Green Chemistry

RSC Publishing

PAPER

View Article Online
View Journal

Efficient $ZnBr_2$-catalyzed reactions of allylic alcohols with indoles, sulfamides and anilines under high-speed vibration milling conditions†

Cite this: DOI: 10.1039/c3gc40262b

Guang-Peng Fan,[a] Zi Liu[a] and Guan-Wu Wang*[a,b]

Received 4th February 2013,
Accepted 4th April 2013

DOI: 10.1039/c3gc40262b

www.rsc.org/greenchem

Solvent-free reactions of allylic alcohols with various nucleophiles including indoles, sulfamides and anilines were efficiently achieved in the presence of 20% $ZnBr_2$ under high-speed vibration milling conditions, and the products were obtained in good to excellent yields with the formation of water as the only byproduct.

Introduction

The Tsuji–Trost reaction using a π-allyl palladium intermediate has served as an important reaction in the synthesis of natural products, pharmaceuticals, functional materials and agrochemicals.[1,2] The reaction usually employs Pd(0) complexes, bases and activated allyl alcohol derivatives. Because of the poor leaving ability of the hydroxyl group, alcohols generally require preactivation by transformation into the corresponding halides, carboxylates, esters, phosphonates, sulfonates or related compounds with good leaving groups. A disadvantage is that large quantities of unwanted byproducts are generated.[3]

The direct reaction between alcohols and nucleophiles would be an ideal process for C–C and C–N bond formation because the preparation of reactive alcohol derivatives would not be required and only H_2O would be generated as a byproduct. Recently, more and more attention has been paid to the direct nucleophilic substitution of alcohols for Tsuji–Trost-type reactions. Several attempts have been carried out to perform this transformation in the presence of palladium and ruthenium catalysts.[2,4] Various Lewis acids including $InCl_3$,[5] $FeCl_3$,[6] $Bi(OTf)_3$,[7] $Yb(OTf)_3$,[8] $Cu(BF_4)_2$,[9] $AuCl_3$[10] and $MoO_2(acac)_2$,[11] as well as Brønsted acids such as *p*-toluenesulfonic,[12] phosphomolybdic acid,[13] proton-exchanged montmorillonite,[14] dodecylbenzenesulfonic acid[15] and heteropoly acids,[16] have been used to catalyze this process. Fluorinated alcohols[17] can also work as promoters in this reaction. Despite the impressive progress, these reaction systems have some drawbacks: the need for expensive and toxic catalysts, high temperatures and poisonous solvents, such as toluene and dioxane.

On the other hand, solvent-free reactions have drawn attention over the past few decades because it can supply environmentally benign protocols and provide clean, efficient, and high-yielding organic processes in modern synthetic chemistry. The mechanical milling technique is a powerful tool to promote solvent-free reactions.[18–21] With our continuous interest in organic reactions under ball milling conditions, we set out to explore the catalytic nucleophilic substitution of allylic alcohols with various carbon and nitrogen nucleophiles involving C–C and C–N bond formation in a ball mill.

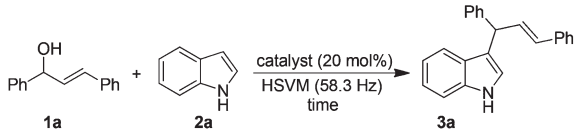
Results and discussion

For the reaction of free (N–H) indoles with alcohols, the selective formation of the *N*-alkylated products or the C3-alkylated products is usually a challenging task.[22] In order to explore this process, the direct substitution between (*E*)-1,3-diphenylprop-2-en-1-ol (**1a**) and indole (**2a**) was chosen as the model reaction and a brief screening of the reaction conditions was undertaken. It was satisfactory that the C3-alkylated product **3a** was obtained exclusively in 89% yield (Table 1, entry 1) in the presence of 20% $ZnBr_2$ for 1 h. The reaction time was screened, and it was found that 1.5 h was enough to complete this reaction with a yield of 97% (Table 1, entries 2 and 3). With the amount of $ZnBr_2$ decreased to 10%, the yield dropped to 88% (Table 1, entry 4) and could not be improved even after prolonging the reaction time to 3 h (Table 1, entry 5). $ZnCl_2$ catalyzed this reaction in 82% yield (Table 1, entry 6), while $Zn(OAc)_2{\cdot}2H_2O$ afforded only a trace amount of **3a** (Table 1, entry 7). Lewis acids $FeCl_3$, $AlCl_3$ and $CuCl_2{\cdot}2H_2O$

[a]*CAS Key Laboratory of Soft Matter Chemistry, Hefei National Laboratory for Physical Sciences at Microscale, and Department of Chemistry, University of Science and Technology of China, Hefei, Anhui 230026, P. R. China.*
E-mail: gwang@ustc.edu.cn; Fax: (+86)551 3607864; Tel: (+86) 551 3607864
[b]*State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou, Gansu 730000, P. R. China*

†Electronic supplementary information (ESI) available: NMR spectra of all compounds. See DOI: 10.1039/c3gc40262b

Table 1 Optimization for the reaction of (*E*)-1,3-diphenylprop-2-en-1-ol with indole under high-speed vibration milling conditions[a]



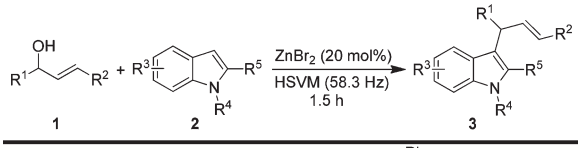
Entry	Catalyst (20%)	Time (h)	Yield[b] (%)
1	$ZnBr_2$	1	89
2	$ZnBr_2$	1.5	97
3	$ZnBr_2$	2	97
4[c]	$ZnBr_2$	1.5	88
5[c]	$ZnBr_2$	3	87
6	$ZnCl_2$	1.5	82
7	$Zn(OAc)_2{\cdot}2H_2O$	1.5	Trace
8	$FeCl_3$	1.5	84
9	$AlCl_3$	1.5	84
10	$CuCl_2{\cdot}2H_2O$	1.5	90
11	$CaCl_2$	1.5	n.r.
12	$Mn(OAc)_3{\cdot}2H_2O$	1.5	Trace
13	PWA	1.5	75
14	*p*-Toluenesulfonic acid	1.5	77
15	$PdCl_2$	1.5	91

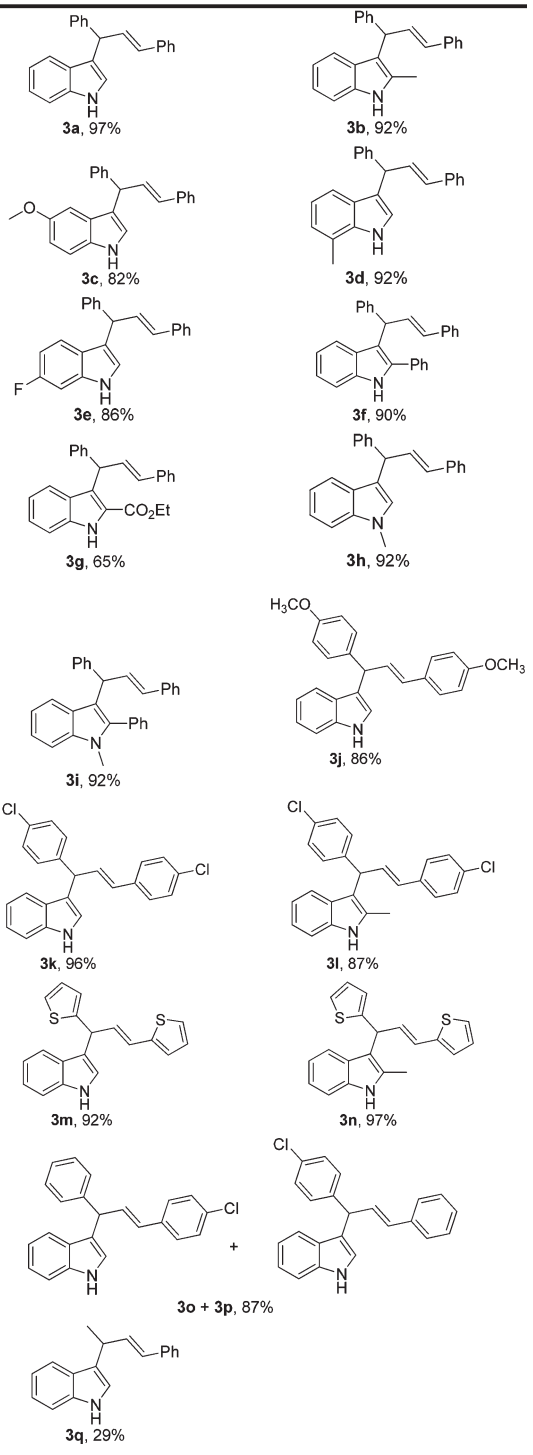
[a] Unless otherwise specified, the reaction mixture of **1a** (1 equiv.), **2a** (1 equiv.) and catalyst (20 mol%) was milled for a given time. [b] Isolated yields obtained by chromatography on silica gel. [c] 10 mol% catalyst was used.

affected the reaction efficiency to give 84–90% yields (Table 1, entries 8–10). In contrast, both $CaCl_2$ and $Mn(OAc)_3{\cdot}2H_2O$ were not effective for this reaction (Table 1, entries 11 and 12). Product **3a** was obtained in 75% yield when 12-tungstophosphoric acid (PWA) was employed as the catalyst (Table 1, entry 13). *p*-Toluenesulfonic acid, a common Brønsted acid, catalyzed this reaction in 77% yield (Table 1, entry 14). It is noteworthy that the use of $PdCl_2$ gave **3a** in 91% yield, which is inferior to that catalyzed by $ZnBr_2$ (Table 1, entry 15 *vs.* entry 3).

With the optimized reaction conditions in hand, the substrate scope was then investigated. The reactions of various substituted indoles with several alcohols were explored, and the results are summarized in Table 2. In general, indoles with electron-donating or electron-withdrawing groups all furnished the desired products **3a–3g** in good to excellent yields. It is of interest to observe that the C2-substituted indole with an electron-withdrawing group could also generate the desired product, albeit in lower yield. The reaction of **1a** with 2-ethoxycarbonylindole gave product **3g** in 65% yield. The $ZnBr_2$-mediated reaction also worked well for *N*-methylindoles and afforded **3h** and **3i** in higher yields than those catalyzed by other Lewis acids.[5] However, 1-acetylindole did not provide any desired products, probably because the *N*-acetyl group decreased the nucleophilicity of the C3-position of the indole. Furthermore, other representative allylic alcohols including (*E*)-1,3-bis(4-methoxyphenyl)prop-2-en-1-ol (**1b**) and (*E*)-1,3-bis(4-chlorophenyl)prop-2-en-1-ol (**1c**) gave **3j**, **3k** and **3l** in 86–96% yields under our typical reaction conditions. The thiophene-substituted allylic alcohol (**1d**) could also be

Table 2 $ZnBr_2$-catalyzed reactions of allylic alcohols with carbon nucleophiles under high-speed vibration milling conditions[a]





[a] Unless otherwise specified, the reaction mixture of **1** (1 equiv.), **2** (1 equiv.) and catalyst (20 mol%) was milled for 1.5 h. The isolated yields were obtained by chromatography on silica gel.

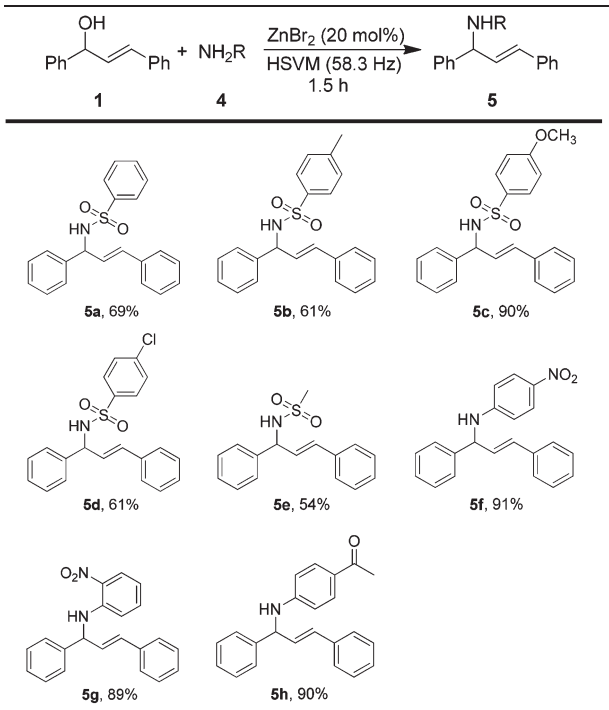
allylated to produce **3m** and **3n** in excellent yields (92–97%) by the present method. Thiophene derivatives are widely used as medicines, such as the antibiotic sufentanil and cephalosporins. Indole derivatives also occur in nature and possess a variety of biological activities. Therefore, **3m** and **3n** may have promising applications in pharmaceutical sciences. It should be pointed out that the sterically hindered 2-substituted indoles behaved well and provided the allylation products **3b**, **3f**, **3g**, **3i**, **3l** and **3n** in comparable yields to those of the 2-unsubstituted counterparts.

The regiochemistry of the reaction was then studied. The dissymmetrical allylic alcohol (*E*)-3-(4-chlorophenyl)-1-phenylprop-2-en-1-ol (**1e**) could be allylated to produce **3o** and **3p** in a total yield of 87%, similar to the previously reported result.[11] We also explored the chemoselectivity of the reaction. 1,3-Diphenylpropan-1-ol and (*E*)-hept-4-en-3-ol were not effective for this reaction. When one of two phenyl groups in **1a** was replaced by a H atom, *i.e.*, (*E*)-3-phenylprop-2-en-1-ol, the reaction did not give the desired product. In contrast, when one of two phenyl groups in **1a** was changed to a methyl group, (*E*)-4-phenylbut-3-en-2-ol selectively afforded product **3q** in 29% yield. The above experimental results demonstrated that the hydroxy group located at both the allylic and benzylic positions was very important for the successful allylation.

To further demonstrate the versatility of our present methodology, the direct substitutions of allylic alcohols with nitrogen nucleophiles including sulfamides and anilines were scrutinized under the present conditions. The reaction conditions and results for the solvent-free reactions of **1a** with nitrogen nucleophiles under high-speed vibration milling conditions are collected in Table 3. As revealed in Table 3, sulfamides with either electron-donating or electron-withdrawing groups were successfully reacted with **1a** to afford the corresponding products **5a–5d** in moderate to good yields. Methane sulfonamide, an aliphatic sulfamide, could also be used and afforded product **5e**, albeit in a lower yield. To our delight, **1a** reacted with 4-nitroaniline and 2-nitroaniline to afford products **5f** and **5g** in 91% and 89% yields, respectively. Product **5h** was formed exclusively with a high yield of 90% when 1-(4-aminophenyl)ethanone was employed as the nucleophile. It is noteworthy that although poorly nucleophilic amines such as sulfonamides or deactivated anilines could undergo the allylation reaction, activated amines did not react with allylic alcohols because electron-rich amines may facilely coordinate to the metal center, and thus inhibited the allylation reaction. The same phenomenon has been reported in the literature.[10,11]

Although mechanochemical nucleophilic reactions under neutral and basic conditions have been described, there is no report on Lewis acid-catalyzed nucleophilic substitution reactions to construct C–C and C–N bonds under mechanochemical conditions.[18f]

Table 3 $ZnBr_2$-catalyzed reactions of allylic alcohols with nitrogen nucleophiles under high-speed vibration milling conditions[a]



[a] Unless otherwise specified, the reaction mixture of **1** (1 equiv.), **4** (1 equiv.) and catalyst (20 mol%) was milled for 1.5 h. The isolated yields were obtained by chromatography on silica gel.

Conclusions

In summary, we have developed an efficient and environmentally friendly methodology for the direct substitution of allylic alcohols with indoles, sulfamides and anilines catalyzed by $ZnBr_2$ under high-speed vibration milling conditions, affording the corresponding allylated products in yields up to 97%, with the formation of water as the only byproduct. The milder reaction conditions, higher yields, better selectivity and no use of solvents make this protocol attractive to the chemistry community.

Experimental section

General procedure for the reactions of allylic alcohols with carbon nucleophiles

A mixture of **1** (0.1 mmol), **2** (0.1 mmol) and $ZnBr_2$ (0.02 mmol) was vigorously shaken by high-speed vibration milling (HSVM) at a frequency of 3500 cycles per min for 1.5 h. Details of the high-speed vibration mill had been described in the literature.[18a,19c] The combined reaction mixture from two runs was collected and dissolved in ethyl acetate. The solution was filtrated to remove the residue and then evaporated to dryness under high vacuum. Finally, the resulting products **3a–3q** were purified by column chromatography on silica gel using ethyl acetate–petroleum ether (60–90 °C) as the eluent.

(*E*)-3-(1,3-Diphenylallyl)-1*H*-indole (3a).[23] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91 (brs, 1H), 7.42 (d, J = 8.0 Hz,

1H), 7.35–7.12 (m, 12H), 7.00 (t, J = 7.5 Hz, 1H), 6.82 (d, J = 1.9 Hz, 1H), 6.71 (dd, J = 15.8, 7.4 Hz, 1H), 6.42 (d, J = 15.8 Hz, 1H), 5.10 (d, J = 7.4 Hz, 1H).

(*E*)-3-(1,3-Diphenylallyl)-2-methyl-1*H*-indole (3b).[23] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (brs, 1H), 7.36–7.32 (m, 5H), 7.28–7.23 (m, 5H), 7.20–7.15 (m, 2H), 7.07 (td, J = 7.6, 1.1 Hz, 1H), 6.96 (td, J = 7.5, 1.0 Hz, 1H), 6.82 (dd, J = 15.8, 7.2 Hz, 1H), 6.41 (dd, J = 15.8, 1.0 Hz, 1H), 5.13 (d, J = 7.2 Hz, 1H), 2.34 (s, 3H).

(*E*)-3-(1,3-Diphenylallyl)-5-methoxy-1*H*-indole (3c).[23] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87 (brs, 1H), 7.37–7.33 (m, 4H), 7.32–7.27 (m, 4H), 7.25–7.16 (m, 3H), 6.86–6.80 (m, 3H), 6.70 (dd, J = 15.8, 7.3 Hz, 1H), 6.44 (d, J = 15.8 Hz, 1H), 5.06 (d, J = 7.3 Hz, 1H), 3.70 (s, 3H).

(*E*)-3-(1,3-Diphenylallyl)-7-methyl-1*H*-indole (3d).[23] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92 (brs, 1H), 7.37–7.16 (m, 11H), 6.98–6.92 (m, 2H), 6.90 (dd, J = 2.4, 0.7 Hz, 1H), 6.72 (dd, J = 15.8, 7.3 Hz, 1H), 6.43 (d, J = 15.8 Hz, 1H), 5.11 (d, J = 7.3 Hz, 1H), 2.47 (s, 3H).

(*E*)-3-(1,3-Diphenylallyl)-6-fluoro-1*H*-indole (3e).[24] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96 (brs, 1H), 7.36 (d, J = 7.2 Hz, 2H), 7.32–7.17 (m, 10H), 7.02 (dd, J = 9.6, 2.3 Hz, 1H), 6.87 (dd, J = 2.3, 1.0 Hz, 1H), 6.77 (ddd, J = 9.6, 8.8, 2.3 Hz, 1H), 6.69 (dd, J = 15.8, 7.4 Hz, 1H), 6.42 (d, J = 15.8 Hz, 1H), 5.07 (d, J = 7.4 Hz, 1H).

(*E*)-3-(1,3-Diphenylallyl)-2-phenyl-1*H*-indole (3f).[23] Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05 (brs, 1H), 7.52 (d, J = 6.9 Hz, 2H), 7.44–7.41 (m, 3H), 7.39–7.31 (m, 6H), 7.27–7.22 (m, 4H), 7.20–7.13 (m, 3H), 6.99 (td, J = 7.6, 0.9 Hz, 1H), 6.88 (dd, J = 15.9, 7.3 Hz, 1H), 6.40 (dd, J = 15.9, 0.9 Hz, 1H), 5.28 (d, J = 7.3 Hz, 1H).

(*E*)-Ethyl 3-(1,3-diphenylallyl)-1*H*-indole-2-carboxylate (3g). Colorless oil. IR (KBr) cm^{-1} 3411, 3338, 3058, 3026, 2980, 2931, 1696, 1573, 1537, 1492, 1447, 1376, 1317, 1241, 1176, 1152, 1130, 1095, 1024, 967, 744, 697, 495, 433; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.95 (s, 1H), 7.52 (d, J = 8.0 Hz, 1H), 7.37–7.35 (m, 5H), 7.28–7.26 (m, 5H), 7.20–7.16 (m, 2H), 6.99 (td, J = 7.6, 0.8 Hz, 1 H), 6.89 (dd, J = 15.8, 7.5 Hz, 1H), 6.50 (d, J = 15.8 Hz, 1H), 6.14 (d, J = 7.5 Hz, 1H), 4.41 (qd, J = 7.1, 1.6 Hz, 2H), 1.40 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 162.3, 143.2, 137.5, 136.3, 131.6, 131.5, 128.5, 128.3, 128.2, 127.3, 126.9, 126.4, 126.2, 125.4, 125.0, 123.5, 123.0, 120.3, 112.0, 61.0, 44.6, 14.5; HR-MS (+APCI) calcd for $C_{26}H_{24}NO_2$: 322.1807 $[M + 1]^+$, found 322.1802.

(*E*)-3-(1,3-Diphenylallyl)-1-methyl-1*H*-indole (3h).[5] Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 8.0 Hz, 1H), 7.37–7.19 (m, 12H), 7.01 (td, J = 7.5, 1.0 Hz, 1H), 6.74 (s, 1H), 6.71 (dd, J = 15.8, 7.4 Hz, 1H), 6.43 (d, J = 15.8 Hz, 1H), 5.11 (d, J = 7.4 Hz, 1H), 3.72 (s, 3H).

(*E*)-3-(1,3-Diphenylallyl)-1-methyl-2-phenyl-1*H*-indole (3i). Yellow solid. IR (KBr) cm^{-1} 3000, 1598, 1466, 1445, 1429, 1335, 1268, 1176, 1128, 1026, 989, 835, 745, 700, 496, 487; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49–7.32 (m, 8H), 7.31–7.27 (m, 4H), 7.25–7.21 (m, 4H), 7.20–7.13 (m, 2H), 7.01 (td, J = 7.5, 0.9 Hz, 1H), 6.81 (dd, J = 15.8, 7.5 Hz, 1H), 6.32 (dd, J = 15.8, 0.9 Hz, 1H), 4.99 (d, J = 7.5 Hz, 1H), 3.60 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.9, 138.6, 137.6, 137.5, 132.5, 131.9, 130.9, 130.6, 128.4, 128.3, 128.2, 128.1, 127.0, 126.5, 126.3, 125.9, 121.6, 120.8, 119.3, 114.1, 109.4, 45.6, 30.9; HR-MS (+APCI) calcd for $C_{30}H_{26}N$: 400.2065 $[M + 1]^+$, found 400.2061.

(*E*)-3-(1,3-Bis(4-methoxyphenyl)allyl)-1*H*-indole (3j). Yellow oil. IR (KBr) cm^{-1} 3350, 2955, 2929, 2836, 1697, 1603, 1510, 1460, 1303, 1251, 1172, 1110, 1030, 832, 749, 606; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.98 (brs, 1H), 7.42 (d, J = 8.0 Hz, 1H), 7.33 (d, J = 8.2 Hz, 1H), 7.28 (d, J = 8.8 Hz, 2H), 7.23 (d, J = 8.8 Hz, 2H), 7.15 (td, J = 7.6, 1.0 Hz, 1H), 7.01 (td, J = 7.5, 0.9 Hz, 1H), 6.88 (dd, J = 2.3, 0.8 Hz, 1H), 6.84 (d, J = 8.8 Hz, 2H), 6.81 (d, J = 8.8 Hz, 2H), 6.56 (dd, J = 15.8, 7.3 Hz, 1H), 6.35 (d, J = 15.8 Hz, 1H), 5.04 (d, J = 7.3 Hz, 1H), 3.78 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.9, 158.1, 136.7, 135.8, 130.8, 130.4, 129.7, 129.4, 127.4, 126.8, 122.5, 122.0, 120.0, 119.4, 119.2, 113.9, 113.8, 111.1, 55.3, 55.2, 45.3; HR-MS (+APCI) calcd for $C_{25}H_{24}NO_2$: 370.1801 $[M + 1]^+$, found: 370.1798.

(*E*)-3-(1,3-Bis(4-chlorophenyl)allyl)-1*H*-indole (3k).[25] Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (brs, 1H), 7.37 (d, J = 8.0, 1H), 7.36 (d, J = 8.2, 1H), 7.28–7.22 (m, 8H), 7.18 (td, J = 7.6, 0.7 Hz, 1H), 7.03 (td, J = 7.5, 0.7 Hz, 1H), 6.89 (d, J = 1.8 Hz, 1H), 6.64 (dd, J = 15.8, 7.2 Hz, 1H), 6.35 (dd, J = 15.8, 0.8 Hz, 1H), 5.08 (d, J = 7.2 Hz, 1H).

(*E*)-3-(1,3-Bis(4-chlorophenyl)allyl)-2-methyl-1*H*-indole (3l). Colorless oil. IR (KBr) cm^{-1} 3388, 2969, 2922, 1693, 1613, 1590, 1487, 1458, 1402, 1321, 1300, 1243, 1164, 1090, 1012, 969, 821, 747; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (brs, 1 H), 7.31–7.22 (m, 10H), 7.09 (td, J = 7.6, 1.1 Hz, 1H), 6.97 (td, J = 7.5, 1.0 Hz, 1H), 6.74 (dd, J = 15.8, 7.2 Hz, 1H), 6.34 (dd, J = 15.8, 1.3 Hz, 1H), 5.07 (dd, J = 7.2, 1.3 Hz, 1H), 2.36 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.7, 135.8, 135.4, 132.9, 132.3, 132.0, 131.7, 129.8, 129.6, 128.7, 128.4, 127.7, 127.5, 121.2, 119.5, 119.2, 112.2, 110.4, 44.5, 12.4; HR-MS (+APCI) calcd for $C_{24}H_{18}{}^{35}Cl_2N$: 390.0811 $[M - 1]^+$, found: 390.0806.

(*E*)-3-(1,3-Di(thiophen-2-yl)allyl)-1*H*-indole (3m). Yellow oil. IR (KBr) cm^{-1} 3409, 3102, 3061, 2923, 2853, 1654, 1613, 1516, 1487, 1453, 1415, 1335, 1222, 1155, 1125, 1094, 1039, 1012, 955, 849, 822, 743, 697; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.98 (brs, 1H), 7.51 (d, J = 8.0 Hz, 1H), 7.34 (d, J = 8.2 Hz, 1H), 7.20–7.16 (m, 3H), 7.10 (d, J = 5.1 Hz, 1H), 7.06 (td, J = 7.5, 0.9 Hz, 1H), 7.00 (d, J = 2.2 Hz, 1H), 6.94 (dd, J = 5.1, 3.5 Hz, 1H), 6.93–6.90 (m, 2H), 6.88 (dd, J = 3.4, 1.1 Hz, 1H), 6.61 (d, J = 15.5 Hz, 1H), 6.55 (d, J = 15.5 Hz, 1H), 5.32 (d, J = 5.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.4, 142.3, 136.5, 131.6, 127.3, 126.7, 126.4, 125.4, 124.9, 124.0, 123.9, 122.4, 122.2, 119.7, 119.6, 118.1, 111.2, 41.0; HR-MS (+APCI) calcd for $C_{19}H_{16}NS_2$: 322.0719 $[M + 1]^+$, found: 322.0715.

(*E*)-3-(1,3-Di(thiophen-2-yl)allyl)-2-methyl-1*H*-indole (3n). Yellow oil. IR (KBr) cm^{-1} 3397, 2920, 2852, 1666, 1614, 1457, 1415, 1231, 955, 744, 698; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77 (brs, 1H), 7.39 (d, J = 8.0 Hz, 1H), 7.26 (d, J = 8.0 Hz, 1H), 7.15 (dd, J = 5.1, 1.1 Hz, 1H), 7.11–7.07 (m, 2H), 7.00 (td, J = 7.5, 0.9 Hz, 1H), 6.93–6.90 (m, 2H), 6.89–6.87 (m, 2H), 6.66 (dd, J = 15.8, 6.1 Hz, 1H), 6.60 (d, J = 15.8 Hz, 1H), 5.27 (d, J = 6.1 Hz, 1H), 2.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.0, 142.4, 135.3, 131.6, 131.1, 127.5, 127.3, 126.6, 125.3, 124.6, 124.0,

123.83, 123.82, 121.1, 119.4, 119.3, 112.7, 110.3, 40.6, 12.3; HR-MS (+APCI) calcd for $C_{20}H_{18}NS_2$: 356.0881 $[M + 1]^+$, found: 356.0876.

(*E*)-3-(3-(4-Chlorophenyl)-1-phenylallyl)-1*H*-indole (3o) and (*E*)-3-(1-(4-chlorophenyl)-3-phenylallyl)-1*H*-indole (3p).[26] The mixture of the two regioisomers could not be separated. yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.97 (s, 1H), 7.42–714 (m, 12H), 7.04–7.00 (m, 1H), 6.88–6.85 (m, 1H), 6.77–6.64 (m, 1H), 6.42–6.35 (m, 1H), 5.11–5.07 (m, 1H).

(*E*)-3-(4-Phenylbut-3-en-2-yl)-1*H*-indole (3q).[17] White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (s, 1H), 7.67 (d, J = 7.9 Hz, 1H), 7.36–7.34 (m, 3H), 7.27 (t, J = 7.6 Hz, 2H), 7.20–7.16 (m, 2H), 7.08 (td, J = 7.5, 0.9 Hz, 1H), 7.01 (dd, J = 2.2, 0.4 Hz, 1H), 6.51 (d, J = 15.9 Hz, 1H), 6.45 (dd, J = 15.9, 5.8 Hz, 1H), 3.93 (p, J = 6.6 Hz, 1H), 1.56 (d, J = 7.0 Hz, 3H).

General procedure for the reactions of allylic alcohols with nitrogen nucleophiles

A mixture of **1** (0.1 mmol), **4** (0.1 mmol) and $ZnBr_2$ (0.02 mmol) was vigorously shaken by HSVM for 1.5 h. The combined reaction mixture from two runs was collected and dissolved in ethyl acetate. The solution was filtrated to remove the residue and then evaporated to dryness under high vacuum. Finally, the resulting products **5a–5h** were purified by column chromatography on silica gel using ethyl acetate–petroleum ether (60–90 °C) as the eluent.

(*E*)-*N*-(1,3-Diphenylallyl)benzenesulfonamide (5a).[24] White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78–7.75 (m, 2H), 7.45 (tt, J = 7.4, 1.2 Hz, 1H), 7.35 (t, J = 7.6 Hz, 2H), 7.28–7.16 (m, 10H), 6.38 (d, J = 15.8 Hz, 1H), 6.11 (dd, J = 15.8, 6.3 Hz, 1H), 5.17–5.11 (m, 2H).

(*E*)-*N*-(1,3-Diphenylallyl)-4-methylbenzenesulfonamide (5b).[24] White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.65 (d, J = 8.2 Hz, 2H), 7.27–7.15 (m, 10H), 7.12 (d, J = 8.2 Hz, 2H), 6.33 (d, J = 15.8 Hz, 1H), 6.07 (dd, J = 15.8, 6.7 Hz, 1H), 5.18 (d, J = 7.3 Hz, 1H), 5.10 (t, J = 6.8 Hz, 1H), 2.30 (s, 3H).

(*E*)-*N*-(1,3-Diphenylallyl)-4-methoxybenzenesulfonamide (5c).[27] White solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.69 (d, J = 8.9 Hz, 2H), 7.27–7.16 (m, 10H), 6.78 (d, J = 8.9 Hz, 2H), 6.35 (d, J = 15.8 Hz, 1H), 6.08 (dd, J = 15.8, 6.8 Hz, 1H), 5.19 (d, J = 7.2 Hz, 1H), 5.09 (t, J = 6.9 Hz, 1H), 3.74 (s, 3H).

(*E*)-4-Chloro-*N*-(1,3-diphenylallyl)benzenesulfonamide (5d). White solid. IR (KBr) cm^{-1} 3261, 3031, 2923, 2852, 1580, 1494, 1474, 1431, 1395, 1324, 1278, 1163, 1089, 1041, 1018, 966, 919, 866, 821, 749, 697, 632, 549, 480; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.65 (d, J = 8.6 Hz, 2H), 7.29–7.16 (m, 12H), 6.38 (d, J = 15.8 Hz, 1H), 6.09 (dd, J = 15.8, 6.5 Hz, 1H), 5.18–5.13 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.4, 139.2, 138.9, 135.8, 132.5, 129.0, 128.8, 128.7, 128.6, 128.13, 128.06, 127.9, 127.1, 126.5, 60.0; HR-MS (+APCI) calcd for $C_{21}H_{19}{}^{35}ClNO_2S$: 384.0820 $[M + 1]^+$, found: 384.0810.

(*E*)-*N*-(1,3-Diphenylallyl)methanesulfonamide (5e).[27] Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.23 (m, 10H), 6.62 (d, J = 15.8 Hz, 1H), 6.33 (dd, J = 15.8, 6.8 Hz, 1H), 5.28 (t, J = 6.9 Hz, 1H), 5.00 (t, J = 7.0 Hz, 1H), 2.77 (s, 3H).

(*E*)-*N*-(1,3-Diphenylallyl)-4-nitroaniline (5f).[11] Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05 (d, J = 9.2 Hz, 2H), 7.40–7.23 (m, 10H), 6.60 (dd, J = 15.8, 0.9 Hz, 1H), 6.58 (d, J = 9.2 Hz, 2H), 6.37 (dd, J = 15.8, 6.1 Hz, 1H), 5.20 (td, J = 5.8, 0.9 Hz, 1H), 4.90 (d, J = 5.4 Hz, 1H).

(*E*)-*N*-(1,3-Diphenylallyl)-2-nitroaniline (5g).[11] Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.51 (d, J = 5.6 Hz, 1H), 8.20 (dd, J = 8.6, 1.6 Hz, 1H), 7.44–7.22 (m, 11H), 6.83 (d, J = 8.3 Hz, 1H), 6.66 (td, J = 7.8, 1.2 Hz, 1H), 6.61 (d, J = 16.1 Hz, 1H), 6.41 (dd, J = 16.1, 6.1 Hz, 1H), 5.32 (t, J = 5.9 Hz, 1H).

(*E*)-1-(4-((1,3-Diphenylallyl)amino)phenyl)ethanone (5h). White solid. IR (KBr) cm^{-1} 3341, 3027, 2920, 2847, 1650, 1593, 1526, 1489, 1448, 1423, 1281, 1183, 1028, 966, 951, 832, 812, 747, 716, 698, 590, 551, 486; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78 (d, J = 8.7 Hz, 2H), 7.41–7.21 (m, 10H), 6.60 (d, J = 8.7 Hz, 2H), 6.59 (d, J = 15.6 Hz, 1H), 6.37 (dd, J = 15.6, 6.1 Hz, 1H), 5.18 (t, J = 5.5 Hz, 1H), 4.67 (d, J = 5.2 Hz, 1H), 2.46 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.3, 151.0, 141.0, 136.3, 131.8, 130.7, 129.4, 129.0, 128.6, 127.94, 127.89, 127.20, 127.16, 126.6, 112.4, 59.9, 26.0; HR-MS (+APCI) calcd for $C_{23}H_{22}NO$: 328.1701 $[M + 1]^+$, found: 328.1699.

Acknowledgements

We are grateful for financial support from the Knowledge Innovation Project of the Chinese Academy of Sciences (KJCX2.YW.H16) and the Key Project of Science and Technology of the Department of Education, Anhui Province, China (KJ2010ZD05).

Notes and references

1 For reviews, see: (*a*) B. M. Trost and D. L. V. Vranken, *Chem. Rev.*, 1996, **96**, 395; (*b*) M. Johannsen and K. A. Jørgensen, *Chem. Rev.*, 1998, **98**, 1689.

2 (*a*) F. Ozawa, H. Okamoto, S. Kawagishi, S. Yamamoto, T. Minami and M. Yoshifuji, *J. Am. Chem. Soc.*, 2002, **124**, 10968; (*b*) K. Manabe and S. Kobayashi, *Org. Lett.*, 2003, **5**, 3241; (*c*) G. W. Kabalka, G. Dong and B. Venkataiah, *Org. Lett.*, 2003, **5**, 893; (*d*) M. Kimura, R. Mukai, N. Tanigawa, S. Tanaka and Y. Tamaru, *Tetrahedron*, 2003, **59**, 7767; (*e*) H. Kinoshita, H. Shinokubo and K. Oshima, *Org. Lett.*, 2004, **6**, 4085; (*f*) Y. Kayaki, T. Koda and T. Ikariya, *J. Org. Chem.*, 2004, **69**, 2595; (*g*) H. Tsukamoto, M. Sato and Y. Kondo, *Chem. Commun.*, 2004, 1200; (*h*) S.-C. Yang, Y.-C. Hsu and K.-H. Gan, *Tetrahedron*, 2006, **62**, 3949; (*i*) K.-H. Gan, C.-J. Jhong and S.-C. Yang, *Tetrahedron*, 2008, **64**, 1204.

3 (*a*) A. Lei and X. Lu, *Org. Lett.*, 2000, **2**, 2357; (*b*) T. Konno, T. Takehana, T. Ishihara and H. Yamanaka, *Org. Biomol. Chem.*, 2004, **2**, 93; (*c*) R. K. Dieter, V. K. Gore and N. Chen, *Org. Lett.*, 2004, **6**, 763; (*d*) G. Helmchen, A. Dahnz, P. Dübon, M. Schelwies and R. Weihofen, *Chem. Commun.*, 2007, 675.

4 (*a*) Y. Nishibayashi, I. Wakiji and M. Hidai, *J. Am. Chem. Soc.*, 2000, **122**, 11019; (*b*) M. Kimura, M. Futamata, K. Shibata and Y. Tamaru, *Chem. Commun.*, 2003, 234; (*c*) Y. Nishibayashi, M. D. Milton, Y. Inada, M. Yoshikawa, I. Wakiji, M. Hidai and S. Uemura, *Chem.–Eur. J.*, 2005, **11**, 1433.
5 M. Yasuda, T. Somyo and A. Baba, *Angew. Chem., Int. Ed.*, 2006, **45**, 793.
6 U. Jana, S. Maiti and S. Biswas, *Tetrahedron Lett.*, 2007, **48**, 7160.
7 H. Qin, N. Yamagiwa, S. Matsunaga and M. Shibasaki, *Angew. Chem., Int. Ed.*, 2007, **46**, 409.
8 (*a*) W. Huang, J. Wang, Q. Shen and X. Zhou, *Tetrahedron Lett.*, 2007, **48**, 3969; (*b*) W. Huang, J. Wang, Q. Shen and X. Zhou, *Tetrahedron*, 2007, **63**, 11636.
9 J. S. Yadav, B. V. S. Reddy, T. S. Rao and K. V. R. Rao, *Tetrahedron Lett.*, 2008, **49**, 614.
10 S. Guo, F. Song and Y. Liu, *Synlett*, 2007, 964.
11 H. Yang, L. Fang, M. Zhang and C. Zhu, *Eur. J. Org. Chem.*, 2009, 666.
12 (*a*) G. Kaur, M. Kaushik and S. Trehan, *Tetrahedron Lett.*, 1997, **38**, 2521; (*b*) J. L. Bras and J. Muzart, *Tetrahedron*, 2007, **63**, 7942; (*c*) P. N. Liu, Z. Y. Zhou and C. P. Lau, *Chem.–Eur. J.*, 2007, **13**, 8610.
13 J. S. Yadav, B. V. S. Reddy and A. S. Reddy, *J. Mol. Catal. A: Chem.*, 2008, **280**, 219.
14 (*a*) K. Motokura, N. Nakagiri, K. Mori, T. Mizugaki, K. Ebitani, K. Jitsukawa and K. Kaneda, *Org. Lett.*, 2006, **8**, 4617; (*b*) K. Motokura, N. Nakagiri, T. Mizugaki, K. Ebitani and K. Kaneda, *J. Org. Chem.*, 2007, **72**, 6006.
15 S. Shirakawa and S. Kobayashi, *Org. Lett.*, 2007, **9**, 311.
16 G.-W. Wang, Y.-B. Shen and X.-L. Wu, *Eur. J. Org. Chem.*, 2008, 4367.
17 P. Trillo, A. Baeza and C. Nájera, *J. Org. Chem.*, 2012, **77**, 7344.
18 For reviews, see: (*a*) G.-W. Wang, Fullerene Mechanochemistry, in *Encyclopedia of Nanoscience and Nanotechnology*, ed. H. S. Nalwa, American Scientific Publishers, Stevenson Ranch, 2004, vol. 3, p. 557; (*b*) K. Komatsu, *Top. Curr. Chem.*, 2005, **254**, 185; (*c*) B. Rodríguez, A. Bruckmann, T. Rantanen and C. Bolm, *Adv. Synth. Catal.*, 2007, **349**, 2213; (*d*) A. L. Garay, A. Pichon and S. L. James, *Chem. Soc. Rev.*, 2007, **36**, 846; (*e*) A. Stolle, T. Szuppa, S. E. S. Leonhardt and B. Ondruschka, *Chem. Soc. Rev.*, 2011, **40**, 2317; (*f*) G.-W. Wang, *Chem. Soc. Rev.*, DOI: 10.1039/c3cs35526h; (*g*) S.-E. Zhu, F. Li and G.-W. Wang, *Chem. Soc. Rev.*, DOI: 10.1039/c3cs35494f.
19 For reactions of fullerenes under ball-milling conditions, see: (*a*) G.-W. Wang, Y. Murata, K. Komatsu and T. S. M. Wan, *Chem. Commun.*, 1996, 2059; (*b*) G.-W. Wang, K. Komatsu, Y. Murata and M. Shiro, *Nature*, 1997, **387**, 583; (*c*) K. Komatsu, G.-W. Wang, Y. Murata, T. Tanaka, K. Fujiwara, K. Yamamoto and M. Saunders, *J. Org. Chem.*, 1998, **63**, 9358; (*d*) G.-W. Wang, T.-H. Zhang, E.-H. Hao, L.-J. Jiao, Y. Murata and K. Komatsu, *Tetrahedron*, 2003, **59**, 55; (*e*) G.-W. Wang, T.-H. Zhang, Y.-J. Li, P. Lu, H. Zhan, Y.-C. Liu, Y. Murata and K. Komatsu, *Tetrahedron Lett.*, 2003, **44**, 4407; (*f*) G.-W. Wang, Y.-J. Li, R.-F. Peng, Z.-H. Liang and Y.-C. Liu, *Tetrahedron*, 2004, **60**, 3921; (*g*) R.-F. Peng, G.-W. Wang, Y.-B. Shen, Y.-J. Li, T.-H. Zhang, Y.-C. Liu, Y. Murata and K. Komatsu, *Synth. Commun.*, 2004, **34**, 2117; (*h*) T.-H. Zhang, G.-W. Wang, P. Lu, Y.-J. Li, R.-F. Peng, Y.-C. Liu, Y. Murata and K. Komatsu, *Org. Biomol. Chem.*, 2004, **2**, 1698; (*i*) Y.-J. Li, R.-F. Peng, Y.-C. Liu and G.-W. Wang, *Chin. Chem. Lett.*, 2004, **15**, 1265; (*j*) X. Cheng, G.-W. Wang, Y. Murata and K. Komatsu, *Chin. Chem. Lett.*, 2005, **16**, 1327; (*k*) G.-W. Wang, Z.-X. Chen, Y. Murata and K. Komatsu, *Tetrahedron*, 2005, **61**, 4851.
20 For reactions of non-fullerene molecules under ball-milling conditions, see: (*a*) Z. Zhang, Y.-W. Dong, G.-W. Wang and K. Komatsu, *Synlett*, 2004, 61; (*b*) Z. Zhang, G.-W. Wang, C.-B. Miao, Y.-W. Dong and Y.-B. Shen, *Chem. Commun.*, 2004, 1832; (*c*) Z. Zhang, J. Gao, J.-J. Xia and G.-W. Wang, *Org. Biomol. Chem.*, 2005, **3**, 1617; (*d*) G.-W. Wang and X.-L. Wu, *Adv. Synth. Catal.*, 200, **349**, 1977; (*e*) X.-L. Wu, J.-J. Xia and G.-W. Wang, *Org. Biomol. Chem.*, 2008, **6**, 548; (*f*) J. Gao and G.-W. Wang, *J. Org. Chem.*, 2008, **73**, 2955; (*g*) G.-W. Wang, Y.-W. Dong, P. Wu, T.-T. Yuan and Y.-B. Shen, *J. Org. Chem.*, 2008, **73**, 7088; (*h*) G.-W. Wang and J. Gao, *Org. Lett.*, 2009, **11**, 2385; (*i*) G.-W. Wang and J. Gao, *Green Chem.*, 2012, **14**, 1125; (*j*) Z. Liu, G.-P. Fan and G.-W. Wang, *Chem. Commun.*, 2012, **48**, 11665.
21 For selected examples in other groups, see: (*a*) V. P. Balema, J. W. Wiench, M. Pruski and V. K. Pecharsky, *J. Am. Chem. Soc.*, 2002, **124**, 6244; (*b*) B. Rodríguez, T. Rantanen and C. Bolm, *Angew. Chem., Int. Ed.*, 2006, **45**, 6924; (*c*) B. Içli, N. Christinat, J. Tönnemann, C. Schüttler, R. Scopelliti and K. Severin, *J. Am. Chem. Soc.*, 2009, **131**, 3154; (*d*) W. Su, J. Yu, Z. Li and Z. Jiang, *J. Org. Chem.*, 2011, **76**, 9144; (*e*) A. M. Belenguer, T. Friščić, G. M. Day and J. K. M. Sanders, *Chem. Sci.*, 2011, **2**, 696; (*f*) D. C. Waddell, I. Thiel, A. Bunger, D. Nkata, A. Maloney, T. Clark, B. Smith and J. Mack, *Green Chem.*, 2011, **13**, 3156; (*g*) R. Schmidt, A. Stolle and B. Ondruschka, *Green Chem.*, 2012, **14**, 1673.
22 S. Nunomoto, Y. Kawakami, Y. Yamashita, H. Takeuchi and S. Eguchi, *J. Chem. Soc., Perkin Trans. 1*, 1990, 111.
23 H. Y. Cheung, W.-Y. Yu, F. L. Lam, T. T.-L. Au-Yeung, Z. Zhou, T. H. Chan and A. S. C. Chan, *Org. Lett.*, 2007, **9**, 4295.
24 Z. Liu, D. Wang, Y. Wu and Y. Chen, *Synth. Commun.*, 2012, **42**, 1813.
25 Z. Cao, Y. Liu, Z. Liu, X. Feng, M. Zhuang and H. Du, *Org. Lett.*, 2011, **13**, 2146.
26 H. Mo and W. Bao, *Adv. Synth. Catal.*, 2009, **351**, 2845.
27 X. Giner, P. Trillo and C. Nájera, *J. Organomet. Chem.*, 2011, **696**, 357.

