

Electronic Supplementary Information

A Recyclable Perfluoroalkylated PCP Pincer Palladium Complex

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Table 3. Selected bond lengths (Å) and bond angles (°) with estimated standard deviations in parenthesis for [NiCl(PCP)] **12**, [NiBr(PCP)], [PdCl(PCP)] and [PtCl(PCP)]

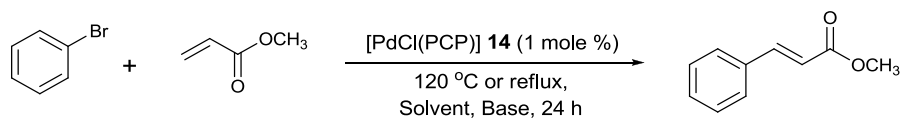
	[NiCl(PCP)]	[NiBr(PCP)] ^a	[PdCl(PCP)] ^b	[PtCl(PCP)] ^c
M-X	2.1979(13)	2.3290(5)	2.367(3)	2.3831(10)
M-P(1)	2.1693(14)	2.177(1)	2.288(3)	2.2794(9)
M-P(2)	2.1732(13)	2.173(1)	2.294(3)	2.2749(10)
M-C(1)	1.923(4)	1.920(3)	1.998(8)	2.002(3)
P(1)-M-P(2)	164.81(5)	165.14(3)	162.0(1)	163.11(3)
C(1)-M-X	178.39(12)	179.75(9)	178.7(3)	178.53(9)
P(1)-M-X	97.11(5)	97.81(3)	98.1(1)	99.51(3)
P(2)-M-X	98.01(5)	96.88(2)	99.9(1)	97.31(4)
C(1)-M-P(1)	82.50(13)	82.1(1)	81.3(3)	81.04(9)
C(1)-M-P(2)	82.43(13)	83.2(1)	80.8(3)	82.18(9)

^a Data taken from ref. 21; ^b data taken from ref. 22; ^c data taken from ref. 23.

Optimisation of the Heck reaction between bromobenzene and methyl acrylate

Since a number of solvent systems and different bases, organic and inorganic, have been used successfully in Heck reactions, a solvent-base screen was first carried out for the model Heck reaction between bromobenzene and methyl acrylate. Using SIMCA, a Design of Experiment (DoE) software package, a range of solvents were characterised by polarity and a range of bases were characterised by basicity. The solvents and bases were then paired in such a way to cover all the different combinations of the different factors i.e. a polar solvent with a base with a low pK_a, a polar solvent with a base with a high pK_a, a non-polar solvent with a base with a low pK_a, a non-polar solvent with a base with a high pK_a.

Table 4. Results from solvent/organic base screen



Entry	Temp. (°C)	Solvent	Organic Base	Yield (%) ^a
1	120	Ethylene glycol	Diethylamine	6.2 ^b
2	67	THF	Piperidine	3.8
3	120	<i>n</i> -Butyl acetate	<i>t</i> -Butylamine	2.9
4	83	<i>t</i> -Butanol	DIPEA	2.2
5	82	Acetonitrile	DBU	1.9
6	102	Dioxane	DBN	1.8
7	120	Di(ethylene glycol) dimethyl ether	2,6-Di- <i>tert</i> -butylpyridine	1.0
8	120	Formamide	Isoquinoline	0.6 ^b
9	81	Cyclohexane	DMAP	0.6
10	102	Dioxane	2,6-Di- <i>tert</i> -butylpyridine	0.5
11	81	Cyclohexane	4-Methylmorpholine	0.5 ^b
12	120	DMF	Dicyclohexylamine	0.4
13	82	2-Propanol	4-Methylcyclohexylamine	0.4
14	120	3-Methyl-1-butanol	2,6-Lutidine	0.4
15	120	Mesitylene	DABCO	0.3
16	69	Diisopropyl ether	Diphenylamine	0.3
17	120	NMP	Triisopropylamine	0.3
18	120	3-Methyl-1-butanol	2,4,6-Collidine	0.2
19	80	Butanone	Pyridine	0.1
20	111	Toluene	<i>N</i> -Methylpiperidine	0.1

^a Determined by assay by HPLC; ^b Palladium black present.

The organic bases were screened first using 1 mole % of the non-fluorinated pincer palladium complex **14** at 120 °C or reflux, if the boiling point of the solvent was lower, for 24 hours. The reaction mixtures were analysed by HPLC and LC-MS and the results are summarised in Table 4. All of the results were disappointing and only 6 out of 20 experiments gave a yield that was > 1 %. The DoE software was used to interpret the experimental data from Table 4 and it indicated that bases with a high pK_a should give the highest yield. Consequently, a series of inorganic bases with

a high pKa were selected and screened for the model Heck reaction (Table 5). Since all of the reactions gave very low yields (<2 %), potassium hydrogen carbonate was evaluated as a mild base in a range of organic solvents. Due to the low solubility of potassium hydrogen carbonate in organic solvents, a phase transfer catalyst, tetra-*n*-butylammonium bromide (TBAB), was also screened in order to help transfer the base into the organic solvent (Figure 5).

Table 5. Solvent/base screen using strong inorganic bases

Entry	Solvent	Base	Yield (%) ^a
1	NMP	Potassium <i>t</i> -butoxide	1.5
2	Dioxane	Cesium hydroxide	0.2
3	THF	Sodium methoxide	0.1
4	Toluene	Sodium amide	0.1

^a Determined by assay by HPLC.

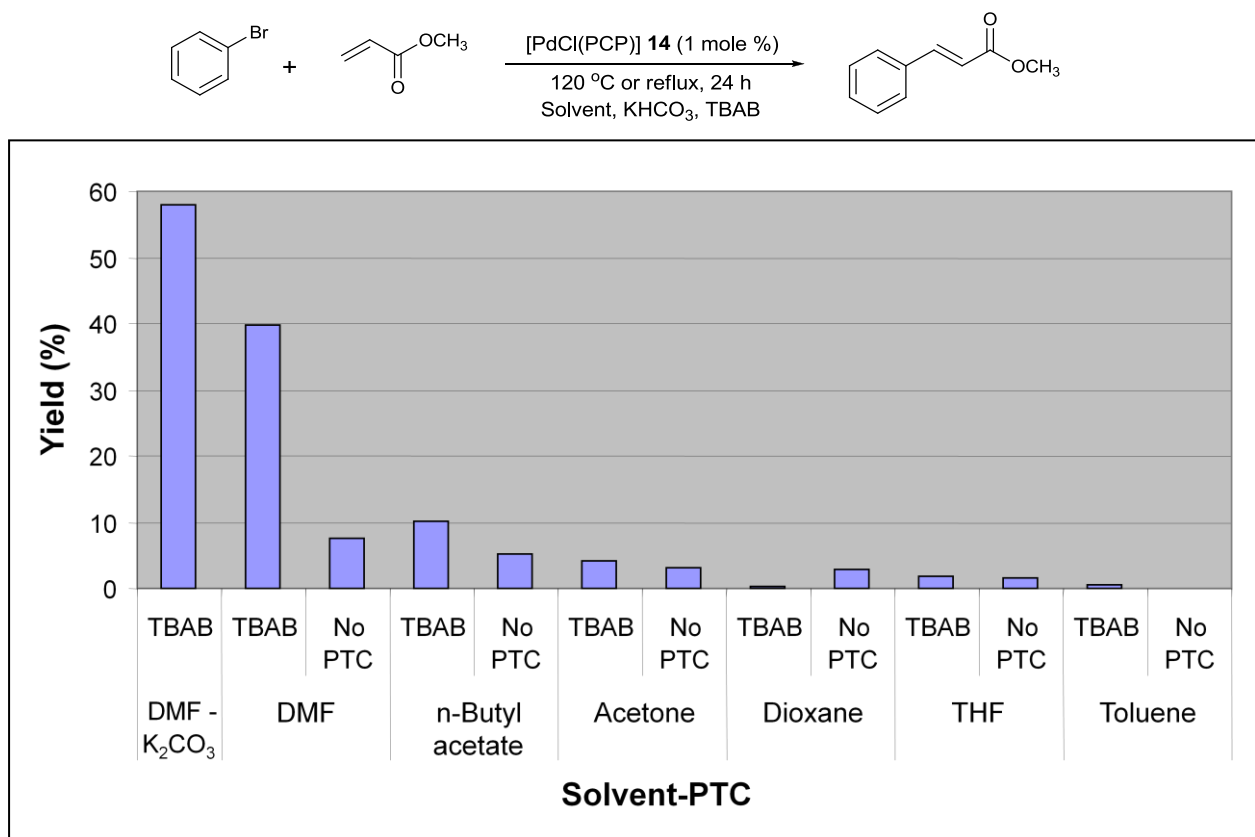


Figure 5. Solvent screen with potassium hydrogen carbonate with and without the phase transfer catalyst, TBAB

Not all of the reactions in Figure 5 yielded product, but there was a general increase in the reaction yield and the reactions that contained TBAB gave higher yields of the product than the reactions that did not contain a phase transfer catalyst. When the reaction was carried out in DMF with TBAB, a 40 % yield was obtained which was by far the best result achieved so far. Potassium carbonate is a stronger base than potassium hydrogen carbonate and so, it was screened under the same reaction conditions in DMF with TBAB and the yield increased to 58 %. Since potassium carbonate gave the best yield, a series of dipolar aprotic solvents were then screened with potassium carbonate as the base and TBAB as the phase transfer catalyst (Figure 6). NMP, DMF and DMA all gave good yields of the product with NMP being the best solvent (62 % yield).

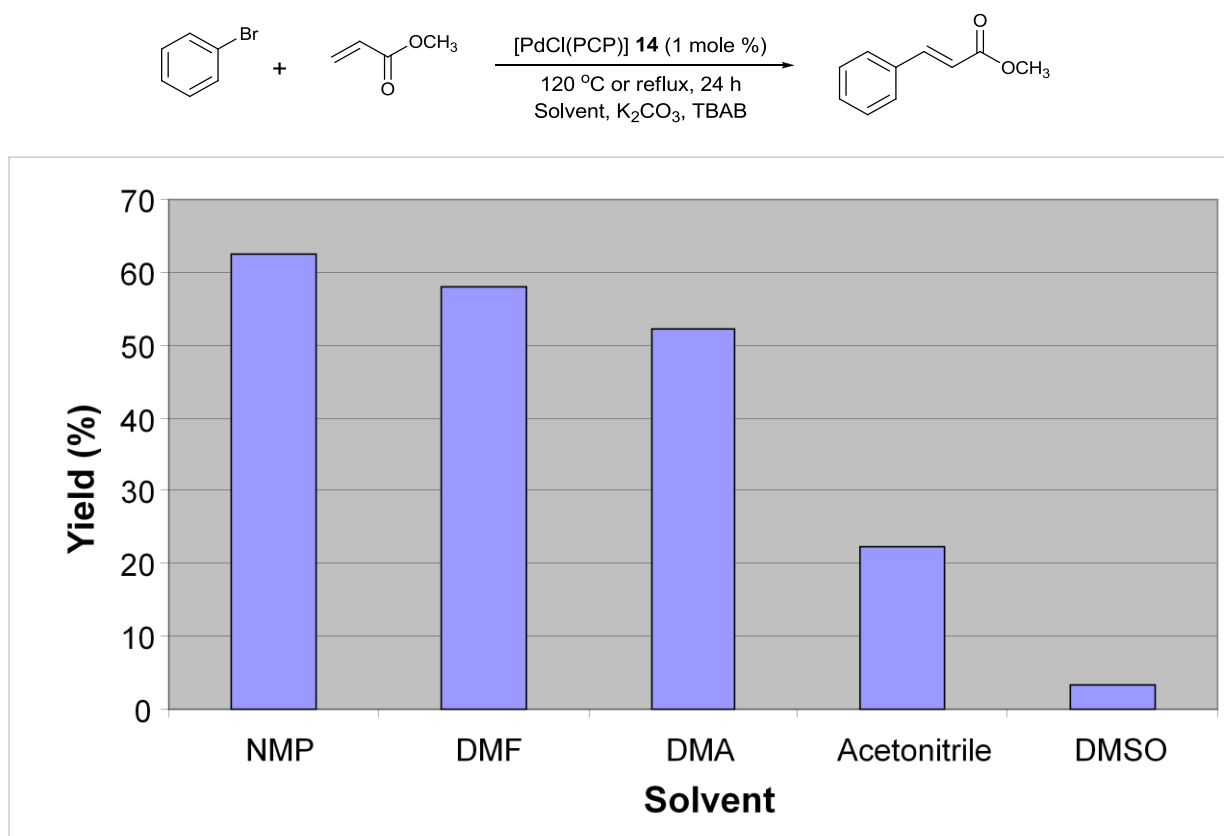


Figure 6. Solvent screen of dipolar aprotic solvents with potassium carbonate and TBAB

Finally, a series of phase transfer catalysts with different cations and anions were investigated (Figure 7). Initially, the anion of the phase transfer cation was varied whilst the organic cation was kept as the tetra-*n*-butylammonium cation. Both bromide and chloride anions gave the product in good yield, but much lower yields were obtained with hydrogen sulphate and iodide anions. The cation component was also varied, but the best results were obtained with the more organophilic tetra-*n*-butylammonium cation, which presumably has the highest solubility in NMP. Finally, potassium hydrogen carbonate was evaluated in the reaction with NMP and TBAB giving the most

successful reaction with the highest yield (70 %).

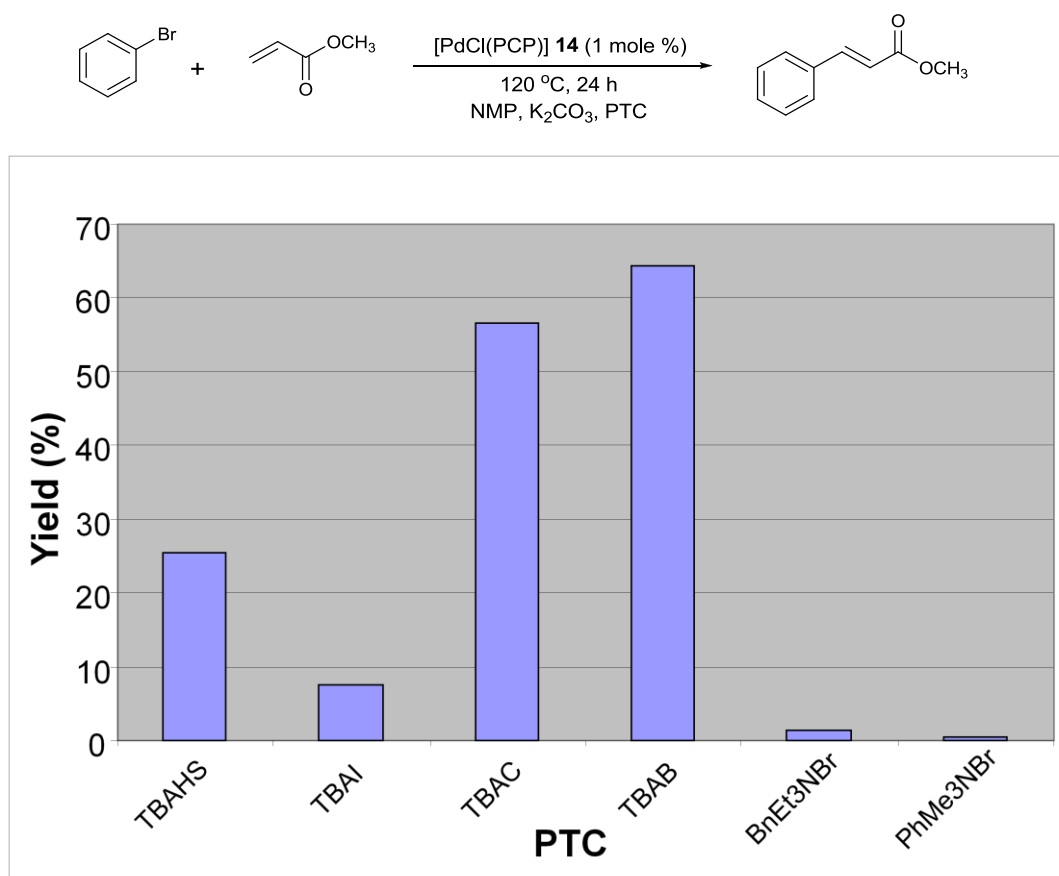


Figure 7. Screen of phase transfer catalysts with NMP and potassium carbonate

Experimental

General procedure for solvent/base/PTC screen for Heck reaction using Microvate reactor

[PdCl(PCP)] **14** (3.0 mg, 1 mole %, 0.0048 mmol), solid bases (0.48 mmol) and PTC (0.096 mmol) were added to microvate reaction tubes. The microvate tubes were purged with argon for 30 min before bromobenzene (0.0754 g, 0.48 mmol), methyl acrylate (0.0517 g, 0.60 mmol), any liquid bases (0.48 mmol) and solvent (1.0 mL) were added. They were heated to 120 °C (or reflux if the boiling point of the solvent was <120 °C) for 24 h. After cooling the tubes to room temperature, the reaction mixtures were poured into 25 mL volumetric flasks and methanol was added. Samples were taken and analysed by HPLC and yields of product were determined by assay. HPLC was conducted on a Agilent 1100 fitted with a Phenomenex Luna C18(2) column (3 µm, 50 mm x 2.0 mm) using 0.05 % v/v TFA in water and 0.05% v/v TFA in acetonitrile as eluants with a 0 % acetonitrile to 95 % acetonitrile gradient over 8 minutes. Detector: UV at 220 nm; temperature: 40 °C; flow rate: 1.0 mL min⁻¹ for 10 min. R_t 4.8 min (*trans*-methyl cinnamate), 5.1 min (bromobenzene).

References

21. F. Bachechi, *Structural Chem.*, 2003, **14**, 263.
22. F. Gorla, L. M. Venanzi, A. Albinati, *Organometallics*, 1994, **13**, 43.
23. S. Fischer, O. F. Wendt, *Acta Cryst.*, 2004, E**60**, m69.