VERSITA

Chemical Papers 65 (3) 338–344 (2011)
DOI: 10.2478/s11696-011-0016-3

ORIGINAL PAPER

Pd-catalysed conjugate addition of arylboronic acids to α,β-unsaturated ketones under microwave irradiation

Viera Poláčková, Vladimír Bariak, Radovan Šebesta*, Štefan Toma

Department of Organic Chemistry, Faculty of Natural Sciences, Comenius University, Mlynská dolina CH-2, 842 15 Bratislava, Slovakia

Received 1 October 2010; Revised 16 December 2010; Accepted 20 December 2010

The Pd-catalysed conjugate addition of arylboronic acids to α,β-unsaturated cyclic ketones was studied under controlled microwave irradiation conditions. A variety of catalysts, bases and solvents was explored in order to achieve optimum yields in the shortest possible reaction time. Under optimised conditions ($Pd(OAc)_2$/2,2′-bipyridine and KF in a mixture of toluene, water, and acetic acid and 10 min microwave irradiation), a range of arylboronic acids was successfully added to several cyclic enones. With chiral phosphane ligands, a promising enantioselectivity was obtained (85 % ee).

Keywords: palladium, catalysis, Michael addition, arylboronic acid, microwave irradiation

Introduction

Microwave irradiation (MWI) is now an established technique in organic synthesis (Kappe, 2004; Kappe et al., 2009; Kappe & Stadler, 2005; Tierney & Lidström, 2005). It is often applied as a substitute for conventional heating in order to accelerate reactions or suppress the decomposition or formation of unwanted by-products. Microwave irradiation is also very useful in the synthesis of biologically active compounds (Gavande et al., 2010; Helan et al., 2010; Kováčová et al., 2010). Moreover, applying a closed-vessel technique enables the heating of solvents far above their boiling point. The higher reaction temperatures at elevated pressures lead to impressive results in respect of reducing reaction times and improving chemical yields (Kappe & Dallinger, 2009). Microwave heating is also beneficial to many transition metal-catalysed carbon-carbon bond forming reactions (Alonso et al., 2008; Barge et al., 2008; Larhed et al., 2002; Singh et al., 2008). Researchers from our laboratory also contributed to the development of microwave-assisted metal-catalysed reactions. We demonstrated that microwave heating was effective in a certain type of Pd-catalysed Suzuki-Miyaura reaction (Poláčková et al., 2006; Poláčková & Toma, 2007), Pd-catalysed allylic substitution with arylboronic acids (Poláčková et al., 2007), and CuI-catalysed aromatic amination (Veverková & Toma, 2008). Elevated reaction temperatures often result in lower enantioselectivity. Microwave heating, however, has been successfully applied to accelerate asymmetric reactions without a decrease in their enantioslectivities (Almansa et al., 2008; Genov et al., 2007, 2008).

The conjugate addition of organometallic reagents to enones is a widely used method for the formation of β-substituted carbonyl compounds, which are versatile synthons for further structural transformations. Rhodium complexes are the catalysts most frequently used for the addition of arylboronic acids to enones. Some Pd-based catalysts have also been described for this reaction (Bedford et al., 2007; Gutnov, 2008; He et al., 2007; Cho et al., 1995; Nishikata et al., 2004; Suzuma et al., 2007; Yamamoto et al., 2006). The first enantioselective Pd-catalysed conjugate addition of arylboronic acids to a variety of α,β-unsaturated compounds was reported by Minnaard (Gini et al., 2005). Product yields and enantioselectivities were high, but

*Corresponding author, e-mail: radovan.sebesta@fns.uniba.sk

Table 1. Spectral data of the compounds prepared

Compound	Spectral data	Reference
II	^{1}H NMR ($CDCl_3$), δ: 1.68–1.94 (m, 2H), 2.02–2.25 (m, 2H), 2.30–2.73 (m, 4H), 2.94–3.10 (m, 1H), 7.09–7.49 (m, 5H) HPLC (hexane/propan-2-ol (φ_r = 98 : 2), 0.8 mL min^{-1}), t_R/min: 18.3 (major), 20.0 (minor)	(Gini et al., 2005)
V	^{1}H NMR ($CDCl_3$), δ: 1.91–2.05 (m, 1H), 2.24–2.56 (m, 4H), 2.64–2.73 (m, 1H), 3.35–3.50 (m, 1H), 7.20–7.38 (m, 5H)	(Gini et al., 2005)
VI	^{1}H NMR ($CDCl_3$), δ: 1.92–2.03 (m, 1H), 2.26–2.36 (m, 2H), 2.41–2.51 (m, 2H), 2.64–2.71 (m, 1H), 3.40 (m, 1H), 7.13 (dtd, J = 0.6 Hz, J = 1.8 Hz, J = 7.2 Hz, 1H), 7.22–7.30 (m, 3H)	(Itooka et al., 2003)
VII	^{1}H NMR ($CDCl_3$), δ: 1.88–2.02 (m, 1H), 2.24–2.52 (m, 4H), 2.62–2.71 (m, 1H), 3.34–3.46 (m, 1H), 7.19 (d, J = 8.1 Hz, 2H), 7.33 (d, J = 8.1 Hz, 2H) ^{13}C NMR ($CDCl_3$), δ: 31.1, 38.8, 41.6, 45.6, 128.1, 128.7, 132.3, 141.5, 217.8	(Kantam et al., 2008)
VIII	^{1}H NMR ($CDCl_3$), δ: 1.96–2.04 (m, 1H), 2.30–2.37 (m, 2H), 2.46–2.52 (m, 2H), 2.70 (dd, J = 18.3 Hz, J = 7.2 Hz, 1H), 3.49 (m, 1H), 7.38 (d, J = 8.1 Hz, 2H), 7.60 (d, J = 8.1 Hz, 2H)	(Takaya et al., 1999)
IX	^{1}H NMR ($CDCl_3$), δ: 2.17–2.27 (m, 1H), 2.34–2.61 (m, 4H), 2.82 (dd, J = 7.2 Hz, J = 18.0 Hz, 1H), 4.18–4.28 (m, 1H), 7.36–7.61 (m, 4H), 7.75 (d, J = 8.1 Hz, 1H), 7.88–7.91 (m, 1H), 8.10 (d, J = 8.1 Hz, 1H)	(Fujio et al., 1998)
X	^{1}H NMR ($CDCl_3$), δ: 1.72–1.89 (m, 2H), 2.05–2.19 (m, 2H), 2.34–2.61 (m, 4H), 2.95–3.03 (m, 1H), 7.09 (td, J = 8.4 Hz, J = 1.8 Hz, 1H), 7.21–7.28 (m, 3H)	(Itooka et al., 2003)
XI	^{1}H NMR ($CDCl_3$), δ: 1.67–1.90 (m, 2H), 2.02–2.22 (m, 2H), 2.29–2.63 (m, 4H), 2.91–3.06 (m, 1H), 7.14 (d, J = 8.1 Hz, 2H), 7.30 (d, J = 8.1 Hz, 2H)	(Cho et al., 1995)
XII	^{1}H NMR ($CDCl_3$), δ: 1.69–1.90 (m, 2H), 2.01–2.20 (m, 2H), 2.29–2.63 (m, 4H), 2.92–3.07 (m, 1H), 7.13–7.24 (m, 2H), 6.96–7.08 (m, 2H)	(Mariz et al., 2008)
XIII	^{1}H NMR ($CDCl_3$), δ: 1.77–1.92 (m, 2H), 2.09–2.21 (m, 2H), 2.38–2.62 (m, 4H), 3.09 (m, 1H), 7.34 (d, J = 8.3 Hz, 2H), 7.59 (d, J = 8.3 Hz, 2H)	(Takaya et al., 1998)
XIV	^{1}H NMR ($CDCl_3$), δ: 1.80–2.04 (m, 2H), 2.11–2.28 (m, 2H), 2.36–2.81 (m, 4H), 3.78–3.87 (m, 1H), 7.36–7.54 (m, 4H), 7.73 (d, J = 7.7 Hz, 1H), 7.83–7.87 (m, 1H), 8.02 (d, J = 8.1 Hz, 1H)	(Cho et al., 1995)
XV	^{1}H NMR ($CDCl_3$), δ: 1.45–1.56 (m, 1H), 1.65–1.79 (m, 2H), 1.93–2.10 (m, 3H), 2.53–2.62 (m, 3H), 2.82–2.92 (m, 2H), 7.16–7.22 (m, 3H), 7.28–7.34 (m, 2H)	(Gini et al., 2005)
XVI	^{1}H NMR ($CDCl_3$), δ: 1.59–1.71 (m, 1H), 1.73–1.95 (m, 2H), 2.02–2.15 (m, 2H), 2.21–2.33 (m, 1H), 2.68–2.74 (m, 2H), 2.79 (td, J = 2.1 Hz, J = 14.2 Hz, 1H), 3.05 (dd, J = 11.7 Hz, 14.2 Hz, 1H), 3.73 (tt, J = 11.4 Hz, J = 2.4 Hz, 1H), 7.35 (d, J = 7,2 Hz, 1H), 7.44–7.55 (m, 3H), 7.73 (d, J = 8.1 Hz, 1H), 7.85–7.88 (m, 1H), 8.06 (d, J = 8.7 Hz, 1H)	(Vandyck et al., 2006)
XVII	^{1}H NMR ($CDCl_3$), δ: 1.46–1.55 (m, 1H), 1.63–1.77 (m, 2H), 1.96–2.10 (m, 3H), 2.52–2.66 (m, 3H), 2.87–2.95 (m, 2H), 7.11 (d, J = 8.4 Hz, 2H), 7.26 (d, J = 8.4 Hz, 2H) ^{13}C NMR ($CDCl_3$), δ: 24.0, 29.1, 39.1, 42.1, 43.9, 51.1, 127.8, 128.7, 131.9, 145.3, 213.1	(Gutsche et al., 1958)
XIX	^{1}H NMR ($CDCl_3$), δ: 2.43–2.51 (m, 1H), 2.61–2.72 (m, 1H), 2.94–3.10 (m, 2H), 3.29–3.39 (m, 1H), 4.36–4.44 (m, 1H), 5.93–5.96 (m, 1H), 7.27–7.40 (m, 10H)	(Comins et al., 2001)
XXI	^{1}H NMR ($CDCl_3$), δ: 1.97–2.10 (m, 1H), 2.59–2.68 (dd, J = 17.6 Hz, 10.7 Hz, 1H), 2.88–2.96 (ddd, J = 17.6 Hz, J = 5.9 Hz, J = 1.6 Hz, 1H), 3.19–3.29 (m, 1H), 4.35–4.43 (m, 1H), 4.48–4.54 (m, 1H), 7.20–7.23 (m, 2H), 7.27–7.30 (m, 1H), 7.34–7.39 (m, 2H)	(Shintani et al., 2005)

reactions were rather slow.

Conjugate addition of arylboronic acids to enones is often, even at higher temperatures, a rather slow reaction. We therefore argued that MWI could be a useful alternative source of energy for this kind of transformation. This paper shows that microwave heating is indeed effective in promoting Pd-catalysed addition of arylboronic acids to cyclic enones. Furthermore, we show that chiral ligands may also be used.

Experimental

Microwave experiments were carried out in the Biotage Initiator reactor (maximum power setting of 300 W). All reactions were performed in an argon atmosphere. The ^{1}H NMR spectra of the compounds dissolved in $CDCl_3$ with tetramethylsilane as an internal standard were measured using a Varian Gemini spectrometer (300 MHz). Enantiomeric excess (ee) was determined by HPLC on Chiralcel OD-H column (Daicel Chemical Industries) with hexane/propan-2-ol as a mobile phase and UV detection at 208 nm. Assignment of the absolute configuration of product *II* was made by comparison of HPLC data with literature values (Mariz et al., 2008). Ligands *XXII* (Hayashi et al., 1980), *XXIII* (Togni et al., 1994), *XXIV* (Almássy

Table 2. Effect of Pd compounds and bases on the Pd-catalysed 1,4-addition of $PhB(OH)_2$ to enone *I* with PPh_3 as the ligand[a]

Entry	Catalyst	Base	Temperature/ °C	Additive	Yield[b]/%
1	$Pd(OAc)_2$	–	130	–	0
2	$Pd(OAc)_2$	Cs_2CO_3	130	$CHCl_3$	20
3	$Pd(OAc)_2$	Cs_2CO_3	170	$CHCl_3$	34
4	$Pd(OAc)_2$	KF	170	–	< 5
5	$Pd(OAc)_2$	KF	170	AcOH	< 5
6	$Pd(OAc)_2$	K_3PO_4	170	–	0
7	$Pd_2dba_3 \cdot CHCl_3$	–	130	–	0
8	$Pd_2dba_3 \cdot CHCl_3$	K_3PO_4	170	–	58
9	$Pd_2dba_3 \cdot CHCl_3$	KF	170	–	40
10	$Pd(PPh_3)_4$	KF	170	–	0

a) Reaction conditions: Pd catalyst (5 mole %), PPh_3 (10 mole %), $PhB(OH)_2$ (3 eq), base (3 eq), MWI, 10 min; *b*) isolated pure product *II*.

et al., 2007), *XXV*, and *XXVI* (Arnold et al., 2000) were prepared according to literature procedures.

Typical procedure for Pd-catalysed conjugate addition of ArB(OH)$_2$ under MWI

$Pd(OAc)_2$ (5 mole %, 5.6 mg, 0.025 mmol) and 2,2′-bipyridine (bpy) (20 mole %, 15.6 mg, 0.1 mmol) were added to a solution of cyclohex-2-enone (*I*) (48.0 mg, 0.5 mmol), arylboronic acid (1.5 mmol), and KF (1.5 mmol, 87.1 mg) in toluene (1 mL), water (0.3 mL), and AcOH (1 mL) under argon. The reaction mixture in a sealed vessel was heated to 170 °C by microwave irradiation in the reactor for 10 min. The reaction mixture was then cooled and neutralised with saturated $NaHCO_3$ (20 mL). The organic layer was extracted with Et_2O (3 × 15 mL). The combined organic extracts were washed with brine, dried (Na_2SO_4), and concentrated under diminished pressure. Flash chromatography (SiO_2, hexane/EtOAc ($\varphi_r = 9 : 1$)) of the crude reaction mixture afforded the product, which was identified by comparison of its ^{1}H NMR spectrum with literature data.

Results and discussion

Our preliminary studies focused on optimisation of the reaction conditions, which included the effect of reaction temperature, time, solvent, palladium precursors, and ligands. The conjugate addition of phenylboronic acid to cyclohex-2-enone (*I*) was chosen as a model reaction (Fig. 1). The aim was to find a simple catalytic system affording high chemical yields in the shortest possible time.

The initial studies were conducted with PPh_3 as ligand. The addition of phenylboronic acid to *I* carried out in the presence of $Pd(OAc)_2$ and PPh_3 gave complicated reaction mixtures, which consisted mostly of the starting materials and biphenyl (homocoupling product of phenylboronic acid) (Table 2, entries 1–6). Of the three simple Pd sources and typical bases used in additions of arylboronic acids, $Pd_2(dba)_3$ in conjunction with K_3PO_4 gave product *II* in the highest yield (58 %) (Table 2, entry 8).

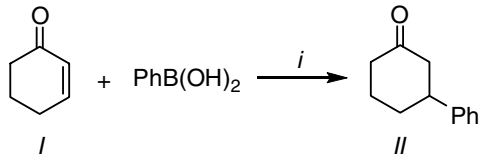


Fig. 1. Conjugate addition of phenylboronic acid to cyclohex-2-enone (*I*). Reaction conditions: *i*) [Pd]/L, toluene/H_2O, MWI.

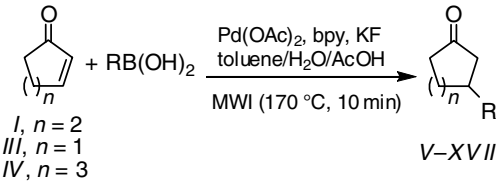
It was shown that 2,2′-bipyridine (bpy) as the ligand had a beneficial effect on the conjugate addition of arylboronic acids to α,β-unsaturated carbonyl compounds by inhibiting β-hydride elimination (Lin & Lu, 2006). We therefore decided to evaluate Pd-bpy complex as the catalyst in the test reaction. However, $Pd(OAc)_2$ and bpy under MWI (130 °C, 10 min) afforded only the starting material. A paper by Lin and Lu inspired us to examine the effect of acetic acid as an additive (Lu & Lin, 2005). The addition of acetic acid to the reaction mixture in the solvent/H_2O did lead to higher yields of 3-phenylcyclohexanone (*II*) (32 % yield in toluene/H_2O, 55 % in THF/H_2O). In anhydrous THF, the results were less remarkable (46 % yield). Interestingly, the addition of acetic acid had no effect on the catalytic system with PPh_3 (Table 2, entry 5). Subsequently, we tested bases using the $Pd(OAc)_2$/bpy catalytic system in the solvent mixture of toluene, water, and acetic acid. Cesium carbonate only afforded a 10 % yield of 3-phenylcyclohexanone (Table 3, entry 8). Chloroform was also documented as a useful additive in the conjugate addition of arylboronic acids (Suzuma et al., 2007). However, in our system, $CHCl_3$ only led to a low yield of product *II* both in Pd $(OAc)_2$, and PPh_3 as well as $Pd(OAc)_2$ and bpy (Table 2, entries 2 and 3; Table 3, entries 5 and 9). On the other hand, the catalytic system $Pd(OAc)_2$/bpy with K_3PO_4 as a base in the presence of acetic acid gave 73 % yield under MWI (170 °C, 10

Table 3. Effect of Pd compounds and bases on the Pd-catalysed 1,4-addition of $PhB(OH)_2$ to enone *I* with bpy as the ligand[a]

Entry	Catalyst	Base	Temperature/°C	Additive	Yield[b]/%
1	$Pd(OAc)_2$	–	130	–	0
2	$Pd(OAc)_2$	–	130	AcOH	32
3	$Pd(OAc)_2$	–	130	THF, H_2O, AcOH	55
4	$Pd(OAc)_2$	KF	170	–	35
5	$Pd(OAc)_2$	KF	170	$CHCl_3$	39
6	$Pd(OAc)_2$	KF	170	AcOH	74
7	$Pd(OAc)_2$	K_3PO_4	170	AcOH	73
8	$Pd(OAc)_2$	Cs_2CO_3	170	AcOH	10
9	$Pd_2dba_3 \cdot CHCl_3$	–	170	AcOH	5
10	$Pd_2dba_3 \cdot CHCl_3$	–	130	–	0
11	$Pd(OAc)_2$	KF	170	AcOH	18[c]

a) Reaction conditions: Pd catalyst (5 mole %), bpy (10 mole %), $PhB(OH)_2$ (3 eq), base (3 eq), MWI, 10 min; *b*) isolated pure products after flash chromatography; *c*) control experiment performed by conventional heating (170 °C, oil bath, 10 min).

Table 4. Conjugate addition of arylboronic acids to cyclic enones



Compound	*n*	R	Yield/%
V	1	phenyl	71
VI	1	3-chlorophenyl	62
VII	1	4-chlorophenyl	73
VIII	1	4-trifluoromethylphenyl	44
IX	1	1-naphthyl	14
X	2	3-chlorophenyl	71
XI	2	4-chlorophenyl	83
XII	2	4-fluorophenyl	48
XIII	2	4-trifluoromethylphenyl	57
XIV	2	1-naphthyl	16
XV	3	phenyl	34
XVI	3	1-naphthyl	18
XVII	3	4-chlorophenyl	38

min). The control experiment (conjugate addition of phenylboronic acid to *I*) performed by conventional heating in an oil bath (170 °C, 10 min) mimicking the microwave conditions gave only an 18 % yield of product *II* (Table 3, entry 11).

Having established good experimental conditions for the addition of phenylboronic acid to *I*, we then investigated the conjugate addition of several arylboronic acids to cyclic enones (Table 4). The reactions of phenylboronic acid substituted with electron-withdrawing substituents, such as chloro-, fluoro-, and trifluoromethyl, resulted in moderate to good yields (39–83 %) of the corresponding addition products (*VI–VIII*, *X–XIII*, *XVII*). Cyclopent-2-enone (*III*) and *I* gave comparable yields of addition products,

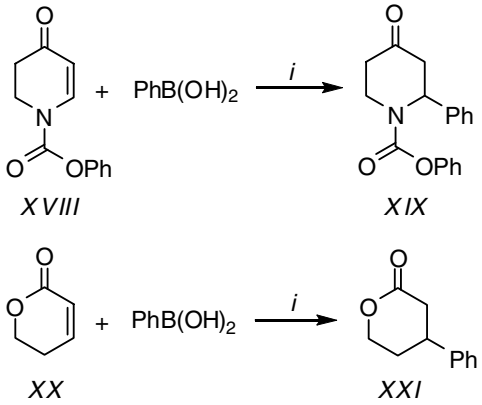


Fig. 2. Conjugate addition of phenylboronic acid to functionalised enones. Optimised reaction conditions: *i*) $Pd(OAc)_2$, bpy, KF, AcOH/toluene/H_2O, MWI (170 °C, 10 min).

while the reactivity of cyclohept-2-enone (*IV*) was lower. Only traces of the addition product with 4-methoxyphenylboronic acid were observed by NMR. Similarly, 1-naphthylboronic acid was less reactive with all enones, and the corresponding products *IX*, *XIV*, and *XVI* were isolated in low yields. A possible reason for the lower reactivity could be a more pronounced steric effect of 1-naphthylboronic acid. This effect was already noted in Pd-catalysed coupling reactions of sterically hindered arylboronic acids (Cammidge & Crépy, 2004; Genov et al., 2006). In this case, we also examined CsF as a base, but the yield of *XIV* was even lower (13 %).

Functionalised substrates, *XVIII* and *XX*, were also submitted to the conjugate addition under optimised conditions (Fig. 2). The resulting products, *XIX* and *XXI*, were isolated in rather low yields (10 % and 18 %, respectively). Compounds such as *XVIII* and *XX* are generally less reactive in conjugate additions; therefore, more energetic conditions would be required to achieve higher product yields.

We also inquired whether a chiral ligand rather

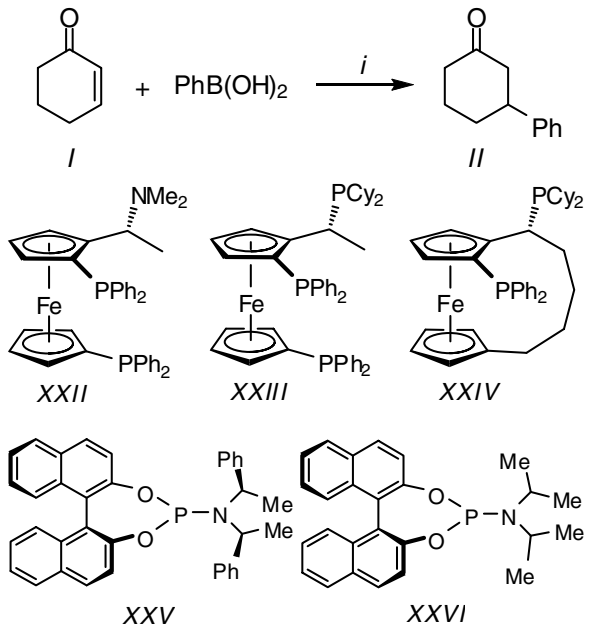


Fig. 3. Conjugate addition of phenylboronic acid to enone *I* using chiral ligands. Reaction conditions: *i*) $Pd_2(dba)_2 \cdot CHCl_3$, ligand (*XXII–XXVI*), $K_3PO_4 \cdot H_2O$, toluene/H_2O, MWI, 10 min.

Table 5. Screening of selected chiral ligands in the addition of $PhB(OH)_2$ to enone I^a

Entry	Ligand	Yield[b]/%	ee[c]/%
1	*XXII*	12	49 (*S*)
2	*XXIII*	21	46 (*S*)
3	*XXIV*	37	85 (*S*)
4	*XXV*	21	19 (*R*)
5	*XXVI*	37	12 (*R*)

a) Reaction conditions: $Pd(OAc)_2$ (5 mole %), chiral ligand (10 mole %), $PhB(OH)_2$ (3 eq), K_3PO_4 (3 eq), MWI; *b*) isolated pure product *II*; *c*) determined by HPLC.

than bpy would induce a reasonable level of enantioselectivity under MWI conditions. Five representative chiral ligands *XXII–XXVI* were tested in the addition of phenylboronic acid to *I* (Fig. 3). With ferrocenyl diphosphane ligands *XXII–XXIV*, the product (*S*)-*II* was isolated with promising enantioselectivities (up to 85 % ee). Under anhydrous conditions, using CsF as the base, yields as well as enantioselectivity were lower (10 % yield, 50 % ee). Although higher enantioselectivities have been reported in several cases under conventional conditions (Gini et al., 2005; Xu et al., 2010), the result obtained with ligand *XXIV* under MWI conditions is interesting and potentially useful. The use of phosphoramidite ligands *XXV* and *XXVI* led to only 19 % and 12 % ee, respectively. However, it should be noted that the reaction conditions using the above ligands were not optimised. Table 5 summarises the results of the screening of chiral ligands.

Conclusions

In conclusion, we report the first microwave-assisted Pd-catalysed conjugate addition of arylboronic acids to α,β-unsaturated cyclic ketones. The employment of a commercially available and inexpensive catalytic system consisting of $Pd(OAc)_2$/bpy in combination with KF as the base in a mixture of toluene/water/acetic acid led to good yields of addition products. A range of arylboronic acids may be added to α,β-unsaturated ketones. Compared with conventional heating, the microwave-assisted reactions proceed with good yields in dramatically shorter reaction times (10 min). Less reactive functionalised substrates may also be used, although product yields were lower under comparable conditions. Catalysts with chiral ferrocene diphosphane ligands afford an interesting level of enantiomeric purity of the addition product (up to 85 % ee).

Acknowledgements. Part of this work was funded by the Slovak Scientific Grant Agency, VEGA grant No. 1/0265/09. NMR measurements were provided within the frame of Slovak State Programme, Project No. 2003SP200280203.

References

Almansa, R., Guijarro, D., & Yus, M. (2008). Microwave-accelerated enantioselective addition of dialkylzinc reagents to *N*-(diphenylphosphinoyl)imines catalysed by β-aminoalcohols with the prolinol skeleton. *Tetrahedron: Asymmetry*, *19*, 1376–1380. DOI: 10.1016/j.tetasy.2008.05.005.

Almássy, A., Barta, K., Franciò, G., Šebesta, R., Leitner, W., & Toma, Š. (2007). [5]Ferrocenophane based ligands for stereoselective Rh-catalyzed hydrogenation and Cu-catalyzed Michael addition. *Tetrahedron: Asymmetry*, *18*, 1893–1898. DOI: 10.1016/j.tetasy.2007.08.011.

Alonso, F., Beletskaya, I. P., & Yus, M. (2008). Non-conventional methodologies for transition-metal catalysed carbon–carbon coupling: a critical overview. Part 2: The Suzuki reaction. *Tetrahedron*, *64*, 3047–3101. DOI: 10.1016/j.tet.2007.12.036.

Arnold, L. A., Imbos, R., Mandoli, A., de Vries, A. H. M., Naasz, R., & Feringa, B. L. (2000). Enantioselective catalytic conjugate addition of dialkylzinc reagents using copper–phosphoramidite complexes; ligand variation and non-linear effects. *Tetrahedron*, *56*, 2865–2878. DOI: 10.1016/s0040-4020(00)00142-3.

Barge, A., Tagliapietra, S., Tei, L., Cintas, P., & Cravotto, G. (2008). Pd-catalyzed reactions promoted by ultrasound and/or microwave irradiation. *Current Organic Chemistry*, *12*, 1588–1612. DOI: 10.2174/138527208786786327.

Bedford, R. B., Betham, M., Charmant, J. P. H., Haddow, M. F., Orpen, A. G., Pilarski, L. T., Coles, S. J., & Hursthouse, M. B. (2007). Simple palladacyclic and platinacyclic catalysts for the 1,4-conjugate addition of arylboronic acids and arylsiloxanes to enones. *Organometallics*, *26*, 6346–6353. DOI: 10.1021/om700724c.

Cammidge, A. N., & Crépy, K. V. L. (2004). Synthesis of chiral binaphthalenes using the asymmetric Suzuki reaction. *Tetrahedron*, *60*, 4377–4386. DOI: 10.1016/j.tet.2003.11.095.

Cho, C. S., Motofusa, S.-i., Ohe, K., Uemura, S., & Shim, S. C. (1995). A new catalytic activity of antimony(III) chloride in palladium(0)-catalyzed conjugate addition of aromatics to α,β-unsaturated ketones and aldehydes with sodium

tetraphenylborate and arylboronic acids. *The Journal of Organic Chemistry*, *60*, 883–888. DOI: 10.1021/jo00109a019.

Comins, D. L., Brooks, C. A., & Ingalls, C. L. (2001). Reduction of *N*-acyl-2,3-dihydro-4-pyridones to *N*-acyl-4-piperidones using zinc/acetic acid. *The Journal Organic Chemistry*, *66*, 2181–2182. DOI: 10.1021/jo001609l.

Fujio, M., Tanaka, M., Wu, X.-M., Funakoshi, K., Sakai, K., & Suemune, H. (1998). ortho-Halogeno substituents effect in asymmetric cyclization of 4-aryl-4-pentenals using a rhodium catalyst. *Chemistry Letters*, *27*, 881–882. DOI: 10.1246/cl.1998.881.

Gavande, N., Johnston, G. A. R., Hanrahan, J. R., & Chebib, M. (2010). Microwave-enhanced synthesis of 2,3,6-trisubstituted pyridazines: application to four-step synthesis of gabazine (SR-95531). *Organic and Biomolecular Chemistry*, *8*, 4131–4136. DOI: 10.1039/C0OB00004C.

Genov, M., Almorín, A., & Espinet, P. (2007). Microwave assisted asymmetric Suzuki-Miyaura and Negishi cross-coupling reactions: synthesis of chiral binaphthalenes. *Tetrahedron: Asymmetry*, *18*, 625–627. DOI: 10.1016/j.tetasy.2007.03.001.

Genov, M., Almorín, A., & Espinet, P. (2006). Efficient synthesis of chiral 1,1′-binaphthalenes by the asymmetric Suzuki–Miyaura reaction: Dramatic synthetic improvement by simple purification of naphthylboronic acids. *Chemistry – A European Journal*, *12*, 9346–9352. DOI: 10.1002/chem.200600616.

Genov, M., Salas, G., & Espinet, P. (2008). Effect of microwave heating in the asymmetric addition of dimethylzinc to aldehydes. *Journal of Organometallic Chemistry*, *693*, 2017–2020. DOI: 10.1016/j.jorganchem.2008.03.003.

Gini, F., Hessen, B., & Minnaard, A. J. (2005). Palladium-catalyzed enantioselective conjugate addition of arylboronic acids. *Organic Letters*, *7*, 5309–5312. DOI: 10.1021/ol052222d.

Gutnov, A. (2008). Palladium-catalyzed asymmetric conjugate addition of aryl–metal species. *European Journal of Organic Chemistry*, *2008*, 4547–4554. DOI: 10.1002/ejoc.200800541.

Gutsche, C. D., Strohmayer, H. F., & Chang, J. M. (1958). Ring enlargements VI. The diazomethane-carbonyl reaction: Product ratios from the reactions of diazomethane with various substituted 2-phenylcyclohexanons. *The Journal Organic Chemistry*, *23*, 1–5. DOI: 10.1021/jo01095a001.

Hayashi, T., Mise, T., Fukushima, M., Kagotani, M., Nagashima, N., Hamada, Y., Matsumoto, A., Kawakami, S., Konishi, M., Yamamoto, K., & Kumada, M. (1980). Asymmetric synthesis catalyzed by chiral ferrocenylphosphine–transition metal complexes. I. Preparation of chiral ferrocenylphosphines. *Bulletin of the Chemical Society of Japan*, *53*, 1138–1151. DOI: 10.1246/bcsj.53.1138.

He, P., Lu, Y., Dong, C.-G., & Hu, Q.-S. (2007). Anionic four-electron donor-based palladacycles as catalysts for addition reactions of arylboronic acids with α,β-unsaturated ketones, aldehydes, and α-ketoesters. *Organic Letters*, *9*, 343–346. DOI: 10.1021/ol062814b.

Helan, V., Mills, A., Drewry, D., & Grant, D. (2010). A rapid three-component MgI_2-mediated synthesis of 3,3-pyrollidinyl spirooxindoles. *The Journal of Organic Chemistry*, *75*, 6693–6695. DOI: 10.1021/jo101077g.

Itooka, R., Iguchi, Y., & Miyaura, N. (2003). Rhodium-catalyzed 1,4-addition of arylboronic acids to α,β-unsaturated carbonyl compounds: Large accelerating effects of bases and ligands. *The Journal of Organic Chemistry*, *68*, 6000–6004. DOI: 10.1021/jo0207067.

Kantam, M. L., Subrahmanyam, V. B., Kumar, K. B. S., Venkanna, G. T., & Sreedhar, B. (2008). Rhodium fluoroapatite catalyzed conjugate addition of arylboronic acids to α,β-unsaturated carbonyl compounds. *Helvetica Chimica Acta*, *91*, 1947–1953. DOI: 10.1002/hlca.200890208.

Kappe, C. O. (2004). Controlled microwave heating in modern organic synthesis. *Angewandte Chemie International Edition*, *43*, 6250–6284. DOI: 10.1002/anie.200400655.

Kappe, C. O., & Dallinger, D. (2009). Controlled microwave heating in modern organic synthesis: highlights from the 2004–2008 literature. *Molecular Diversity*, *13*, 71–193. DOI: 10.1007/s11030-009-9138-8.

Kappe, C. O., Dallinger, D., & Murphree, S. S. (2009). *Practical microwave synthesis for organic chemists: Strategies, instruments, and protocols*. Weinheim, Germany: Wiley–VCH.

Kappe, C. O., & Stadler, A. (2005). *Microwaves in organic and medicinal chemistry* (Series: *Methods and principles in medicinal chemistry*, Vol. *25*). Weinheim, Germany: Wiley–VCH.

Kováčová, S., Kováčiková, L., Lácová, M., Boháč, A., & Sališová, M. (2010). Microwave assisted one pot synthesis of 7-substituted 2-(2-oxo-2*H*-chromen-3-yl)acetic acids as precursors of new anti-tumour compounds. *Chemical Papers*, *64*, 806–811. DOI: 10.2478/s11696-010-0059-x.

Larhed, M., Moberg, C., & Hallberg, A. (2002). Microwave-accelerated homogeneous catalysis in organic chemistry. *Accounts of Chemical Research*, *35*, 717–727. DOI: 10.1021/ar010074v.

Lin, S., & Lu, X. (2006). Palladium–bipyridine catalyzed conjugate addition of arylboronic acids to α,β-unsaturated carbonyl compounds in aqueous media. *Tetrahedron Letters*, *47*, 7167–7170. DOI: 10.1016/j.tetlet.2006.07.154.

Lu, X., & Lin, S. (2005). Pd(II)-bipyridine catalyzed conjugate addition of arylboronic acid to α,β-unsaturated carbonyl compounds. *The Journal of Organic Chemistry*, *70*, 9651–9653. DOI: 10.1021/jo051561h.

Mariz, R., Luan, X., Gatti, M., Linden, A., & Dorta, R. (2008). A chiral bis-sulfoxide ligand in late-transition metal catalysis; rhodium-catalyzed asymmetric addition of arylboronic acids to electron-deficient olefins. *Journal of the American Chemical Society*, *130*, 2172–2173. DOI: 10.1021/ja710665q.

Nishikata, T., Yamamoto, Y., & Miyaura, N. (2004). 1,4-Addition of arylboronic acids and arylsiloxanes to α,β-unsaturated carbonyl compounds via transmetalation to dicationic palladium(II) complexes. *Organometallics*, *23*, 4317–4324. DOI: 10.1021/om0498044.

Poláčková, V., & Toma, Š. (2007). Effect of microwave irradiation on the reactivity of chloroarenes in Suzuki—Miyaura reaction. *Chemical Papers*, *61*, 41–45. DOI: 10.2478/s11696-006-0093-x.

Poláčková, V., Toma, Š., & Augustínová, I. (2006). Microwave-promoted cross-coupling of acid chlorides with arylboronic acids: a convenient method for preparing aromatic ketones. *Tetrahedron*, *62*, 11675–11678. DOI: 10.1016/j.tet.2006.09.055.

Poláčková, V., Toma, Š., & Kappe, C. O. (2007). Microwave-assisted arylation of *rac*-(*E*)-3-acetoxy-1,3-diphenylprop-1-ene with arylboronic acids. *Tetrahedron*, *63*, 8742–8745. DOI: 10.1016/j.tet.2007.06.045.

Shintani, R., Duan, W.-L., Nagano, T., Okada, A., & Hayashi, T. (2005). Chiral phosphine–olefin bidentate ligands in asymmetric catalysis: Rhodium-catalyzed asymmetric 1,4-addition of aryl boronic acids to maleimides. *Angewandte Chemie International Edition*, *44*, 4611–4614. DOI: 10.1002/anie.200501305.

Singh, B. K., Kaval, N., Tomar, S., van der Eycken, E., & Parmar, V. S. (2008). Transition metal-catalyzed carbon–carbon bond formation Suzuki, Heck, and Sonogashira reactions using microwave and microtechnology. *Organic Process Research & Development*, *12*, 468–474. DOI: 10.1021/op800047f.

Suzuma, Y., Yamamoto, T., Ohta, T., & Ito, Y. (2007). Asymmetric 1,4-addition reaction of arylboronic acid to enone catalyzed by palladium with ferrocene-based phosphine ligand. *Chemistry Letters*, *36*, 470–471. DOI: 10.1246/cl.2007.470.

Takaya, Y., Ogasawara, M., & Hayashi, T. (1999). Rhodium-catalyzed asymmetric 1,4-addition of arylboron compounds generated *in situ* from aryl bromides. *Tetrahedron Letters*, *40*, 6957–6961. DOI: 10.1016/s0040-4039(99)01412-4.

Takaya, Y., Ogasawara, M., Hayashi, T., Sakai, M., & Miyaura, N. (1998). Rhodium-catalyzed asymmetric 1,4-addition of aryl- and alkenylboronic acids to enones. *Journal of the American Chemical Society*, *120*, 5579–5580. DOI: 10.1021/ja980666h.

Tierney, J. P., & Lidström, P. (Eds.) (2005). *Microwave assisted organic synthesis*. Oxford, UK: Wiley–Blackwell.

Togni, A., Breutel, C., Schnyder, A., Spindler, F., Landert, H., & Tijani, A. (1994). A novel easily accessible chiral ferrocenyldiphosphine for highly enantioselective hydrogenation, allylic alkylation, and hydroboration reactions. *Journal of the American Chemical Society*, *116*, 4062–4066. DOI: 10.1021/ja00088a047.

Vandyck, K., Matthys, B., Willen, M., Robeyns, K., Van Meervelt, L., & Van der Eycken, J. (2006). Rhodium-catalyzed asymmetric conjugate additions of boronic acids to enones using DIPHONANE: A novel chiral bisphosphine ligand. *Organic Letters*, *8*, 363–366. DOI: 10.1021/ol0522788.

Veverková, E., & Toma, Š. (2008). Study of CuI catalyzed coupling reactions of aryl bromides with imidazole and aliphatic amines under microwave dielectric heating. *Chemical Papers*, *62*, 334–338. DOI: 10.2478/s11696-008-0033-z.

Xu, Q., Zhang, R., Zhang, T., & Shi, M. (2010). Asymmetric 1,4-addition of arylboronic acids to 2,3-dihydro-4-pyridones catalyzed by axially chiral NHC–Pd(II) complexes. *The Journal of Organic Chemistry*, *75*, 3935–3937. DOI: 10.1021/jo1006224.

Yamamoto, T., Iizuka, M., Ohta, T., & Ito, Y. (2006). Palladium catalyzed conjugate 1,4-addition of organoboronic acids to α,β-unsaturated ketones. *Chemistry Letters*, *35*, 198–199. DOI: 10.1246/cl.2006.198.