *t*-BuOK also gave a comparable yield (Table 1, entry 9), which excluded the action of transition-metal impurities in this reaction.[6] We then optimized the reaction under transitional-metal-free conditions. Interestingly, the use of other *tert*-butoxide salts (*t*-BuONa and *t*-BuOLi) gave only negligible amounts of product (Table 1, entries 10 and 11). However, Cs_2CO_3 was also an effective base, providing **3a** in 80% yield with slightly improved stereoselectivity (*Z*/*E*, 4:1; Table 1, entry 12). Although excellent regioselectivity (12:1) was obtained by using KOH as base, the desired product was isolated in only 21% yield (Table 1, entry 13). The use of stronger bases (LiHMDS, NaHMDS and KHMDS) gave inferior yields (Table 1, entries 14–16). The yields of this reaction were also strongly dependant on the amount of *t*-BuOK employed (Table 1, entries 17 and 18). The use of either more or less than two equivalents of *t*-BuOK resulted in reduced yields. Furthermore, conducting the reaction at either higher or lower temperature was not beneficial for the reaction, and only reduced yields were obtained in either case (Table 1, entries 19 and 20).

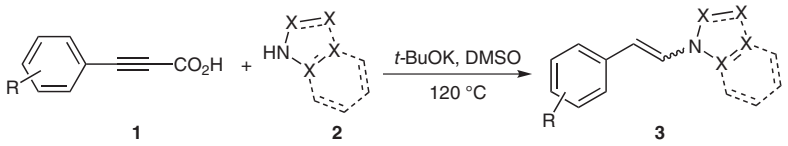
After identification of the optimal reaction conditions, the substrate scope of the reaction was evaluated by using a range of 3-arylpropiolic acids and N-heterocycles. Phenyl propiolic acid reacted smoothly with various N-heterocycles to afford the corresponding *N*-vinyl heterocycles in moderate to good yields (Table 2, entries 1–10). The stereoselectivity of this reaction depended on the electronic properties of the N-heterocycle used. A slight excess of the *E*-isomer was isolated when heterocycles with one nitrogen atom was used, except pyrazole (Table 2, entries 1–3). In contrast, the *Z*-isomer was found to be the major product when other N-heterocycles with more than one nitrogen atom were used (Table 2, entries 2–8). The effect of substituents of the 3-arylpropiolic acid on this decarboxylative hydroamination process was also evaluated (Table 2, entries 9–22). 3-Arylpropiolic acids with electron-rich or electron-deficient substituents could participate in this cascade reaction with good to excellent yields (Table 2, entries 9–22). Electron-rich 3-arylpropiolic acids favored the formation of *Z* isomers (Table 2, entries 9–16), whereas electron-deficient propiolic acids predominantly afforded the *E*-isomer (Table 2, entries 17–22). It is noteworthy that excellent stereoselectivities (*E*/*Z* >12:1) were obtained when 2-halophenylpropiolic acids reacted with imidazole (Table 2, entries 17–19).

To gain some insights into the reaction pathway of this decarboxylative hydroamination process, several control reactions were carried out. In the absence of imidazole, phenylacetylene was observed by GC to form in 25% yield when 2-phenylpropiolic acid was subjected to the

standard reaction conditions (Scheme 2, equation 1).[7] On the other hand, when phenylacetylene reacted with imidazole in the presence of 1.1 equivalents of *t*-BuOK, *N*-styrylimidazole (**3a**) could be isolated in 35% yield (*Z*/*E* = 1:3; Scheme 2, equation 2).[8] The results of these two control reactions indicate that phenylacetylene might be a reaction intermediate. Based on those observations, we propose that this reaction proceeds through decarboxylation of 2-phenylpropiolic acid under the effect of *t*-BuOK to afford phenylacetylene, which is captured by hydroamination with the N-heterocycle to afforded the corresponding *N*-vinyl heterocycle.

In conclusion, decarboxylative hydroamination of 3-arylpropiolic acids with N-heterocycles has been developed under transition-metal-free conditions. This decarboxylative hydroamination process was found to be compatible with a range of 3-arylpropiolic acids and N-heterocycles to produce valuable *N*-vinyl heterocycles. According to the results of initial mechanistic studies, decarboxylation of 3-arylpropiolic acids followed by hydroamination of the resulting acetylene mediated by *t*-BuOK is proposed for the reaction pathway.

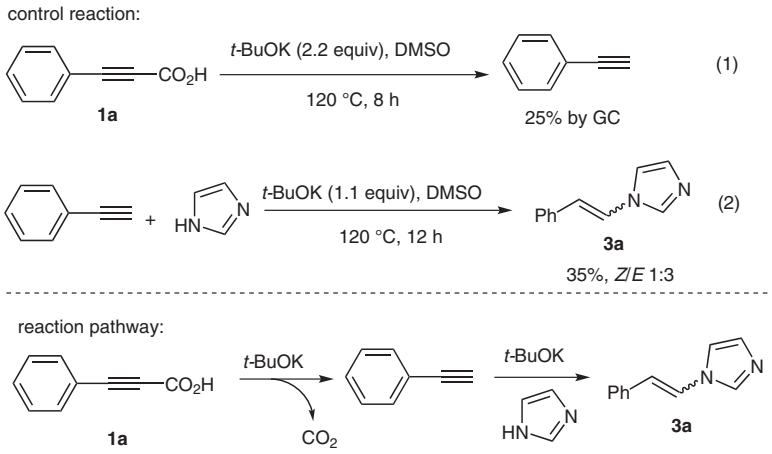
Table 2 Substrate Scope of the Decarboxylative Hydroamination of 3-Arylpropiolic Acid with N-Heterocycles[a]



1 2 3

Entry	R	Heterocycle (equiv)	3	Yield (%)[b]	*Z*/*E*[c]
1	H	pyrrole	**3b**	86	1:2.7
2		indole	**3c**	83	1:1.4
3		pyrazole	**3d**	91	1:1.3
4		2-phenylimidazole	**3e**	65	3.7:1
5		4-methylimidazole	**3f**	74	3.8:1.7:2.0:1
6		benzimidazole	**3g**	75	1.6:1
7		1,2,4-trizole	**3h**	68	6.6:1
8		benzotriazole	**3i**	75	1.6:1
9	2-Me	imidazole	**3j**	86	2.3:1
10		pyrazole	**3k**	87	1:1.6
11	3-Me	imidazole	**3l**	89	2.3:1
12		pyrazole	**3m**	91	1.6:1
13	4-Me	imidazole	**3n**	91	10:1
14		pyrazole	**3o**	98	3:1
15	2-MeO	imidazole	**3p**	62	3.8:1
16	4-MeO	imidazole	**3q**	50	19:1
17	2-Cl	imidazole	**3r**	98	1:18
18		pyrazole	**3s**	98	*E* only
19	2-Br	imidazole	**3t**	99	1:12
20		pyrazole	**3u**	90	1:3.5
21	4-Br	imidazole	**3v**	96	1:1.9
22		pyrazole	**3w**	85	1:1.6

[a] Reaction conditions: **1** (0.6 mmol), **2** (0.5 mmol), base (1.0 mmol), DMSO (2 mL), 120 °C, 24 h.
[b] Isolated yield.
[c] Ratio was determined by ^{1}H NMR spectroscopic analysis.



Scheme 2 Control reaction and proposed mechanism

Unless otherwise noted, all commercially available reagents were obtained from commercial suppliers and used without further purification. Solvents were purified by standard methods and stored over molecular sieves. All reactions were performed using oven-dried glassware under a nitrogen atmosphere. Organic solutions were concentrated with a Büchi rotary evaporator. Column chromatography was carried out over silica gel (40–60 μm, 230–400 mesh, Silicycle P60) and TLC was performed using Merck 60 F254 precoated silica gel plates. ^{1}H and ^{13}C NMR spectra were recorded with a Mercury spectrometer in $CDCl_3$/DMSO-d_6 using TMS as internal reference with chemical shift values being reported in ppm. Chemical shifts for ^{1}H NMR spectra are reported in ppm relative to TMS. The following abbreviations are used to indicate multiplicities: s = singlet, d = doublet, t = triplet, dd = doublet of doublets, dq = doublet of quartets, m = multiplet. All coupling constants (*J*) are reported in hertz (Hz). Mass spectra were recorded with a Shimadzu LCMS-2010EV mass spectrometer (ESI). High-resolution mass spectra were recorded with an Ion Spec 4.7 Tesla FTMS mass spectrometer (MALDI) or a Bruker APEXIII 7.0 TESLA FTMS (ESI).

Decarboxylative Hydroamination; General Procedure

3-Arylpropiolic acid **1** (0.5 mmol, 1.2 equiv), heterocycle **2** (0.6 mmol, 1.0 equiv), and *t*-BuOK (10.0 mmol, 2.0 equiv) were added to a dried test tube. The tube was sealed with a septum and purged with N_2 three times. DMSO (2 mL) was added by using a syringe at r.t. under N_2 atmosphere. The resulting mixture was heated to 120 °C and stirred for 24 h. After cooling to r.t., H_2O was added to the reaction mixture, and the aqueous layer was extracted three times with EtOAc. The organic layers were combined, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by column chromatography (petroleum ether–EtOAc) to provide the desired product **3**.

(*Z*)-1-Styryl-1*H*-imidazole [(*Z*)-3a]

Yield: 51 mg (60%); pale-yellow liquid.

IR (acetone): 3109, 3055, 1658, 1492, 1447, 1073, 696 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.47 (s, 1 H), 7.31–7.27 (m, 3 H), 7.12–7.10 (m, 2 H), 7.04 (s, 1 H), 6.86 (s, 1 H), 6.74 (d, *J* = 9.5 Hz, 1 H), 6.36 (d, *J* = 9.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 137.0, 133.7, 129.6, 128.8, 128.5, 128.3, 123.36, 123.38, 118.5.

MS (ESI): *m*/*z* = 171.1 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{11}H_{11}N_2$: 171.0917; found: 171.0921.

(*E*)-1-Styryl-1*H*-imidazole [(*E*)-3a]

Yield: 26 mg (30%); pale-yellow solid; mp 83–85 °C.

IR (acetone): 3107, 2923, 1659, 1487, 939, 755, 732, 668, 655 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.77 (s, 1 H), 7.43–7.29 (m, 7 H), 7.16 (s, 1 H), 6.76 (d, *J* = 14.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 136.4, 134.4, 130.5, 128.9, 128.1, 126.2, 122.7, 118.9, 116.3.

MS (ESI): *m*/*z* = 171.1 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{11}H_{11}N_2$: 171.0917; found: 171.0919.

(*Z*)-1-Styryl-1*H*-pyrrole [(*Z*)-3b]

Yield: 20 mg (23%); colorless oil.

IR (acetone): 2923, 1714, 668 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.29–7.16 (m, 5 H), 6.70 (d, *J* = 11.5 Hz, 1 H), 6.63 (t, *J* = 2.5 Hz, 2 H), 6.13 (t, *J* = 2.5 Hz, 2 H), 6.08 (d, *J* = 11.5 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 135.2, 128.92, 128.87, 128.6, 128.5, 127.7, 126.5, 121.0, 118.4, 109.6.

MS (ESI): *m*/*z* = 170.2 [M + H]$^+$.

(*E*)-1-Styryl-1*H*-pyrrole [(*E*)-3b]

Yield: 54 mg (63%); brown solid; mp 96–98 °C.

IR (acetone): 1659, 1483, 939, 726 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.41 (d, *J* = 7.5 Hz, 2 H), 7.38 (t, J_1 = 2.0 Hz, J_2 = 5.5 Hz, 2 H), 7.33 (d, *J* = 15.0 Hz, 1 H), 7.28–7.25 (m, 1 H), 7. 02 (t, *J* = 2.0 Hz, 2 H), 6. 63 (d, *J* = 14.5 Hz, 1 H), 6.32 (t, *J* = 2.0 Hz, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 135.7, 128.8, 127.03, 126.95, 125.8, 119.1, 114.3, 110.5.

MS (ESI): *m*/*z* = 170.1 [M + H]$^+$.

HRMS (EI): *m*/*z* [M – H]$^+$ calcd for $C_{11}H_{10}N_2$: 168.0808; found: 168.0815.

(*Z*)-1-Styryl-1*H*-indole [(*Z*)-3c]

Yield: 38 mg (35%); pale-white solid; mp 77–79 °C.

IR (acetone): 3054, 1647, 1460, 742 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.64 (d, *J* = 7.5 Hz,1 H), 7.39 (d, *J* = 8.0 Hz,1 H), 7.28–7.17 (m, 7 H), 7.04 (d, *J* = 3.0 Hz, 1 H), 6.98 (d, *J* = 9.5 Hz, 1 H), 6.51 (d, *J* = 3.5 Hz, 1 H), 6.30 (d, *J* = 9.0 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 135.9, 135.0, 128.7, 128.6, 128.4, 127.5, 127.1, 123.3, 122.4, 120.9, 120.7, 119.6, 110.1, 103.9.

MS (ESI): *m*/*z* = 220.1 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{16}H_{14}N^+$: 220.1121; found: 220.1122.

(*E*)-1-Styryl-1*H*-indole [(*E*)-3c]
Yield: 66 mg (60%); white solid; mp 120–122 °C.

IR (acetone): 1649, 1459, 933, 718, 694 cm^{-1}.

^{1}H NMR (500 MHz, DMSO-d_6): δ = 8.11 (d, *J* = 15.0 Hz, 1 H), 7.96–7.95 (m, 2 H), 7.64–7.60 (m, 3 H), 7.37 (t, *J* = 7.5 Hz, 2 H), 7.27–7.21 (m, 2 H), 7.13 (t, *J* = 7.5 Hz, 1 H), 6.96 (d, *J* = 15.0 Hz, 1 H), 6.72 (d, *J* = 3.0 Hz, 1 H).

^{13}C NMR (125 MHz, DMSO-d_6): δ = 136.7, 135.9, 129.1, 128.8, 127.0, 126.3, 124.8, 124.3, 123.0, 121.23, 121.20, 113.7, 111.0, 105.7.

MS (ESI): *m*/*z* = 220.1 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{16}H_{14}N^+$: 220.1121; found: 220.1125.

(*Z*)-1-Styryl-1*H*-pyrazole [(*Z*)-3d]
Yield: 34 mg (40%); pale-yellow oil.

IR (acetone): 2925, 1654, 1400, 752, 696 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.60 (d, *J* = 1.5 Hz, 1 H), 7.34–7.27 (m, 4 H), 7.22 (d, *J* = 1.5 Hz, 1 H), 7.20 (s, 1 H), 7.03 (d, *J* = 10.0 Hz, 1 H), 6.27 (d, *J* = 9.5 Hz, 1 H), 6.21 (t, *J* = 1.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 140.3, 134.4, 129.5, 128.7, 128.6, 127.9, 127.0, 119.0, 106.6.

MS (ESI): *m*/*z* = 171.0 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{11}H_{10}N_2Na$: 193.0742; found: 193.0737.

(*E*)-1-Styryl-1*H*-pyrazole [(*E*)-3d]
Yield: 44 mg (51%); pale-yellow oil.

IR (acetone): 1896, 1392, 745, 692 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.69–7.68 (m, 1 H), 7.53 (d, *J* = 14.5 Hz, 1 H), 7.45 (s, 1 H), 7.44 (s, 1 H), 7.37 (t, *J* = 7.5 Hz, 2 H), 7.29–7.26 (m, 1 H), 7.07 (d, *J* = 14.5 Hz, 1 H), 6.41 (t, *J* = 2.0 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 141.1, 135.0, 128.8, 127.9, 127.6, 126.4, 126.2, 117.0, 107.3.

MS (ESI): *m*/*z* = 171.0 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{11}H_{10}N_2Na$: 193.0742; found: 193.0738.

(*Z*)-2-Phenyl-1-styryl-1*H*-imidazole [(*Z*)-3e]
Yield: 63 mg (51%); pale-yellow liquid.

IR (acetone): 3058, 2924, 1468, 772, 694 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.77 (d, *J* = 6.8 Hz, 2 H), 7.43–7.37 (m, 3 H), 7.28–7.26 (m, 3 H), 7.16–7.13 (m, 3 H), 6.86 (s, 1 H), 6.71 (d, *J* = 9.2 Hz, 1 H), 6.42 (d, *J* = 8.8 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 133.3, 129.2, 128.82, 128.76, 128.6, 128.5, 128.43, 124.40, 125.2, 123.8, 120.9.

MS (ESI): *m*/*z* = 247.2 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{17}H_{15}N_2^+$: 247.1230; found: 247.1237.

(*E*)-2-Phenyl-1-styryl-1*H*-imidazole [(*E*)-3e]
Yield: 17 mg (14%); pale-yellow liquid.

IR (acetone): 2924, 1469, 695 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.68 (d, *J* = 6.5 Hz, 2 H), 7.50–7.47 (m, 3 H), 7.41 (s, 2 H), 7.49–7.36 (m, 5 H), 7.24 (s, 1 H), 6.79 (d, *J* = 14.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 129.6, 129.3, 129.2, 128.9, 128.8, 128.7, 128.6, 124.4, 125.1, 126.3, 123.7, 120.2, 117.7.

MS (ESI): *m*/*z* = 247.2 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{17}H_{15}N_2^+$: 247.1230; found: 247.1222.

4-Methyl-1-styryl-1*H*-imidazole and 5-Methyl-1-styryl-1*H*-imidazole (3f)
Obtained as a mixture of four stereoisomers 0.7:1.4:1.1:1.0.

Yield: 68 mg (74%); pale-yellow liquid.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.79 (s, 0.62 H), 7.63 (s, 1 H), 7.43–7.24 (m, 19 H), 7.18 (s, 0.36 H), 7.16–7.14 (m, 2 H), 7.00 (s, 1.35 H), 6.98–6.96 (m, 1.81 H), 6.84 (d, *J* = 8.0 Hz, 1.50 H), 6.77 (d, *J* = 14.5 Hz, 0.72 H), 6.67 (d, *J* = 2.5 Hz, 1 H), 6.64 (d, *J* = 8.0 Hz, 1 H), 6.58–6.56 (m, 2 H), 6.51 (d, *J* = 9.5 Hz, 1 H), 6.26 (d, *J* = 9.0 Hz, 1 H), 2.29 (d, *J* = 1.0 Hz, 2.16 H), 2.27 (s, 4.26 H), 2.18 (s, 3.24 H), 2.13 (d, *J* = 1.0 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.4, 136.7, 136.2, 136.1, 134.4, 128.96, 128.92, 128.9, 128.8, 128.7, 128.54, 128.47, 128.4, 128.3, 128.0, 126.4, 126.2, 126.1, 122.5, 122.2, 120.5, 118.5, 115.1, 112.8, 13.5, 13.3, 9.6, 9.2.

MS (ESI): *m*/*z* = 185.3 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1071.

(*Z*)-1-Styryl-1*H*-benzo[*d*]imidazole [(*Z*)-3g]
Yield: 50 mg (45%); pale-yellow solid; mp 115–116 °C.

IR (acetone): 1484, 764, 696 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.83–7.81 (m, 2 H), 7.37–7.30 (m, 3 H), 7.24 (t, *J* = 3.0 Hz, 3 H), 7.10–7.08 (m, 2 H), 6.87 (d, *J* = 9.5 Hz, 1 H), 6.59 (d, *J* = 8.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 143.2, 142.0, 133.6, 133.0, 128.8, 128.48, 128.46, 125.4, 123.6, 122.8, 120.40, 120.31, 110.3.

MS (ESI): *m*/*z* = 221.1 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{13}N_2^+$: 221.1073; found: 221.1076.

(*E*)-1-Styryl-1*H*-benzo[*d*]imidazole [(*E*)-3g]
Yield: 32 mg (29%); pale-yellow solid; mp 85–87 °C.

IR (acetone): 1488, 1458, 741 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.27 (s, 1 H), 7.87 (d, *J* = 7.5 Hz, 1 H), 7.64 (d, *J* = 8.0 Hz, 1 H), 7.55 (d, *J* = 14.5 Hz, 1 H), 7.50 (d, *J* = 7.5 Hz, 2 H), 7.44–7.34 (m, 5 H), 7.01 (d, *J* = 14.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 140.8, 134.6, 129.0, 128.5, 128.2, 126.2, 124.0, 123.7, 123.2, 121.3, 120.8, 120.2, 110.4.

MS (ESI): *m*/*z* = 221.1 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{13}N_2^+$: 221.1073; found: 221.1079.

(*Z*)-1-Styryl-1*H*-1,2,4-triazole [(*Z*)-3h]
Yield: 51 mg (59%); pale-yellow liquid.

IR (acetone): 3084, 3056, 1657, 1501, 1131, 696, 672 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.98 (s, 1 H), 7.90 (s, 1 H), 7.31–7.26 (m, 3 H), 7.11–7.10 (dd, J_1 = 7.5 Hz, J_2 = 2.0 Hz, 2 H), 6.91 (d, *J* = 10.0 Hz, 1 H), 6.52 (d, *J* = 9.5 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 151.7, 143.2, 133.1, 129.0, 128.6, 128.3, 124.4, 123.2.

MS (ESI): *m*/*z* = 172.1 $[M + H]^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{10}H_{10}N_3^+$: 172.0869; found: 172.0866.

(*E*)-1-Styryl-1*H*-1,2,4-triazole [(*E*)-3h]
Yield: 8 mg (9%); pale-yellow oil.

IR (acetone): 2925, 1661, 1506, 1275, 1001, 748, 672 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.32 (s, 1 H), 8.05 (s, 1 H), 7.52 (d, *J* = 14.5 Hz, 1 H), 7.46 (d, *J* = 9.0 Hz, 2 H), 7.39 (t, *J* = 7.5 Hz, 2 H), 7.33 (tt, J_1 = 9.0 Hz, J_2 = 2.5 Hz, 1 H), 7.28 (d, *J* = 13.0 Hz, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.4, 142.2, 133.8, 129.0, 128.6, 126.6, 121.9, 121.4.

MS (ESI): *m*/*z* = 172.0 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{10}H_{10}N_3^+$: 172.0869; found: 172.0872.

1-Styryl-1*H*-benzo[*d*][1,2,3]triazole (3i)
Yield: 83 mg (75%); pale-yellow oil; *Z*/*E* = 1.6:1.

IR (acetone): 2923, 1655, 1488, 1455, 1052, 743 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.12 (d, *J* = 8.4 Hz, 1.55 H), 8.06 (d, *J* = 8.0 Hz, 1 H), 7.95 (d, *J* = 14.8 Hz, 1.60 H), 7.77 (d, *J* = 8.4 Hz, 1.60 H), 7.61–7.55 (m, 5 H), 7.48 (d, *J* = 14.8 Hz, 2.20 H), 7.42 (t, *J* = 7.6 Hz, 4 H), 7.35 (d, *J* = 7.6 Hz, 1.60 H), 7.32–7.28 (m, 3 H), 7.19–7.13 (m, 3 H), 6.99 (d, *J* = 7.2 Hz, 2.77 H), 6.78 (d, *J* = 8.8 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 134.4, 129.0, 128.8, 128.7, 128.53, 128.48, 128.3, 127.7, 127.6, 126.6, 124.6, 124.1, 121.8, 121.2, 121.1, 120.5, 119.9, 110.9, 110.0.

MS (ESI): *m*/*z* = 222.0 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{14}H_{12}N_3^+$: 222.1026; found: 222.1025.

(*Z*)-1-(2-Methylstyryl)-1*H*-imidazole [(*Z*)-3j]
Yield: 55 mg (60%); pale-yellow liquid.

IR (acetone): 2923, 1662, 1490, 1074, 742, 656 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.38 (s, 1 H), 7.21 (d, *J* = 3.6 Hz, 2 H), 7.14–7.10 (m, 1 H), 7.06 (d, *J* = 7.6 Hz, 1 H), 6.91 (s, 1 H), 6.82 (d, *J* = 10.0 Hz, 1 H), 6.68 (s, 1 H), 6.28 (d, *J* = 9.6 Hz, 1 H), 2.21 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.2, 136.2, 133.6, 130.4, 129.4, 128.5, 128.2, 126.2, 123.0, 118.9, 118.3, 19.7.

MS (ESI): *m*/*z* = 185.3 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1067.

(*E*)-1-(2-Methylstyryl)-1*H*-imidazole [(*E*)-3j]
Yield: 24 mg (26%); pale-yellow liquid.

IR (acetone): 2923, 1655, 1496, 1485, 1079, 750.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.76 (s, 1 H), 7.43–7.42 (m, 1 H), 7.28 (s, 1 H), 7.21 (d, *J* = 3.2 Hz, 3.4 H), 7.17 (d, *J* = 13.2 Hz, 1.6 H), 6.93 (d, *J* = 14.4 Hz, 1 H), 2.39 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 135.8, 133.4, 130.6, 130.4, 128.6, 128.1, 126.4, 125.3, 123.6, 117.1, 116.3, 19.9.

MS (ESI): *m*/*z* = 185.4 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1067.

1-(2-Methylstyryl)-1*H*-pyrazole (3k)
Yield: 80 mg (87%); orange liquid; *Z*/*E* = 1:1.6.

IR (acetone): 2923, 1655, 1392, 748 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.67 (d, *J* = 2.0 Hz, 3.2 H), 7.54 (s, 1 H), 7.47–7.45 (m, 1.7 H), 7.40 (s, 0.6 H), 7.36 (s, 1.2 H), 7.27–7.13 (m, 12 H), 7.04 (d, *J* = 2.4 Hz, 1 H), 6.40 (s, 1.6 H), 6.19 (d, *J* = 9.6 Hz, 1 H), 6.12 (s, 1 H), 2.41 (s, 5.10 H), 2.22 (s, 3.06 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.1, 140.0, 136.0, 134.2, 134.0, 130.5, 130.3, 128.8, 128.7, 128.1, 128.0, 127.6, 127.1, 126.3, 126.1, 125.1, 115.5, 115.0, 20.0, 19.7.

MS (ESI): *m*/*z* = 185.4 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

1-(3-Methylstyryl)-1*H*-imidazole (3l)
Yield: 82 mg (89%); pale-yellow liquid; *Z*/*E* = 2.3:1.

IR (acetone): 2913, 1655, 1392, 748 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.73 (s, 0.4 H), 7.46 (s, 0.88 H), 7.32 (d, *J* = 14.7 Hz, 0.44 H), 7.25–7.01 (m, 5.8 H), 6.88 (d, *J* = 16.8 Hz, 2.8 H), 6.72–6.67 (m, 1.5 H), 6.31 (d, *J* = 9.0 Hz, 1 H), 2.35 (s, 1.33 H), 2.26 (s, 3.18 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.8, 138.6, 137.4, 136.7, 134.3, 133.6, 130.3, 129.40, 129.36, 129.33, 129.20, 129.0, 128.8, 127.1, 125.6, 124.0, 123.6, 122.5, 122.2, 119.7, 118.9, 116.6, 21.6, 21.5.

MS (ESI): *m*/*z* = 185.4 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

(*Z*)-1-(3-Methylstyryl)-1*H*-pyrazole (3m)
Yield: 84 mg (91%); pale-yellow liquid; *Z*/*E* = 1.7:1.

IR (acetone): 2920, 1660, 1392, 751 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.66 (s, 1 H), 7.59 (s, 1 H), 7.51 (d, *J* = 14.8 Hz, 0.59 H), 7.31 (d, *J* = 2.0 Hz, 1 H), 7.25–7.17 (m, 3.2 H), 7.09–6.99 (m, 5.2 H), 6.39 (s, 0.54 H), 6.23 (d, *J* = 9.6 Hz, 1 H), 6.19 (s, 1 H), 2.37 (s, 2 H), 2.3 (s, 3.17 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.0, 140.2, 138.4, 138.2, 135.0, 134.3, 129.5, 129.3, 128.7, 128.6, 128.5, 128.4, 127.9, 126.9, 126.3, 125.6, 123.3, 119.1, 117.0, 21.4, 21.3.

MS (ESI): *m*/*z* = 185.3 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

(*Z*)-1-(4-Methylstyryl)-1*H*-imidazole [(*Z*)-3n]
Yield: 76 mg (83%); pale-yellow liquid.

IR (acetone): 2922, 1694, 1654, 1510, 1491, 1073, 656 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.49 (s, 1 H), 7.10 (d, *J* = 8.5 Hz, 2 H), 7.06 (s, 1 H), 6.99 (d, *J* = 8.5 Hz, 2 H), 6.90 (s, 1 H), 6.70 (d, *J* = 9.5 Hz, 1 H), 6.35 (d, *J* = 9.5 Hz, 1 H), 2.33 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 138.4, 130.7, 129.5, 129.43, 129.40, 128.5, 123.9, 121.8, 118.6, 21.3.

MS (ESI): *m*/*z* = 185.1 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

(*E*)-1-(4-Methylstyryl)-1*H*-imidazole [(*E*)-3n]
Yield: 7 mg (8%); pale-yellow oil.

IR (acetone): 2921, 1494, 1082, 1026 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.77 (s, 1 H), 7.33–7.31 (m, 3 H), 7.20–7.16 (m, 3 H), 6.74 (d, *J* = 14.5 Hz, 1 H), 2.38 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 138.4, 131.5, 129.6, 129.5, 128.4, 126.1, 124.1, 121.9, 119.1, 21.2.

MS (ESI): *m*/*z* = 185.1 [M + H]$^+$.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1068.

(*Z*)-1-(4-Methylstyryl)-1*H*-pyrazole [(*Z*)-3o]
Yield: 68 mg (74%); pale-yellow liquid.

IR (acetone): 2922, 1655, 1516, 1440, 1392, 752 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.60 (d, *J* = 1.0 Hz, 1 H), 7.34 (d, *J* = 2.5 Hz, 1 H), 7.13–7.07 (m, 4 H), 6.97 (d, *J* = 9.5 Hz, 1 H), 6.24 (d, *J* = 10.0 Hz, 1 H), 6.21 (t, *J* = 2.0 Hz, 1 H), 2.33 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 140.2, 137.8, 131.4, 129.5, 129.3, 128.6, 126.5, 119.5, 106.5, 21.3.

MS (ESI): *m*/*z* = 185.3 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

(*E*)-1-(4-Methylstyryl)-1*H*-pyrazole [(*E*)-3o]
Yield: 22 mg (24%); pale-yellow oil.

IR (acetone): 2922, 1658, 1392, 751 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.67–7.66 (m, 2 H), 7.49 (d, *J* = 14.5 Hz,1 H), 7.33 (d, *J* = 8.5 Hz, 2 H), 7.17 (d, J_1 = 2.5 Hz, 2 H), 7.03 (d, *J* = 14.0 Hz, 1 H), 6.40 (t, *J* = 2.0 Hz, 1 H), 2.37 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 140.9, 137.5, 132.1, 129.5, 127.8, 126.1, 125.7, 117.0, 107.1, 21.2.

MS (ESI): *m*/*z* = 185.3 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{12}H_{13}N_2^+$: 185.1073; found: 185.1070.

(*E*)-1-(2-Methoxystyryl)-1*H*-imidazole (3p)
Yield: 62 mg (62%); pale-yellow oil; *Z*/*E* = 3.8:1.

IR (acetone): 3002, 2836, 1657, 1491, 1248, 1024, 754 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.76 (s, 0.23 H), 7.47 (s, 1 H), 7.30–7.26 (m, 2 H), 6.99 (s, 1 H), 6.91–6.84 (m, 3 H), 7.78 (d, *J* = 9.5 Hz, 1 H), 6.40 (d, *J* = 9.0 Hz, 1 H), 3.91 (s, 0.72 H), 3.79 (s, 3.37 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 156.9, 137.0, 136.4, 130.1, 129.7, 129.4, 129.08, 129.06, 127.5, 123.6, 123.2, 122.6, 120.9, 120.7, 118.5, 117.5, 116.3, 115.0, 111.0, 110.8, 55.5, 55.4.

MS (ESI): *m*/*z* = 201.4 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{12}H_{13}N_2O^+$: 201.1022; found: 201.1020.

(*E*)-1-(3-Methoxystyryl)-1*H*-imidazole (3q)
Yield: 50 mg (50%); pale-yellow liquid; *Z*/*E* = 19:1.

IR (acetone): 3001, 2837, 1607, 1512, 1491, 1254, 1179, 1029 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.52 (s, 1 H), 7.09 (s, 1 H), 7.00 (d, *J* = 8.5 Hz, 2 H), 6.90 (s, 1 H), 6.80 (d, *J* = 8.5 Hz, 2 H), 6.65 (d, *J* = 9.5 Hz, 1 H), 6.33 (d, *J* = 9.5 Hz, 1 H), 3.84 (s, 0.16 H), 3.80 (s, 3.18 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 159.6, 136.9, 130.0, 129.4, 128.6, 125.8, 124.5, 120.8, 118.6, 114.2, 114.1, 55.2.

MS (ESI): *m*/*z* = 201.3 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{12}H_{13}N_2O^+$: 201.1022; found: 201.1020.

1-(2-Chlorostyryl)-1*H*-imidazole (3r)
Yield: 100 mg (98%); pale-yellow liquid; *Z*/*E* = 1:18.

IR (acetone): 3110, 3073, 1656, 1494, 1294, 1025, 749 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.78 (s, 1 H), 7.53 (d, *J* = 1.5 Hz, 1 H), 7.42 (d, *J* = 7.5 Hz, 1 H), 7.33–7.23 (m, 4 H), 7.17 (s, 1 H), 7.10 (d, *J* = 15.0 Hz, 1 H), 6.88 (d, *J* = 9.5 Hz, 0.06 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 136.6, 133.3, 132.7, 130.7, 130.0, 129.1, 127.2, 126.3, 124.6, 116.3, 115.1.

MS (ESI): *m*/*z* = 205.4 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{10}ClN_2^+$: 205.0527; found: 205.0528.

(*E*)-1-(2-Chlorostyryl)-1*H*-pyrazole (3s)
Yield: 100 mg (98%); pale-yellow liquid; *E*-isomer only.

IR (acetone): 2924, 1655, 1392, 747 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.75 (d, *J* = 2.5 Hz, 1 H), 7.70 (s, 1 H), 7.51–7.57 (m, 2 H), 7.41 (d, *J* = 8.0 Hz, 1 H), 7.37 (d, *J* = 15.0 Hz, 1 H), 7.28–7.20 (m, 2 H), 6.43 (s, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 141.5, 133.3, 130.0, 128.6, 128.5, 127.9, 127.0, 126.2, 113.2, 107.6.

MS (ESI): *m*/*z* = 205.9 $[M + H]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{10}ClN_2^+$: 205.0527; found: 205.0527.

1-(2-Bromostyryl)-1*H*-imidazole (3t)
Yield: 123 mg (99%); pale-yellow liquid; *Z*/*E* = 1:12.

IR (acetone): 2923, 1657, 1467, 1087, 749 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.78 (s, 1 H), 7.61 (d, *J* = 8.5 Hz, 1 H), 7.51 (d, *J* = 8.0 Hz, 1 H), 7.34–7.26 (m, 3 H), 7.18–7.15 (m, 2 H), 7.08 (d, *J* = 14.0 Hz, 1 H), 6.87 (d, *J* = 9.5 Hz, 0.08 H), 6.74 (d, *J* = 9.0 Hz, 0.08 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.0, 134.4, 133.5, 130.3, 129.7, 128.0, 126.7, 124.6, 124.1, 118.8, 116.8.

MS (ESI): *m*/*z* = 249.1 $[M]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{10}BrN_2^+$: 249.0022; found: 249.0027.

1-(2-Bromostyryl)-1*H*-pyrazole (3u)
Yield: 113 mg (90%); pale-yellow liquid; *Z*/*E* = 1:3.5.

IR (acetone): 3067, 1655, 1520, 1439, 1391, 746 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.70 (d, *J* = 2.4 Hz, 1 H), 7.66 (s, 1 H), 7.61–7.49 (m, 2.72 H), 7.43 (d, *J* = 14.4 Hz, 1 H), 7.31 (d, *J* = 14.4 Hz, 1 H), 7.28–7.07 (m, 4 H), 6.38 (s, 1 H), 6.18 (d, *J* = 10.0 Hz, 0.33 H), 6.14 (s, 0.28 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.7, 140.6, 135.2, 133.4, 133.1, 130.6, 129.6, 128.7, 128.4, 128.2, 127.9, 127.7, 126.5, 124.1, 116.5, 115.8, 107.8, 107.2.

MS (ESI): *m*/*z* = 249.1 $[M]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{10}BrN_2^+$: 249.0022; found: 249.0034.

1-(4-Bromostyryl)-1*H*-imidazole (3v)
Yield: 120 mg (96%); pale-yellow liquid; *Z*/*E* = 1:1.9.

IR (acetone): 3122, 2923, 1660, 1487, 1294, 1072, 767 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.76 (s, 2 H), 7.51–7.47 (m, 4.63 H), 7.42 (d, *J* = 9.0 Hz, 2 H), 7.34 (d, *J* = 15.0 Hz, 2 H), 7.28–7.27 (m, 6.25 H), 7.16 (s, 1 H), 7.06 (s, 1 H), 6.97 (d, *J* = 8.5 Hz, 2 H), 6.85 (s, 1 H), 6.77 (d, *J* = 9.0 Hz, 1 H), 6.68 (d, *J* = 14.5 Hz, 1.85 H), 6.29 (d, *J* = 9.5 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.5, 136.9, 132.7, 132.2, 132.1, 131.9, 130.1, 129.4, 128.8, 127.8, 123.9, 122.8, 122.7, 122.4, 122.3, 119.6, 119.0, 116.9.

MS (ESI): *m*/*z* = 249.1 $[M]^+$.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{10}BrN_2^+$: 249.0022; found: 249.0019.

1-(4-Bromostyryl)-1*H*-pyrazole (3w)
Yield: 106 mg (85%); pale-yellow foam; *Z*/*E* = 1:1.6.

IR (acetone): 3116, 1487, 1391, 933, 753 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.69 (s, 1 H), 7.66 (d, *J* = 2.4 Hz, 1 H), 7.62 (d, *J* = 1.2 Hz, 0.61 H), 7.52 (s, 0.5 H), 7.48 (d,

J = 8.8 Hz, 2.59 H), 7.44 (d, J = 7.6 Hz, 1.28 H), 7.32 (d, J = 2.4 Hz, 0.66 H), 7.29 (d, J = 8.4 Hz, 2.28 H), 7.08 (d, J = 8.4 Hz, 1.26 H), 7.02 (d, J = 9.6 Hz, 0.6 H), 7.01 (d, J = 14.8 Hz, 1 H), 6.42 (t, J = 2.0 Hz, 1 H), 6.25 (t, J = 2.0 Hz, 0.62 H), 6.18 (d, J = 10.0 Hz, 0.63 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.5, 140.8, 134.2, 133.4, 132.14, 132.12, 132.09, 132.06, 131.92, 131.90, 130.58, 130.56, 129.7, 128.4, 127.85, 127.83, 127.81, 127.78, 127.76, 127.50, 127.0, 122.0, 121.4, 118.2, 115.9, 107.7, 107.1.

MS (ESI): m/z = 249.1 $[M]^+$.

HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{11}H_{10}BrN_2^+$: 249.0022; found: 249.0022.

Acknowledgment

We are grateful for financial support from the National Natural Science Foundation of China (grant No. 21202187, 21372239).

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

References

(1) For selected reviews, see: (a) Gooβen, L. J.; Rodríguez, N.; Gooβen, K. *Angew. Chem. Int. Ed.* **2008**, *47*, 3100. (b) Baudoin, O. *Angew. Chem. Int. Ed.* **2007**, *46*, 1373. (c) You, S.-L.; Dai, L.-X. *Angew. Chem. Int. Ed.* **2006**, *45*, 5246. (d) Tunge, J.; Burger, A. E. *Eur. J. Org. Chem.* **2005**, 1715.

(2) For sp–sp^3 bond formation, see: (a) Rayabarapu, D. K.; Tung, J. A. *J. Am. Chem. Soc.* **2005**, *127*, 13510. (b) Zhang, W.-W.; Zhang, X.-G.; Li, J.-H. *J. Org. Chem.* **2010**, *75*, 5259. (c) Torregrosa, R. R.; Ariyarathna, P. Y.; Chattopadhyay, K.; Tunge, J. A. *J. Am. Chem. Soc.* **2010**, *132*, 9280. (d) Choe, J.; Yang, J.; Park, K.; Palani, T.; Lee, S. *Tetrahedron Lett.* **2012**, *53*, 6908. For sp–sp^2 bond formation, see: (e) Moon, J.; Jang, M.; Lee, S. *J. Org. Chem.* **2009**, *74*, 1403. (f) Wang, Z. Y.; Ding, Q. P.; He, X. D.; Wu, J. *Tetrahedron* **2009**, *65*, 4635. (g) Wang, Z. Y.; Ding, Q. P.; He, X. D.; Wu, J. *Org. Biomol. Chem.* **2009**, *7*, 863. (h) Gooβen, L. J.; Zimmermann, B.; Knauber, T. *Angew. Chem. Int. Ed.* **2008**, *47*, 7103. (i) Gooβen, L.; Rudolphi, J. F.; Oppel, C.; Rodríguez, N. *Angew. Chem. Int. Ed.* **2008**, *47*, 3043. (j) Gooβen, L. J.; Rodríguez, N.; Linder, C. *J. Am. Chem. Soc.* **2008**, *130*, 15248. (k) Wang, C.; Tunge, J. A. *J. Am. Chem. Soc.* **2008**, *130*, 8118. (l) Moon, J.; Jeong, M.; Nam, H.; Ju, J.; Moon, J. H.; Jung, H. M.; Lee, S. *Org. Lett.* **2008**, *10*, 945. (m) Zhao, D.; Gao, C.; Su, X.; He, Y.; You, J.; Xue, Y. *Chem. Commun.* **2010**, *46*, 9049. (n) Qu, X.; Li, T.; Sun, P.; Zhu, Y.; Yang, H.; Mao, J. *Org. Biomol. Chem.* **2011**, *9*, 6938. (o) Feng, C.; Loh, T.-P. *Chem. Commun.* **2010**, *46*, 4779. For sp–sp bond formation, see: (p) Yu, M.; Pan, D.; Jia, W.; Chen, W.; Jiao, N. *Tetrahedron Lett.* **2010**, *51*, 1287. (q) Park, J.; Park, E.; Kim, A.; Park, S.-A.; Lee, Y.; Chi, K.-W.; Jung, Y. H.; Kim, I. S. *J. Org. Chem.* **2011**, *76*, 2214. (r) Kim, Y.; Park, A.; Park, K.; Lee, S. *Tetrahedron Lett.* **2011**, *52*, 1766. For sp–heteroatom bond formation, see: (s) Ranjit, R.; Duan, Z.; Zhang, P. X.; Liu, X. *Org. Lett.* **2010**, *12*, 4134. (t) Jia, W.; Jiao, N. *Org. Lett.* **2010**, *12*, 2000. (u) Hu, J.; Zhao, N.; Yang, B.; Wang, G.; Guo, L. N.; Liang, Y. M.; Yang, S. D. *Chem. Eur. J.* **2011**, *17*, 5516. (v) Priebbenow, D. L.; Becker, P.; Bolm, C. *Org. Lett.* **2013**, *15*, 6155.

(3) (a) Reychler, A. *Bull. Soc. Chim. Fr.* **1897**, 515. (b) Gattermann, L. *Justus Liebigs Ann. Chem.* **1906**, *347*, 353.

(4) For recent developments in cross-coupling reactions under transition-metal-free conditions, see: (a) Shirakawa, E.; Watabe, R.; Murakami, T.; Hayashi, T. *Chem. Commun.* **2013**, *49*, 5219. (b) Shirakawa, E.; Hayashi, Y.; Itoh, K.; Watabe, R.; Uchiyama, N.; Konagaya, W.; Masui, S.; Hayashi, T. *Angew. Chem. Int. Ed.* **2012**, *51*, 218.

(5) (a) Ross, W. J.; Jamieson, W. B.; McCowen, M. C. *J. Med. Chem.* **1973**, *16*, 347. (b) Hamada, Y.; Shinomoto, S.; Yamada, I.; Koike, H. EP 162359, **1985**, *Chem. Abstr.* **1986**, *104*, 168465v. (c) Cockerrill, A. F.; Rackham, D. M.; Franklin, N. C.; Norman, C. *J. Chem. Soc., Perkin Trans. 2* **1973**, 509. (d) Gist-Brocades, N. V. NL 8005204, **1982**, *Chem. Abstr.* **1982**, *100*, 492276. (e) Kurdaziel, K.; Glowiak, T. *J. Coord. Chem.* **2002**, *55*, 327. (f) Mano, N.; Kim, Y.; Zhang, H. H.; Heller, A. *J. Am. Chem. Soc.* **2002**, *124*, 6480. (g) Branowska, D. *Synthesis* **2003**, 2096. (h) Beghdadi, S.; Miladi, I. A.; Addis, D.; Romdhane, H. B.; Bernard, J.; Drockenmuller, E. *Polym. Chem.* **2012**, *3*, 1680.

(6) Extra-pure *t*-BuOK (sublimed grade, 99.99% trace metals basis) was purchased from Sigma–Aldrich.

(7) Phenylacetylene was found to be labile in the presence of *t*-BuOK because no phenylacetylene was detected by GC under the same reaction conditions after 24 h.

(8) No product was isolated when *t*-BuOK (2.2 equiv) was used, probably due to the instability of phenylacetylene in the presence of excess *t*-BuOK.

