Available online at www.sciencedirect.com
ScienceDirect
Journal of Molecular Catalysis A: Chemical 261 (2007) 267–275
JOURNAL OF MOLECULAR CATALYSIS A: CHEMICAL
www.elsevier.com/locate/molcata

Palladium-catalyzed Heck arylation of 5-hexen-2-one in ionic liquid: A novel approach to arylated γ,δ-unsaturated ketones

Jun Mo, Jiwu Ruan, Lijin Xu, Zeynab Hyder, Ourida Saidi, Shifang Liu, Wen Pei, Jianliang Xiao *

Liverpool Center for Materials and Catalysis, Department of Chemistry, University of Liverpool, Liverpool L69 7ZD, UK

Received 21 June 2006; received in revised form 8 August 2006; accepted 9 August 2006
Available online 14 September 2006

Abstract

γ-Arylated γ,δ-unsaturated ketones have been prepared in good to excellent yields via the Pd-catalyzed Heck arylation of an electron-rich olefin, 5-hexen-2-one (**1**), with aryl bromides (**2a**–**2l**) in the ionic liquid [bmim][BF_4]. The reaction is highly regioselective, leading predominantly to branched, γ-arylated products with Pd-DPPP [DPPP = 1,3-bis(diphenylphosphino)propane] catalysis. However, the choice of ligand is found to be crucial for regiocontrol; a change of ligand from DPPP to 1,1′-bis(diphenylphosphino)ferrocene (DPPF) affords predominantly the (*E*)-type, δ-arylated γ,δ-unsaturated ketones. The method is simple, effective, and applicable to the coupling of both electron-rich and electron-deficient aryl bromides with no need for any halide scavengers.

Keywords: Homogeneous catalysis; Heck arylation; Regioselectivity; Unsaturated ketones; Ionic liquids

1. Introduction

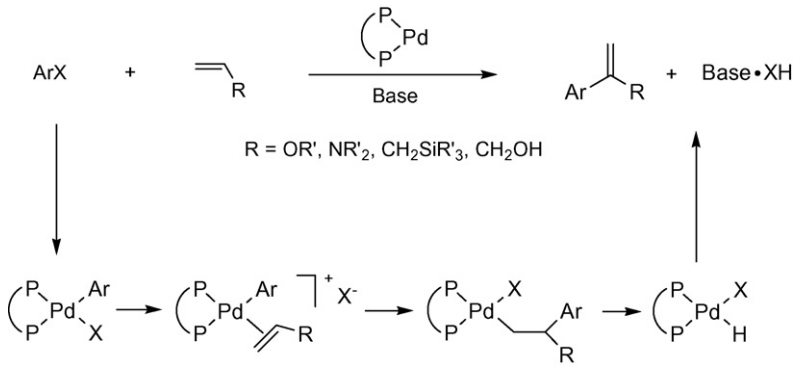
Palladium-catalyzed Heck arylation or vinylation of olefins is now one of the most powerful tools for C–C bond formation in organic synthesis [1]. The Heck arylation of electron-deficient olefins generally affords linear products. However, the arylation of electron-rich olefins has shown to be problematic due to the formation of a mixture of linear and branched products under normal Heck conditions [2]. To address the regioselectivity issue facing this class of olefins, the arylation is most frequently carried out by employing aryl triflates instead of halides or by adding stoichiometrical silver or thallium salts as halide scavengers when aryl halides are chosen [3,4]. A significant drawback of the chemistry is that triflates are in general not commercially available and thermally labile, and the inorganic additives create new problems, for instance, toxicity and high cost.

Recently room temperature ionic liquids such as those based on imidazolium salts have been widely used as alternatives to hazardous organic solvents for clean chemical reactions [5,6]. In a program aimed at developing metal-catalyzed reactions in ionic liquids [7], we demonstrated that, using the ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate ([bmim][BF_4]) as solvent, the Heck arylation of a series of electron-rich olefins including vinyl ethers, vinyl enamides, and allyltrimethylsilane could be accomplished in excellent regioselectivity with aryl bromides and iodides with no need for aryl triflates or halide scavengers [7a-c,e,g]. Our results indicate that this arylation reaction in ionic liquids follows the ionic pathway of the Heck reaction, thus giving rise to the branched products (Scheme 1) [3,8]. The corresponding neutral route involves phosphorus instead of halide dissociation and tends to give linear olefins. Although the detailed mechanism of the arylation remains to be delineated, there is little doubt that the ionic environment provided by the ionic liquids plays a key role in promoting the ionic mechanism [7a,b,9]. Similar results have been obtained by Hallberg, Larhed and co-workers in their study of Heck reactions in the ionic liquid 1-butyl-3-methylimidazolium hexafluorophosphate and in wet DMF [6d,10]. More recently, this method has been extended to the regioselective arylation by heteroaryl halides of unsaturated alcohols [11].

γ,δ-Unsaturated ketones are abundant in natural products [12]. To date many synthetic approaches have been attempted,

* Corresponding author. Tel.: +44 151 7942937; fax: +44 151 7943589.
E-mail address: j.xiao@liv.ac.uk (J. Xiao).

1381-1169/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.molcata.2006.08.024



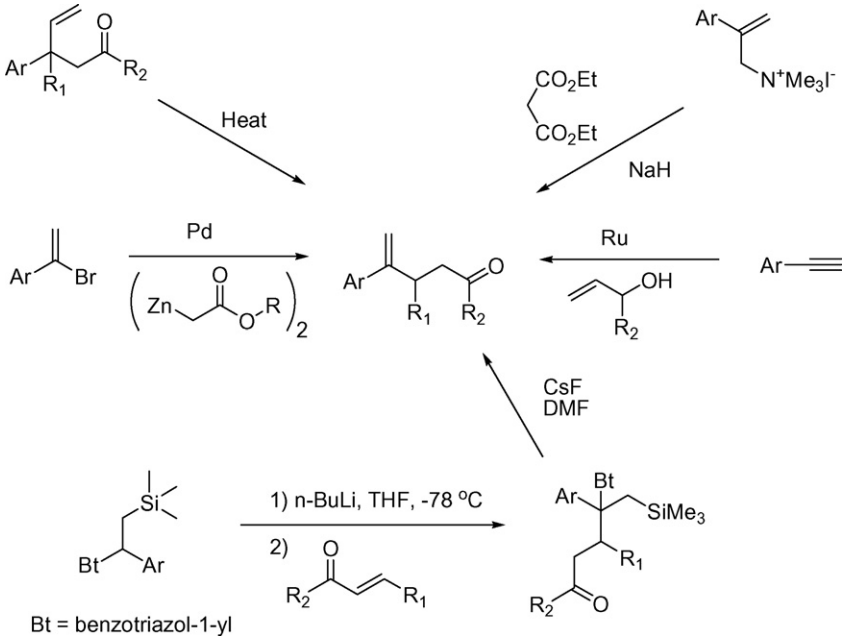
Scheme 1. Arylation of electron-rich olefins via the cationic Heck pathway.

and a number of γ,δ-unsaturated ketones with different substituents have been prepared [13–15]. However, methods to prepare γ-aryl-substituted γ,δ-unsaturated ketones are limited. There are the reaction of quaternary ammonium salts derived from 2-aryl-3-(*N*,*N*-dimethylamino)-1-propenes with enolate anions [15a], Pd-catalyzed reaction of aryl-substituted vinyl bromides with zinc enolates in the presence of $Ti(OiPr)_4$ [15b], the ene-retro-ene rearrangement of 4-aryl-4-methylhex-5-en-2-ones to 5-aryl-4-methylhex-5-en-2-ones [15c], Pd-catalyzed benzannulation of conjugated enynes [15d], Ni-catalyzed electroreductive conjugate addition of alkenyl halides to electron-deficient olefins [15e], and the addition of 2-benzotriazolyl-2-arylethylsilanes to α,β-unsaturated ketones [15f]. Some examples are shown in Scheme 2. In view of the synthetic importance of γ-aryl-substituted γ,δ-unsaturated ketones, it is desirable to develop convenient methodologies for their synthesis from readily available starting materials. Herein we report that the electron-rich olefin, 5-hexen-2-one **1**, can be regioselectively arylated in [bmim][BF_4], providing a facile and effective method for preparing γ-aryl-substituted γ,δ-unsaturated ketones.

2. Experimental

2.1. General remarks

All reactions were carried out under a nitrogen atmosphere. Chromatographic purifications were performed on silica gel (mesh 230–400) by the flash technique. 1-Butyl-3-methylimidizolium tetrafluoroborate ([bmim][BF_4]) was prepared according to the literature method [16]. Following vacuum-drying at 80 °C for 8 h, the ionic liquid was stored under nitrogen at ambient temperature. $AgNO_3$ titration showed the chloride content of the ionic liquid to be below detection limit (<0.2%). 5-Hexen-2-one, aryl halides **2a**–**2l**, $Pd(OAc)_2$, 1,2-bis(diphenylphosphino)ethane (DPPE), 1,3-bis(diphenylphosphino)propane (DPPP), 1,4-bis(dipenylphosphino)butane (DPPB), 1,1-bis(diphenylphosphino)ferrocene (DPPF), *racemic*-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (*rac*-BINAP), 4,5-bis(diphenylphosphino)-9,9-dimethylxanthene (XANTPHOS), and diisopropylamine were purchased from Lancaster and Aldrich and were used as received. ^1H and ^{13}C



Scheme 2. Synthesis of arylated γ,δ-unsaturated ketones.

NMR spectra were recorded on a Gemini 400 spectrometer at 400 (^{1}H) and 100 MHz (^{13}C) in ppm with reference to TMS internal standard in $CDCl_3$. Mass spectra were obtained by chemical ionization (CI). All the products were satisfactorily characterized by ^{1}H and ^{13}C NMR, MS, HRMS and when possible, comparison of their NMR spectra has been made with available literature data and/or those of authentic samples. 5-Phenylhex-5-en-2-one **3d** [17] and (*E*)-6-phenylhex-5-en-2-one **4d** [18] have been reported previously.

2.2. Procedures for arylation

An oven-dried, two-necked round-bottom flask containing a stir bar was charged with an aryl bromide **2** (1.0 mmol), $Pd(OAc)_2$ (0.025 mmol), DPPP (0.05 mmol), and [bmim][BF_4] (2 mL) under nitrogen at room temperature. Following degassing three times, 5-hexen-2-one **1** (1.1 mmol) and HN^iPr_2 (1.2 mmol) were injected sequentially. The flask was placed in an oil bath, and the mixture was stirred and heated at 115 °C. After a reaction time of 24 h, the flask was removed from the oil bath and cooled to room temperature. A small sample was then taken for NMR analysis, which showed that the reaction had completed. The rest of the mixture was extracted with CH_2Cl_2 (3 × 20 mL), and the combined organic layer was washed with water until neutrality, dried ($MgSO_4$), filtered, and concentrated *in vacuo*. The γ arylated product was isolated out of the crude product by flash chromatography on silica gel using a mixture of ethyl acetate and hexane (5/95 to 30/70) as eluant. When DPPP was replaced with DPPF, the isolated product was the δ arylated ketone. The identity and purity of the product was confirmed by ^{1}H and ^{13}C NMR, MS, HRMS and by comparison of their NMR spectra with available literature data. The isolated yields of the products are given in Tables 2 and 3.

2.3. Analytic data

2.3.1. 5-(4-Fluorophenyl)hex-5-en-2-one (**3a**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37–7.33 (m, 2H), 7.03–6.99 (m, 2H), 5.23 (s, 1H), 5.05 (s, 1H), 2.76 (t, J = 6.0 Hz, 2H), 2.58 (t, J = 6.0 Hz, 2H), 2.12 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.8, 162.4 (d, J_{CF} = 245 Hz), 146.3, 136.8 (d, J_{CF} = 3 Hz), 127.7 (d, J_{CF} = 8 Hz), 115.2 (d, J_{CF} = 21 Hz), 112.7, 42.3, 30.0, 29.4; CI-MS *m/z* 193 [(M + H)$^+$, 100], 149 (38); HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1028; Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 74.90; H, 6.82.

2.3.2. 4-(5-Oxohex-1-en-2-yl)benzonitrile (**3b**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64–7.61 (m, 2H), 7.50–7.47 (m, 2H), 5.34 (s, 1H), 5.21 (s, 1H), 2.78 (t, J = 6.0 Hz, 2H), 2.59 (t, J = 6.0 Hz, 2H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.6, 146.2, 145.7, 132.6, 127.1, 119.1, 115.8, 111.6, 42.3, 30.4, 29.0; CI-MS *m/z* 217 [(M + NH_4)$^+$, 100]; HRMS Calcd for $C_{13}H_{17}N_2O$: 217.1341. Found: 217.1346; Anal. Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03; Found: C, 78.21; H, 6.58; N, 7.00.

2.3.3. 5-(4-Acetylphenyl)hex-5-en-2-one (**3c**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95–7.92 (m, 2H), 7.50–7.47 (m, 2H), 5.40 (s, 1H), 5.19 (s, 1H), 2.81 (t, J = 6.0 Hz, 2H), 2.62–2.58 (m, 5H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.7, 197.6, 146.3, 145.4, 136.2, 128.6, 126.2, 114.8, 42.1, 30.1, 28.9, 26.6; CI-MS *m/z* 234 [(M + NH_4)$^+$, 100]; 217 [(M + H)$^+$, 59]; HRMS Calcd for $C_{14}H_{17}O_2$: 217.1229. Found: 217.1233. Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 78.01; H, 7.52.

2.3.4. 5-Phenylhex-5-en-2-one (**3d**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09–8.07 (m, 5H), 5.29 (s, 1H), 5.07 (s, 1H), 2.78 (t, J = 5.1 Hz, 2H), 2.58 (t, J = 5.1 Hz, 2H), 2.12 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.2, 147.1, 140.6, 128.4, 127.6, 126.1, 112.8, 42.4, 30.0, 29.3; CI-MS *m/z* 175 [(M + H)$^+$, 100]; HRMS Calcd for $C_{12}H_{15}O$: 175.1123. Found: 175.1120. Anal. Calcd for $C_{12}H_{14}O$: C, 82.72; H, 8.10. Found: C, 82.66; H, 8.12.

2.3.5. 5-(4-Toly)hex-5-en-2-one (**3e**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33–7.25 (m, 2H), 7.15–7.12 (m, 2H), 5.29 (s, 1H), 5.02 (s, 1H), 2.76 (t, J = 6.3 Hz, 2H), 2.58 (t, J = 6.3 Hz, 2H), 2.34 (s, 3H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.4, 147.4, 138.1, 137.8, 129.5, 126.3, 112.3, 42.9, 30.3, 29.7, 21.4; CI-MS *m/z* 189 [(M + H)$^+$, 100], 173 (25); HRMS Calcd for $C_{13}H_{17}O$: 189.1279. Found: 189.1279. Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.86; H, 8.55.

2.3.6. 5-(4-Methoxyphenyl)hex-5-en-2-one (**3f**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35–7.31 (m, 2H), 6.88–6.85 (m, 2H), 5.21 (s, 1H), 4.89 (s, 1H), 3.79 (s, 3H), 2.76 (t, J = 6.0 Hz, 2H), 2.59 (t, J = 6.0 Hz, 2H), 2.12 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.5, 159.6, 146.9, 133.4, 127.6, 114.2, 111.6, 55.7, 42.9, 30.4, 29.8; CI-MS *m/z* 205 [(M + H)$^+$, 100]; HRMS Calcd for $C_{13}H_{17}O_2$: 205.1229. Found: 205.1230. Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90. Found: C, 76.28; H, 7.94.

2.3.7. 5-(3-Fluorophenyl)hex-5-en-2-one (**3g**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29–7.26 (m, 1H), 7.17–7.16 (m, 1H), 7.15–7.14 (m, 1H), 7.09–7.07 (m, 1H), 5.31 (s, 1H), 5.10 (s, 1H), 2.76 (t, J = 6.0 Hz, 2H), 2.56 (t, J = 6.0 Hz, 2H), 2.13 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.0, 162.4 (d, J_{CF} = 244 Hz), 146.5,143.5 (d, J_{CF} = 7 Hz), 130.2 (d, J_{CF} = 8 Hz), 122.1 (d, J_{CF} = 3 Hz), 114.9 (d, J_{CF} = 21 Hz), 113.6 (d, J_{CF} = 22 Hz), 112.9, 43.8, 29.5, 27.2; CI-MS *m/z* 193 [(M + H)$^+$, 100], 149 (25); HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1028. Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 74.90; H, 6.82.

2.3.8. 5-(3-Methoxyphenyl)hex-5-en-2-one (**3h**)

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26–7.22 (m, 1H), 6.98–6.96 (m, 1H), 6.93–6.92 (m, 1H), 6.84–6.81 (m, 1H), 5.28 (s, 1H), 5.06 (s, 1H), 3.79 (s, 3H), 2.76 (t, J = 6.0 Hz, 2H), 2.58 (t, J = 6.0 Hz, 2H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.3, 160.1, 147.6, 142.6, 129.8, 119.0, 113.3, 113.2, 112.5,

55.6, 42.8, 30.4, 29.8; CI-MS *m/z* 205 [(M + H)$^+$, 100]; HRMS Calcd for $C_{13}H_{17}O_2$: 205.1229. Found: 205.1230.

*2.3.9. 5-(2-Fluorophenyl)hex-5-en-2-one (**3i**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25–7.21 (m, 2H), 7.12–7.03 (m, 2H), 5.24 (s, 1H), 5.17 (s, 1H), 2.76 (t, J = 6.1 Hz, 2H), 2.53 (t, J = 6.1 Hz, 2H), 2.10 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.9, 159.8 (d, J_{CF} = 246 Hz), 143.5, 130.0 (d, J_{CF} = 4 Hz), 129.4 (d, J_{CF} = 15 Hz), 129.1 (d, J_{CF} = 8 Hz), 124.1 (d, J_{CF} = 4 Hz), 116.4, 115.9 (d, J_{CF} = 23 Hz), 42.2, 30.5, 29.9; CI-MS *m/z* 193 [(M + H)$^+$, 100]; HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1026. Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 75.24; H, 6.87.

*2.3.10. 5-(2-Toly)hex-5-en-2-one (**3j**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41–7.40 (m, 1H), 7.07–7.01 (m, 3H), 5.07 (s, 1H), 4.78 (s, 1H), 2.77 (t, J = 6.3 Hz, 2H), 2.48 (t, J = 6.3 Hz, 2H), 2.35 (s, 3H), 2.10 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.6, 141.9, 138.0, 136.8, 129.5, 128.0, 126.7, 125.7, 112.5, 41.8, 33.9, 30.9, 18.1; CI-MS *m/z* 189 [(M + H)$^+$, 100]; HRMS Calcd for $C_{13}H_{17}O$: 189.1279. Found: 189.1277. Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.66; H, 8.54.

*2.3.11. 5-(2-Methoxyphenyl)hex-5-en-2-one (**3k**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27–7.23 (m, 1H), 7.12–7.10 (m, 1H), 6.93–6.85 (m, 2H), 5.14 (s, 1H), 5.02 (s, 1H), 3.81 (s, 3H), 2.77 (t, J = 6.3 Hz, 2H), 2.47 (t, J = 6.3 Hz, 2H), 2.10 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.8, 156.9, 148.0, 131.8, 130.5, 129.0, 121.0, 115.0, 111.2, 55.8, 42.8, 30.9, 30.2; CI-MS *m/z* 205 [(M + H)$^+$, 100], 147 (25); HRMS Calcd for $C_{13}H_{17}O_2$: 205.1229. Found: 205.1231. Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90. Found: C, 76.40; H, 7.92.

*2.3.12. 5-(2-Naphthalen)hex-5-en-2-one (**3l**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83–7.78 (m, 4H), 7.57–7.54 (m, 1H), 7.49–7.44 (m, 2H), 5.43 (s, 1H), 5.17 (s, 1H), 2.90 (t, J = 7.2 Hz, 2H), 2.62 (t, J = 7.2 Hz, 2H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.1, 146.9, 137.8, 133.3, 132.9, 128.2, 128.0, 127.5, 126.2, 126.0, 124.7, 124.5, 113.3, 42.4, 30.1, 29.2; CI-MS *m/z* 225 [(M + H)$^+$, 100], 181 (25); HRMS Calcd for $C_{16}H_{17}O$: 225.1279. Found: 225.1279. Anal. Calcd for $C_{16}H_{16}O$: C, 85.68; H, 7.19. Found: C, 85.81; H, 7.22.

*2.3.13. (E)-6-(4-Fluorophenyl)hex-5-en-2-one (**4a**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30–7.27 (m, 2H), 7.02–6.96 (m, 2H), 6.37 (d, J = 15.8 Hz, 1H), 6.11 (dt, J = 15.8, 7.0 Hz, 1H), 2.60 (t, J = 7.0 Hz, 2H), 2.47 (q, J = 7.0 Hz, 2H), 2.17 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.0, 162.0 (d, J_{CF} = 244 Hz), 133.5 (d, J_{CF} = 4 Hz), 129.6, 128.6 (d, J_{CF} = 2 Hz), 127.4, 115.4 (d, J_{CF} = 21 Hz), 43.1, 30.0, 27.0; CI-MS *m/z* 193 [(M + H)$^+$, 100], 149 (38); HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1028. Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 74.90; H, 6.80.

*2.3.14. 4-[(E)-5-Oxohex-1-enyl]benzonitrile (**4b**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58–7.55 (m, 2H), 7.40–7.38 (m, 2H), 6.42 (d, J = 16.0 Hz, 1H), 6.35 (dt, J = 16.0, 7.0 Hz, 1H), 2.64 (t, J = 7.0 Hz, 2H), 2.52 (q, J = 7.0 Hz, 2H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.7, 142.3, 133.6, 132.7, 129.8, 126.9, 119.4, 110.7, 43.0, 30.3, 27.4; CI-MS *m/z* 217 [(M + NH_4)$^+$, 100]; HRMS Calcd for $C_{13}H_{17}N_2O$: 217.1341. Found: 217.1346. Anal. Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03; Found: C, 78.28; H, 6.62; N, 6.99.

*2.3.15. (E)-6-(4-Acetylphenyl)hex-5-en-2-one (**4c**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85–7.82 (m, 2H), 7.40–7.38 (m, 2H), 6.40 (d, J = 16.0 Hz, 1H), 6.28 (dt, J = 16.0, 7.1 Hz, 1H), 2.63 (t, J = 7.1 Hz, 2H), 2.52 (q, J = 7.1 Hz, 2H), 2.48 (s, 3H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.0, 198.2, 140.6, 137.1, 130.3, 129.4, 127.1, 123.1, 44.5, 31.0, 29.3, 28.6; CI-MS *m/z* 234 [(M + NH_4)$^+$, 100]; HRMS Calcd for $C_{14}H_{17}O_2$: 217.1229. Found: 217.1231. Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 77.91; H, 7.51.

*2.3.16. (E)-6-Phenyl-hex-5-en-2-one (**4d**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34–7.20 (m, 5H), 6.41 (d, J = 15.8 Hz, 1H), 6.21 (dt, J = 15.8, 7.0 Hz, 1H), 2.62 (t, J = 7.2 Hz, 2H), 2.48 (q, J = 7.0 Hz, 2H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.1, 137.4, 130.8, 128.8, 128.5, 127.1, 126.0, 43.2, 30.1, 27.1; CI-MS *m/z* 175 [(M + H)$^+$, 100]; HRMS Calcd for $C_{12}H_{15}O$: 175.1123. Found: 175.1120. Anal. Calcd for $C_{12}H_{14}O$: C, 82.72; H, 8.10. Found: C, 82.91; H, 8.14.

*2.3.17. (E)-6-(3-Fluorophenyl)hex-5-en-2-one (**4g**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26–7.22 (m, 1H), 7.09–7.01 (m, 2H), 6.90–6.88 (m, 1H), 6.38 (d, J = 15.8 Hz, 1H), 6.22 (dt, J = 15.8, 7.2 Hz, 1H), 2.62 (t, J = 7.1 Hz, 2H), 2.48 (q, J = 7.2 Hz, 2H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.2, 163.5 (d, J_{CF} = 244 Hz), 140.1 (d, J_{CF} = 7 Hz), 130.7, 130.3 (d, J_{CF} = 9 Hz), 130.1 (d, J_{CF} = 3 Hz), 122.3, 114.2 (d, J_{CF} = 21 Hz), 112.8 (d, J_{CF} = 22 Hz), 43.3, 30.4, 27.3; CI-MS *m/z* 193 [(M + H)$^+$, 100]; HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1028. Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 74.67; H, 6.85.

*2.3.18. (E)-6-(2-Fluorophenyl)hex-5-en-2-one (**4i**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43–7.39 (m, 1H), 7.29–7.26 (m, 1H), 7.20–7.17 (m, 1H), 7.09–6.99 (m, 1H), 6.56 (d, J = 16.1 Hz, 1H), 6.28 (dt, J = 16.1, 7.3 Hz, 1H), 2.64 (t, J = 7.3 Hz, 2H), 2.52 (q, J = 7.3 Hz, 2H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.9, 158.5 (d, J_{CF} = 244 Hz), 130.3, 130.0 (d, J_{CF} = 3 Hz), 129.4 (d, J_{CF} = 15 Hz), 129.1 (d, J_{CF} = 8 Hz), 124.1 (d, J_{CF} = 3 Hz), 122.4, 115.9 (d, J_{CF} = 23 Hz), 43.4, 30.4, 27.8; CI-MS *m/z* 193 [(M + H)$^+$, 100]; HRMS Calcd for $C_{12}H_{14}FO$: 193.1029. Found: 193.1026. Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 75.21; H, 6.86.

*2.3.19. (E)-6-(2-Toly)hex-5-en-2-one (**4j**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38–7.36 (m, 1H), 7.15–7.10 (m, 3H), 6.61 (d, J = 16.0 Hz, 1H), 6.05 (dt, J = 16.0, 7.0 Hz, 1H), 2.61 (t, J = 7.0 Hz, 2H), 2.53 (q, J = 7.0 Hz, 2H), 2.33 (s, 3H),

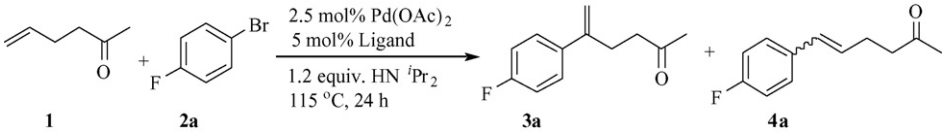
2.17 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.1, 136.9, 135.4, 130.6, 130.5, 129.1, 127.4, 126.4, 125.9, 43.7, 30.4, 27.9, 20.1; CI-MS *m/z* 189 [$(M+H)^+$, 100]; HRMS Calcd for $C_{13}H_{17}O$: 189.1279. Found: 189.1283. Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.67; H, 8.55.

3. Results and discussion

Following the procedures we developed for the internal arylation of other olefins [7b], we first examined the feasibility of arylation of **1** with 4-fluorobromobenzene **2a** as a model reaction. Since **1** is electronically different from the olefins we had studied previously and there appeared to be no report of the Heck reaction of **1**, we thought it would be of interest to determine if **1** could be γ-arylated in common solvent. Hence, a series of standard organic solvents (toluene, dioxane, acetonitrile, DMAc, DMF and DMSO) were screened as well, and the results are presented in Table 1. In a typical reaction, a mixture of **1**, **2a**, $Pd(OAc)_2$, DPPP and HN^iPr_2 was heated in a chosen solvent for 24 h under an atmosphere of N_2 to give the γ-arylated product **3a** and δ-arylated analogue **4a**. As can be seen, all the reactions went to completion in 24 h, but the results differ considerably. Clearly, the regioselectivity is solvent-dependent. As might be expected, all the standard organic solvents, some of which are commonly used in Heck reactions, afforded preferentially the (*Z*)- and (*E*)-δ-arylated γ,δ-unsaturated ketone. In line with our previous observations made with other electron-rich olefins [7b], the use of [bmim][BF_4] as reaction medium afforded predominately the branched, γ-aryl-substituted ketone **3a**, as evidenced by the γ/δ ratio of 86/14. It is also notable that in [bmim][BF_4] the (*E*)-δ-arylated γ,δ-unsaturated ketone is the only linear isomer observed by ^{1}H NMR. We also found that the regioselectivity was not affected by the ionic liquid being wet (up to 5% water, in volume). As with the arylation of other electron-rich olefins in ionic liquids [6d,7a-c,11], these initial results indicate that [bmim][BF_4] promotes the ionic pathway in the arylation of **1** (Scheme 1). In support of this, **3a** was formed as the major product in DMF in the presence of the halide scavenger TlOAc [3b]. No coupling was observed when K_2CO_3 was chosen as the base, however.

Reminiscent of the arylation of vinyl ethers with aryl bromides in [bmim][BF_4] [7b], replacement of DPPP with the monodentate phosphine ligand PPh_3 or other bidentate phosphine ligands gave rise to a much lower **3a**/**4a** ratio, reflecting the effects of subtle changes in ligand structure on the olefin insertion step, in which the regioselectivity is presumably determined. With PPh_3 as ligand, the reaction went to completion and afforded predominantly the linear products. Precipitation was observed when DPPE was used. However, the use of the bidentate ligands DPPB, DPPF, BINAP, and XANTPHOS allowed preferential formation of the δ-arylated product **4a**, which was predominantly the (*E*)-isomer, and in the case of DPPF and BINAP, the (*Z*)-isomer was not detected by NMR. This opens up a possibility for the synthesis of **3** or (*E*)-**4** by a simple switch of ligand. The lower γ/δ ratios observed with the other diphosphines could stem from partial phosphorus dissociation, which opens the neutral pathway, or increased steric hindrance in the transition state leading to the γ insertion as a result of larger

Table 1
Optimization tests on the Heck arylation of 5-hexen-2-one **1** by 1-bromo-4-fluorobenzene **2a**[a]

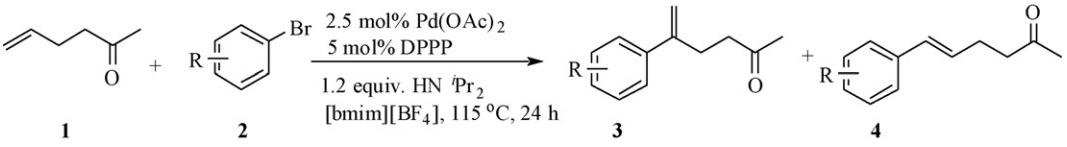


1 **2a** **3a** **4a**

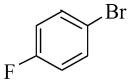
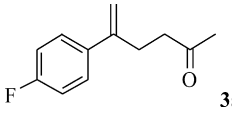
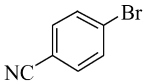
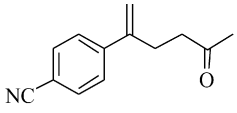
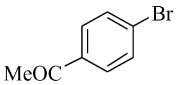
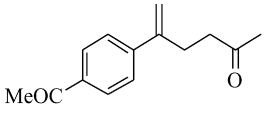
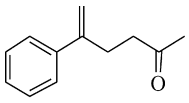
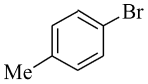
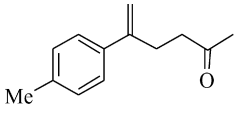
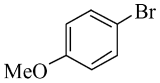
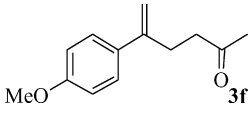
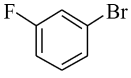
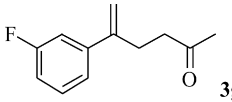
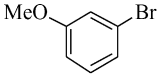
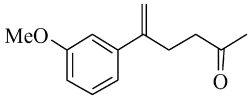
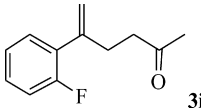
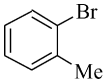
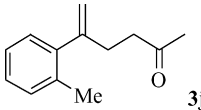
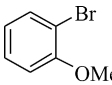
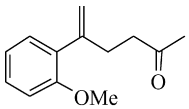
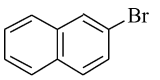
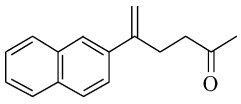
Solvent	Ligand	Bite angle [b]	Base	Conv. (%)[c]	**3a**/**4a**[d]	*E*/*Z*[e]
Toluene	DPPP	91	HN^iPr_2	100	20/80	80/20
Dioxane	DPPP	91	HN^iPr_2	100	32/68	93/7
Actonitrile	DPPP	91	HN^iPr_2	100	24/76	97/3
DMAc	DPPP	91	HN^iPr_2	100	13/87	95/5
DMF	DPPP	91	HN^iPr_2	100	17/83	93/7
DMSO	DPPP	91	HN^iPr_2	100	35/65	92/8
[bmim][BF_4]	DPPP	91	HN^iPr_2	100	86/14	>99/1
[bmim][BF_4]	PPh_3	–	HN^iPr_2	100	21/79	98/2
[bmim][BF_4]	DPPE	85	HN^iPr_2	0	–	–
[bmim][BF_4]	DPPF	96	HN^iPr_2	100	26/74	>99/1
[bmim][BF_4]	DPPB	98	HN^iPr_2	100	25/75	97/3
[bmim][BF_4]	*rac*-BINAP	92	HN^iPr_2	100	37/63	>99/1
[bmim][BF_4]	XANTPHOS	112	HN^iPr_2	100	23/77	95/5
[bmim][BF_4]	DPPP	91	K_2CO_3	<1	–	–
DMF	DPPP	91	TlOAc	100	73/27	>99/1

[a] Reaction conditions: 1.1 mmol **1**, 1.0 mmol **2a**, 2.5 mol% $Pd(OAc)_2$, 5 mol% ligand, and 1.2 equiv. HN^iPr_2 using 2 ml solvent at 115 °C for 24 h. The product was analyzed by ^{1}H NMR.
[b] From [19].
[c] Conversion of **2a** to **3a** and **4a**.
[d] Molar ratio of **3a**/**4a**.
[e] Ratio of *trans*/*cis* isomers of **4a**.

Table 2
Heck arylation of 5-hexen-2-one **1** by aryl bromides **2** in [bmim][BF_4][a]



1 **2** **3** **4**

Entry	Aryl bromide	Product	**3/4**[b]	Yield (%)[c]
1	 **2a**	 **3a**	86/14	80
2	 **2b**	 **3b**	90/10	83
3	 **2c**	 **3c**	84/16	76
4	 **2d**	 **3d**	81/19	73
5	 **2e**	 **3e**	95/5	90
6	 **2f**	 **3f**	80/20	72
7	 **2g**	 **3g**	82/18	76
8	 **2h**	 **3h**	97/3	91
9	 **2i**	 **3i**	97/3	92
10	 **2j**	 **3j**	97/3	92
11	 **2k**	 **3k**	99/1	93
12	 **2l**	 **3l**	82/18	74

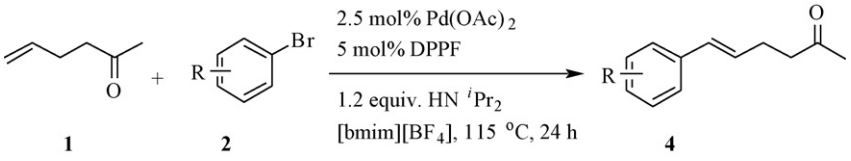
[a] Reaction conditions: 1.1 mmol **1**, 1.0 mmol **2**, 2.5 mol% $Pd(OAc)_2$, 5 mol% DPPP and 1.2 equiv. HN^iPr_2 at 115 °C for 24 h using 2 ml of [bmim][BF_4] as solvent. All reactions afforded 100% conversion as determined by ^{1}H NMR.
[b] Determined by ^{1}H NMR.
[c] Isolated yield of compound **3**.

ligand bite angles and/or more rigid ligand backbones. In light of a recent DFT study concerning the migration of vinyl into propene in $[L_2Pd(vinyl)(propene)]^+$, the electronic bias toward either γ or δ insertion for **1** is expected to be small [8a], indicating that the regioselectivity could be easily influenced by steric factors.

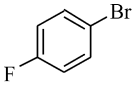
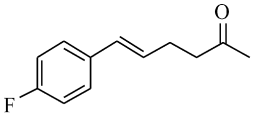
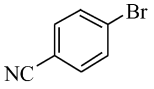
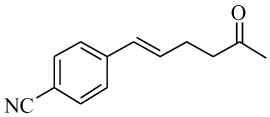
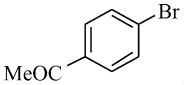
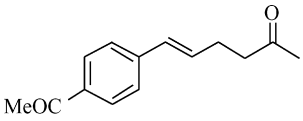
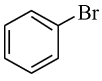
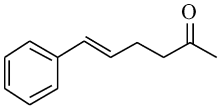
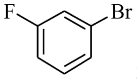
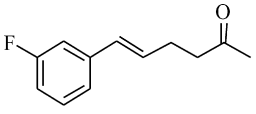
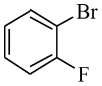
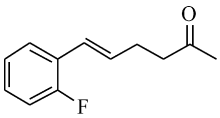
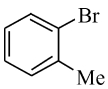
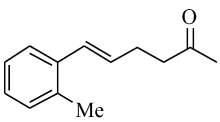
The arylation of **1** in [bmim][BF_4] was then extended to a variety of aryl bromides, and the results are summarized in Table 2. Good to excellent regioselectivities together with high isolated yields were achieved regardless of the nature of the substituents on the aryl ring. Thus, bromobenzenes bearing either strongly electron-withdrawing or electron-donating substituents, such as–CN or–OMe, all furnished good to excellent isolated yields with up to 99/1 γ/δ ratios (entries 1–11). There appears to be no correlation between the electronic properties of the substitutes at the aryl rings and the observed γ/δ ratios; this is evident from entries 1–6. But there appears to be an effect of substitution position on the regioselectivity and reactivity. As can be seen, substrates with *ortho* substitution on the phenyl ring reacted more favourably to give products with higher γ regioselectivities when compared with substrates bearing *meta* or *para* substituents (entries 9 versus 1 and 7; entries 10 versus 5; entries 11 versus 6 and 8). Similar observation is made by Hallberg and co-workers in their study of the regioselective arylation of allyl amine [20].

As aforementioned, when DPPF or BINAP, instead of DPPP, is used as ligand, the reaction becomes more regioselective toward the (*E*)-δ–arylated product **4**, with no *Z* isomer detected by NMR. To demonstrate the synthetic utility of the reaction, we carried out the arylation of **1** by **2** under the same conditions

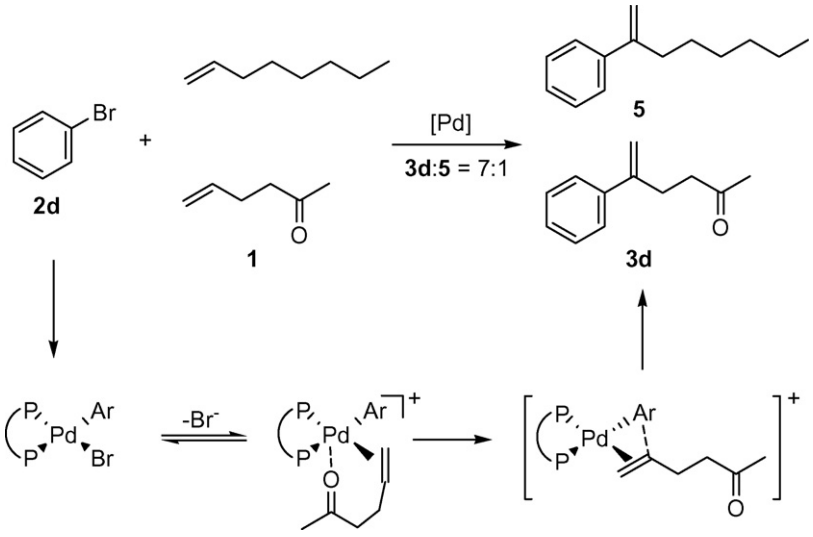
Table 3
Heck arylation of **1** with **2** by Pd-DPPF catalysis in [bmim][BF_4][a]



1 **2** **4**

Entry	Aryl bromide	Product	**3/4**[b]	Yield (%)[c]
1	 **2a**	 **4a**	26/74	65
2	 **2b**	 **4b**	25/75	67
3	 **2c**	 **4c**	18/82	77
4	 **2d**	 **4d**	23/77	70
5	 **2g**	 **4g**	20/80	72
6	 **2i**	 **4i**	30/70	63
7	 **2j**	 **4j**	17/83	78

[a] Reaction conditions: 1.1 mmol **1**, 1.0 mmol **2**, 2.5 mol% $Pd(OAc)_2$, 5 mol% DPPF and 1.2 equiv. HN^iPr_2 at 115 °C for 24 h using 2 ml of [bmim][BF_4] as solvent. All reactions afford 100% conversion as determined by ^{1}H NMR.
[b] Determined by ^{1}H NMR.
[c] Isolated yield of compound **4**.



Scheme 3. Competitive olefination by **1** and 1-octene in [bmim][BF_4] with Pd-DPPP catalysis under the conditions given in Table 2 except that the olefinic substrate was a 1:1 mixture of the two olefins. The resulting products contained **3d** and **5** in a molar ratio of 7/1 (100% conversion; the minor linear products are not shown).

as those employed before except for DPPP being replaced with DPPF. The results on the selective formation of the (*E*)-type δ-arylated γ,δ-unsaturated ketones is shown in Table 3. As can be seen, the (*E*)-δ-arylated ketones were obtained in good yields under the given conditions, although the regioselectivity is generally lower than that for the γ product when using Pd-DPPP catalysis. The preferential formation of δ-arylated ketones may result from the arylation proceeding via the neutral Heck pathway made possible by partial phosphorus dissociation. There are examples in which DPPF acts as a monodentate ligand [21]. (*E*)-Type δ-arylated γ,δ-unsaturated ketones have been synthesized by several methods including catalytic reactions [18]. The present reaction provides an additional entrance to these valuable compounds.

The results obtained with Pd-DPPP in [bmim][BF_4] are consistent with the arylation proceeding via the cationic mechanism (Scheme 1), although no halide scavenger is used. A very similar regioselectivity was observed with the unfunctionalized 1-hexene when the ionic pathway was made favorable; the selectivity was reversed to favour external arylation when the neutral pathway was in operation [3b]. The DFT calculations aforementioned predicate the same swing of regioselectivity with reaction pathways [8a]. Considering that the electronic properties of the C=C bond in the two olefins should be similar, they are expected to give regioselectivities that vary in a similar way in accordance with the reaction mechanisms, e.g. internal arylation when the ionic mechanism in operation. In addition, this similarity in regioselectivity suggests that the carbonyl group in **1** is not coordinated to Pd(II), and hence a five-coordinated palladium is not involved, in the insertion step [22]. However, it does not rule out the possibility of **1** chelating to the palladium in other steps of the catalytic cycle [23]. In fact, a competition reaction between **1** and 1-octene in their reaction with **2d** afforded the results shown in Scheme 3, which could be explained by a mechanism involving chelation-assisted substitution of the bromide anion by **1**, which enhances the concentration of Pd(II)-**1** and thus leads to a faster arylation rate for **1**.

4. Conclusions

In summary, we have developed a new method for the synthesis of γ-aryl-substituted γ,δ-unsaturated ketones by Pd-DPPP catalyzed regioselective Heck arylation of 5-hexen-2-one in ionic liquid. Various aryl bromides can be directly employed as the arylating agents with no need for any halide scavengers such as Ag(OTf) or Tl(OAc). Our results are consistent with the reaction proceeding via the ionic Heck pathway made possible by the ionic medium. Of both practical and theoretical interest is that the regioselectivity can be reversed with a simple change in ligand to favour the δ-arylated ketones. Thus, the chemistry presents an easy method for arylated γ,δ-unsaturated ketones, which are otherwise difficult to access.

Acknowledgment

We thank Johnson Matthey for the loan of palladium.

References

[1] (a) N.T.S. Phan, M. Van Der Sluys, C.W. Jones, Adv. Synth. Catal. 348 (2006) 609;
(b) M. Larhed, A. Hallberg, in: E.-I. Negishi (Ed.), Handbook of Organopalladium Chemistry for Organic Synthesis, vol. 1, Wiley-Interscience, New York, 2002, p. 1133;
(c) A.F. Littke, G.C. Fu, Angew. Chem. Int. Ed. 41 (2002) 4176;
(d) N.J. Whitcombe, K.K. Hii, S.E. Gibson, Tetrahedron 57 (2001) 7449;
(e) I.P. Beletskaya, A.V. Cheprakov, Chem. Rev. 100 (2000) 3009;
(f) J.T. Link, L.E. Overman, in: F. Diederich, P.J. Stang (Eds.), Metal-Catalyzed Cross-coupling Re-actions, Wiley-VCH, Weinheim, 1998 (Chapter 6);
(g) S. Brase, A. de Meijere, in: F. Diederich, P.J. Stang (Eds.), Metal-Catalyzed Cross-coupling Re-actions, Wiley-VCH, Weinheim, 1998 (Chapter 3);
(h) J. Tsuji, Palladium Reagents and Catalysts: Innovations in Organic Synthesis, Wiley, Chichester, 1995;
(i) A. de Meijere, F.E. Meyer, Angew. Chem., Int. Ed. Engl. 33 (1994) 2379;
(j) L.S. Hegedus, Transition Metals in the Synthesis of Complex Organic

Molecules, second ed., Sausalito, California, 1999 (Chapter 4.6);
(k) R.F. Heck, Org. React. 27 (1982) 345.
[2] For some recent examples of regioisomer formation, see:
(a) V. Calò, A. Nacci, A. Monopoli, M. Spinelli, Eur. J. Org. Chem. (2003) 1382;
(b) A. Nejjar, C. Pinel, L. Djakovitch, Adv. Synth. Catal. 345 (2003) 612;
(c) K. Maeda, E.J. Farrington, E. Galardon, B.D. John, J.M. Brown, Adv. Synth. Catal. 344 (2002) 104;
(d) M. Feuerstein, H. Doucet, M. Santellic, Tetrahedron Lett. 43 (2002) 2191;
(e) A.F. Littke, G.C. Fu, J. Am. Chem. Soc. 123 (2001) 6989;
(f) L. Djakovitch, K. Koehler, J. Am. Chem. Soc. 123 (2001) 5990;
(g) D.E. Bergbreiter, P.L. Osburn, A. Wilson, E.M. Sink, J. Am. Chem. Soc. 122 (2000) 9058;
(h) M. Ludwig, S. Stromberg, M. Svesson, B. Akermark, Organometallics 18 (1999) 970;
(i) S.W. Wright, D.L. Hageman, L.D. McClure, J. Heterocycl. Chem. 35 (1998) 719;
(j) W.A. Herrmann, C. Brossmer, C.P. Reisinger, T.H. Riermeier, K. Öfele, M. Beller, Chem. Eur. J. 3 (1997) 1357.
[3] (a) G.D. Davis Jr., A. Hallberg, Chem. Rev. 89 (1989) 1433;
(b) W. Cabri, I. Candiani, Acc. Chem. Res. 28 (1995) 2;
(c) G.T. Crisp, Chem. Soc. Rev. 27 (1998) 427.
[4] Examples of regioselective arylation of electron-rich olefins:
(a) A.L. Hansen, T. Skrydstrup, J. Org. Chem. 70 (2005) 5997;
(b) A.L. Hansen, T. Skrydstrup, Org. Lett. 7 (2005) 5585;
(c) K.S.A. Vallin, Q. Zhang, M. Larhed, D.P. Curran, A. Hallberg, J. Org. Chem. 68 (2003) 6639;
(d) P. Nilsson, M. Larhed, A. Hallberg, J. Am. Chem. Soc. 123 (2001) 8217;
(e) W. Cabri, I. Canadiniani, A. Bedeschi, R. Santi, J. Org. Chem. 58 (1993) 7421.
[5] (a) J. Dupont, J. Spencer, Angew. Chem. Int. Ed. 43 (2004) 5296;
(b) T. Welton, Coord. Chem. Rev. 248 (2004) 2459;
(c) P. Wasserscheid, T. Welton (Eds.), Ionic Liquids in Synthesis, Wiley–VCH, Weinheim, 2003;
(d) J. Dupont, R.F. de Souza, P.A.Z. Suarez, Chem. Rev. 102 (2002) 3667;
(e) P. Wassercheid, W. Keim, Angew. Chem. Int. Ed. 39 (2000) 3772;
(f) T. Welton, Chem. Rev. 99 (1999) 2071.
[6] Recent examples of Heck coupling in ionic liquids:
(a) A.J. Carmichael, M.J. Earle, J.D. Holbrey, P.B. McCormac, K.R. Seddon, Org. Lett. 1 (1999) 997;
(b) V.P.W. Bohm, W.A. Herrmann, Chem. Eur. J. 6 (2000) 1017;
(c) S. Bouquillon, B. Ganchegui, B. Estrine, F. Henin, J. Muzart, J. Organomet. Chem. 634 (2001) 153;
(d) K.S.A. Vallin, P. Emilsson, M. Larhed, A. Hallberg, J. Org. Chem. 67 (2002) 6243;
(e) S.B. Park, H. Alper, Org. Lett. 5 (2003) 3209;
(f) X. Xie, B. Chen, J. Lu, J. Han, X. She, X. Pan, Tetrahedron Lett. 45 (2004) 6235;
(g) D. Zhao, Z. Fei, T.J. Geldbach, R. Scopelliti, P.J. Dyson, J. Am. Chem. Soc. 126 (2004) 15876;
(h) S. Liu, T. Fukuyama, M. Sato, I. Ryu, Synlett (2004) 1814;
(i) J. Xiao, B. Twamley, J.M. Shreeve, Org. Lett. 6 (2004) 3845;
(j) H. Hagiwara, Y. Sugawara, T. Hoshi, T. Suzuki, Chem. Commun. (2005) 2942;
(k) C.C. Cassol, A.P. Umpierre, G. Machado, S.I. Wolke, J. Dupont, J. Am. Chem. Soc. 127 (2005) 3298;
(l) V. Calo, A. Nacci, A. Monopoli, E. Ieva, N. Cioffi, Org. Lett. 7 (2005) 617.
[7] (a) J. Mo, J. Xiao, Angew. Chem. Int. Ed. 45 (2006) 4152;
(b) J. Mo, L. Xu, J. Xiao, J. Am. Chem. Soc. 127 (2005) 751;
(c) J. Mo, S. Liu, J. Xiao, Tetrahedron 61 (2005) 9902;
(d) J. Ross, J. Xiao, Chem. Eur. J. 9 (2003) 4900;
(e) L. Xu, J. Mo, C. Baillie, J. Xiao, J. Organomet. Chem. 687 (2003) 301;
(f) J. Ross, J. Xiao, Green Chem. 4 (2002) 129;
(g) L. Xu, W. Chen, J. Ross, J. Xiao, Org. Lett. 3 (2001) 295;
(h) J. Ross, W. Chen, L. Xu, J. Xiao, Organometallics 20 (2001) 138;
(i) L. Xu, W. Chen, J. Xiao, Organometallics 19 (2000) 1123.
[8] (a) R.J. Deeth, A. Smith, J.M. Brown, J. Am. Chem. Soc. 126 (2004) 7144;
(b) M.M.S. Andappan, P. Nilsson, H. von Schenck, M. Larhed, J. Org. Chem. 69 (2004) 5212;
(c) H. von Schenck, B. Akermark, M. Svensson, J. Am. Chem. Soc. 125 (2003) 3503.
[9] (a) M.A. Klingshirn, G.A. Broker, J.D. Holbrey, K.H. Shanghnessy, R.D. Rogers, Chem. Commun. (2002) 1394;
(b) C. Chiappe, D. Pieraccini, J. Org. Chem. 69 (2004) 6059.
[10] K.S.A. Vallin, M. Larhed, A. Hallberg, J. Org. Chem. 66 (2001) 4340.
[11] W. Pei, J. Mo, J. Xiao, J. Organomet. Chem. 690 (2005) 3546.
[12] (a) T. Masso, A. Portella, E. Rus, Perfum. Flavor. 15 (1990) 39;
(b) Atta-ur-Rahman, in: Atta-ur-Rahman (Ed.), Natural Product Chemistry, Springer–Verlag, Berlin, 1986, p. 330;
(c) R.R. Schmidt, in: Atta-ur-Rahman (Ed.), Natural Product Chemistry, Springer–Verlag, Berlin, 1986, p. 383.
[13] (a) F. Naf, P. Degen, Helv. Chim. Acta 54 (1971) 1939;
(b) H. Onoue, I. Moritani, S.I. Murahashi, Tetrahedron Lett. 14 (1973) 121;
(c) G.P. Boldrini, D. Savoia, E. Tagliavini, C. Trombini, A. Umani-Ronchi, J. Organomet. Chem. 268 (1984) 97;
(d) Y. Inoue, M. Toyofuku, M. Taguchi, S. Okada, H. Hashimoto, Bull. Chem. Soc. Jpn. 59 (1986) 885;
(e) A.R. Katritzky, Z. Huang, Y. Fang, J. Org. Chem. 64 (1999) 7625.
[14] (a) A.V.R. Rao, V.H. Deshpande, S.P. Reedy, Synth. Commun. 14 (1984) 469;
(b) V. Fiandanese, G. Marchese, F. Naso, Tetrahedron Lett. 29 (1988) 3587;
(c) P. Jacob, H.C. Brown, J. Am. Chem. Soc. 98 (1976) 7832;
(d) T.H. Kim, S. Isoe, Chem. Commun. (1983) 730;
(e) T. Nishiyama, J.F. Woodhall, E.N. Lawson, W. Kitching, J. Org. Chem. 54 (1989) 2183;
(f) M. Koreeda, J.I. Luengo, J. Am. Chem. Soc. 107 (1985) 5572.
[15] (a) J.T. Gupton, D. Krolikowski, M. Rusler, Synth. Commun. 19 (1989) 2415;
(b) K. Itoh, N. Hamaguchi, M. Miura, M. Nomura, J. Chem. Soc. Perkin Trans. I (1992) 2833;
(c) A. Srikrishna, K. Krishnan, S. Venkateswarlu, P.P. Kumar, J. Chem. Soc. Perkin Trans. I (1995) 2033;
(d) S. Saito, M.M. Salter, V. Gevorgyan, N. Tsuboya, K. Tando, Y. Yamamoto, J. Am. Chem. Soc. 118 (1996) 3970;
(e) S. Condon-Gueugnot, D. Dupre, J.Y. Nedelec, J. Perichon, Synthesis (1997) 1457;
(f) A.R. Katritzky, M.V. Voronkov, D. Toader, J. Org. Chem. 63 (1998) 9987.
[16] (a) Y. Chauvin, L. Mussmann, H. Olivier, Angew. Chem. Int. Ed. 34 (1995) 2698;
(b) P.A.Z. Suarez, J.E.L. Dullius, S. Einloft, R.F. de Souza, J. Dupont, Polyhedron 15 (1996) 1217.
[17] D.L. Boger, R.J. Mathvink, J. Org. Chem. 54 (1989) 1777.
[18] (a) D.J. Fox, D.S. Pedersen, S. Warren, Chem. Commun. (2004) 2598;
(b) E.C. Burger, J.A. Tunge, Org. Lett. 6 (2004) 2603;
(c) M. Yasuda, S. Tsuji, Y. Shigeyoshi, A. Baba, J. Am. Chem. Soc. 124 (2004) 7440;
(d) S. Oi, Y. Honma, Y. Inoue, Org. Lett. 4 (2002) 667;
(e) R.A. Batey, A.N. Thadani, D.V. Smil, Org. Lett. 1 (1999) 1683.
[19] P. Dierkes, P.W.N.M. van Leeuwen, J. Chem. Soc. Dalton Trans. (1999) 1519.
[20] K. Olofsson, M. Larhed, A. Hallberg, J. Org. Chem. 65 (2000) 7235, and the references therein.
[21] G. Bandoli, A. Dolmella, Coord. Chem. Rev. 209 (2000) 161.
[22] (a) E.G. Samsel, J.R. Norton, J. Am. Chem. Soc. 106 (1984) 5505;
(b) D.L. Thorn, R. Hoffmann, J. Am. Chem. Soc. 100 (1978) 2079.
[23] A. Ashimori, B. Bachand, M.A. Calter, S.P. Govek, L.E. Overman, D.J. Poon, J. Am. Chem. Soc. 120 (1998) 6488.