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Tetrahedron Letters 46 (2005) 2483–2485

Tetrahedron Letters

Low temperature recyclable catalyst for Heck reactions using ultrasound

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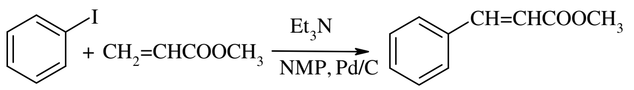
Received 8 December 2004; revised 1 February 2005; accepted 7 February 2005

Abstract—The Heck reaction of iodobenzene with methyl acrylate in NMP as a solvent has been studied using Pd/C as a catalyst in the presence of ultrasound at room temperature. The ultrasound increased the rate of the reaction. The effect of base, solvent and recyclability of catalyst were studied in the presence of ultrasound and without ultrasound. The reaction only takes place in the presence of ultrasound. The catalyst could be recycled using HCOONa-ultrasound.

The Heck reaction has received much attention in recent years as it offers a versatile method for the generation of new carbon–carbon bonds.[1] The reaction is normally carried out with a palladium catalyst, a phosphine ligand and a base in homogeneous solution. However, the phosphine ligands are sensitive to oxygen and a homogeneous system has major drawbacks related to product/catalyst separation and catalyst recycling. Also, a relatively large amount of catalyst is needed for a reasonable conversion and the catalyst recycling is often hampered by early precipitation of palladium. The use of Pd/C as a heterogeneous catalyst overcomes these disadvantages and the catalyst is air-stable and recyclable. There are several reports on the Heck reaction of aryl halides with alkenes in the presence of Pd/C[2] or a palladium catalyst dispersed on various supporting materials in the presence[3] and absence[4] of ligands. The major drawbacks of the Pd/C catalyst are the need for a high temperature and a long reaction time.

Ultrasound is known to accelerate diverse types of organic reactions and it is established as an important technique in organic synthesis.[5] Heterogeneous reactions, which are otherwise slow due to poor mass transfer are accelerated by sonication due to cavitation. Sonication also increases the reaction rate and avoids the use of high reaction temperatures. Srinivasan and co-workers reported the use of ultrasound for Heck reactions using $Pd(OAc)_2$ and an ionic liquid under an argon atmosphere.[6] This homogeneous catalyst is associated with problems, such as catalyst and product separation, recycling and the use of an ionic liquid. We now report a Pd/C catalysed Heck reaction in the presence of ultrasound (Scheme 1).

It is known that supported palladium leaches out into a solvent and the reactions are catalysed mainly by these dissolved palladium species. A few workers have given quantitative data for palladium leaching from catalysts[2f,7] and redeposition of catalysts.[2c,7b] The dissolved palladium species can redeposit onto a support after the reaction so that the catalysts are recyclable without loss of activity. Such redeposition is possible using two methods. (1) Thermal redeposition: in which the catalyst system is heated at a higher temperature under agitation and Pd is redeposited.[2f] (2) Chemical redeposition: in this case a reducing agent is added to the solution, for example, sodium formate. Recently, Koehler and co-workers[2b] and Sasson and co-workers[2c] used sodium formate for redeposition of Pd onto the support. Chemical



Scheme 1. Heck reaction of iodobenzene with methyl acrylate using Pd/C in the presence of ultrasound.

Keywords: Heck reaction; Ultrasound; Heterogeneous catalysis; Palladium leaching; Aryl halides.

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0040-4039/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2005.02.035

redeposition is particularly attractive for the present reaction system as it allows redeposition of a Pd species on a support at room temperature. We attempted effective chemical redeposition of the catalyst using the reducing agent sodium formate in the presence of ultrasound. In the present work, the supported palladium catalyst is used without ligands for the Heck reaction of iodobenzene with methyl acrylate using triethylamine as a base in the presence of ultrasound.[8] The effect of different solvents on the reaction has been studied in the presence of ultrasound (Table 1).

The selection of a solvent for a sonochemical reaction is a crucial factor as the cavitational intensity changes with solvent and depends on the nature of the solvent. The cavitational intensity in water is always maximum and the cavitational intensity in other solvents is compared with that in water.[9] The rate of reaction was much higher in NMP and DMAc as compared to other solvents. At the same time, the leaching of palladium was also higher for NMP, DMAc and DMF, but was not observed in the remaining three solvents. The reaction did not take place in the absence of ultrasound. The best solvent for the reaction was NMP and hence it was used for further studies. The reactions were also attempted in both NMP and DMAc without sonication, but no reaction took place at room temperature. Thus sonication has a key role in accelerating the reaction.

A significant correlation of catalytic activity with the base was found. Higher conversion was obtained with triethylamine than with inorganic bases, possibly due to the higher leaching of Pd in the presence of an organic base. We also studied the effect of using triethylamine with sodium carbonate, but the conversion was not improved (Table 2).

The reaction was also studied using different catalysts (Table 3). Among the three catalysts investigated, Pd/C was found to be the best for this reaction in the presence of ultrasound. It was observed that the conventional Pd(OAc)$_2$/PPh$_3$ catalyst gave a lower yield. A very small yield (1–2%) was observed using the catalyst [Pd(OAc)$_2$]–NaY[10] and also when using the Pd/C catalyst with a substrate like bromobenzene.

The amount of palladium which had leached into the solvent after the reaction was determined by ICP-AES. The leaching of palladium in NMP was 5.04 ppm, while in DMAc it was 5.11 ppm. The leaching of palladium for the first recycle sample was found to be 5.03 ppm. More leaching was observed for 10% Pd/C in comparison to [Pd(OAc)$_2$]–NaY. When triethylamine was used in the reaction, higher leaching of palladium took place as compared to an inorganic and a mixed base. The leaching of palladium into NMP before redeposition was 5.04 ppm, while after redeposition it was 1.85 ppm.[11] Using the reducing agent sodium formate and ultrasound, the redeposition of Pd on the support could be effectively accomplished at room temperature. The Pd/C catalyst was recycled twice (Table 4) and the catalyst showed good activity for both recycles.

Table 1. Effect of different solvents on the Heck reaction in the presence of ultrasound[a]

Entry	Solvent	Conv. of iodobenzene (%)	Yield (%)	Rate of reaction (mol cm^{-3} s^{-1})
1	NMP	71	70	1.03×10^{-8}
2	DMAc	64	63	9.35×10^{-9}
3	DMF	47	33	6.87×10^{-9}
4	Ethyl alcohol	43	5.3	6.28×10^{-9}
5	Toluene	8	1.2	1.16×10^{-9}
6	THF	7	3.5	1.02×10^{-9}

[a] Iodobenzene (10 mmol), methyl acrylate (10 mmol), triethylamine (10 mmol), Pd/C (0.2 g), solvent (15 mL), time = 10 h, NMP = *N*-methyl-2-pyrrolidone, DMAc = *N*,*N*-dimethylacetamide, THF = tetrahydrofuran, DMF = *N*,*N*-dimethylformamide.

Table 2. Effect of different bases on the Heck reaction[a]

Entry	Base	Conv. of iodobenzene (%)	Yield (%)	Rate of reaction (mol cm^{-3} s^{-1})
1	Triethylamine	71	70	1.03×10^{-8}
2	Sodium acetate	23	4	3.36×10^{-9}
3	Sodium carbonate	20	3	2.92×10^{-9}
4	Et$_3$N–NaOAc	17	2	2.48×10^{-9}

[a] Iodobenzene (10 mmol), methyl acrylate (10 mmol), base (10 mmol), Pd/C (0.2 g), NMP solvent (15 mL), time = 10 h.

Table 3. Effect of different catalysts on the Heck reaction[a]

Entry	Catalyst	Conv. of iodobenzene (%)	Yield (%)	Rate of reaction (mol cm^{-3} s^{-1})
1	Pd/C	71	70	1.03×10^{-8}
2	Pd(OAc)$_2$/PPh$_3$	27	17	3.94×10^{-9}
3	Pd(OAc)$_2$[b]/PPh$_3$	63	60	9.21×10^{-9}
4	Pd(OAc)$_2$–NaY[c]	18	1	2.63×10^{-9}

[a] Iodobenzene (10 mmol), methyl acrylate (10 mmol), base (10 mmol), catalyst (0.2 g), NMP solvent (15 mL), time = 10 h.

[b] Quantity of Pd(OAc)$_2$ was doubled.

[c] Bromobenzene instead of iodobenzene.

Scanning electron microscope (SEM) analysis of the Pd/C catalyst was carried out. The used catalyst was washed with methylene chloride and water to remove organic and inorganic matter. The average particle size of the fresh catalyst was from 85 to 90 μm and that of the used catalyst was 10–13 μm.

In conclusion, the Heck reaction of iodobenzene and methyl acrylate in NMP catalysed by Pd/C at ambient temperature is considerably accelerated by ultrasound. The reaction can be carried out under phosphine-free conditions. The catalyst shows high activity under

Table 4. Recyclability of the catalyst for the Heck reaction[a]

Entry	Cycle	Conv. of iodobenzene (%)	Yield (%)	Rate of reaction (mol cm^{-3} s^{-1})
1	0	71	70	1.03×10^{-8}
2	1	70	65	1.02×10^{-8}
3	2	60	58	8.77×10^{-8}

[a] Iodobenzene (10 mmol), methyl acrylate (10 mmol), triethylamine (10 mmol), Pd/C (0.2 g), NMP (15 mL), time = 10 h.

ambient conditions (air and moisture) and is conveniently separated from the reaction mixture. The Pd/C can be effectively recycled twice. SEM shows that the particle size of the catalyst is considerably reduced after the first cycle and the smaller particle size increases the rate of reaction.

The Pd species in solution can be redeposited onto the support after the reaction using a reducing agent such as sodium formate in the presence of ultrasound. This catalyst system allows reaction at lower temperature and increases the reaction rate as compared to conventional Pd/C catalysed Heck reactions, but retains the advantage of recyclability.

Acknowledgements

This work was supported by the UGC unassigned grant of the University of Mumbai, India.

References and notes

1. (a) Meijere, A. de.; Meyer, F. E. *Angew. Chem.* **1994**, *106*, 2473–2506; (b) Meijere, A. de.; Meyer, F. E. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2379–2411.
2. (a) Xie, X.; Lu, J.; Chen, B.; Han, J.; She, X.; Pan, X. *Tetrahedron Lett.* **2004**, *45*, 809–811; (b) Heidenreich, R. G.; Krauter, J. G. E.; Pietsch, J.; Koehler, K. *J. Mol. Catal. A: Chem.* **2002**, *182–183*, 499–509; (c) Mukhopadhyay, S.; Rothenberg, G.; Joshi, A.; Baidossi, M.; Sasson, Y. *Adv. Synth. Catal.* **2002**, *344*, 348–354; (d) Gruber, M.; Chouzier, S.; Koehler, K.; Djakovitch, L. *Appl. Catal., A* **2004**, *265*, 161–169; (e) Hagiwara, H.; Shimizu, Y.; Hoshi, T.; Suzuki, T.; Ando, M.; Ohkubo, K.; Yokoyama, C. *Tetrahedron Lett.* **2001**, *42*, 4349–4351; (f) Zhao, F.; Bhanage, B. M.; Shirai, M.; Arai, M. *Chem. Eur. J.* **2000**, *6*, 843–848.
3. (a) Choudary, B. M.; Sarma, M. R. *Tetrahedron Lett.* **1990**, *31*, 1495–1496; (b) Kiviaho, J.; Hanaoka, T.; Sugi, Y. *J. Mol. Catal. A: Chem.* **1995**, *101*, 25–31; (c) Tonks, L.; Anson, M. S.; Hellgardt, K.; Mirza, A. R.; Thompson, D. F.; Williams, J. M. J. *Tetrahedron Lett.* **1997**, *38*, 4319–4322; (d) Wali, A.; Pillai, S. M.; Satish, S. *React. Kinet. Catal. Lett.* **1997**, *60*, 189–194.
4. (a) Djakovitch, L.; Koehler, K. *J. Am. Chem. Soc.* **2001**, *123*, 5990–5999; (b) Prockl, S. S.; Wolfgang, K. M.; Gruber, A.; Koehler, K. *Angew. Chem., Int. Ed.* **2004**, *43*, 1881–1882; (c) Savoia, D.; Trombini, C.; Umani-Ronchi, A.; Verardo, G. *J. Chem. Soc., Chem. Commun.* **1981**, *23*, 541–542; (d) Ramchandani, R. K.; Uphade, B. S.; Vinod, M. P.; Wakharkar, R. D.; Choudhary, V. R.; Sudalai, A. *Chem. Commun.* **1997**, 2071–2072; (e) Li, J.; Mau, A. W.-H.; Strauss, C. R. *Chem. Commun.* **1997**, *23*, 1275–1276; (f) Augustine, R. L.; O'Leary, S. T. *J. Mol. Catal. A: Chem.* **1995**, *95*, 277–285; (g) Mehnert, C. P.; Weaver, D. W.; Ying, J. Y. *J. Am. Chem. Soc.* **1998**, *120*, 12289–12296.
5. (a) Mason, T. J.; Lorimer, J. P. *Applied Sonochemistry. The Uses of Power Ultrasound in Chemistry and Processing*; Wiley-VCH, 2002; (b) Mason, T. J. *Practical Sonochemistry User Guide to Applications in Chemistry and Chemical Engineering*; Ellis Horwood: Chichester, UK, 1991; (c) Soudagar, S. R.; Samant, S. D. *Ultrason. Sonochem.* **1995**, *2*, S15–S18; (d) Bhatkhande, B. S.; Adhikari, M. V.; Samant, S. D. *Ultrason. Sonochem.* **2002**, *9*, 31–35; (e) Ambulgekar, G. V.; Samant, S. D.; Pandit, A. B. *Ultrason. Sonochem.* **2005**, *12*, 85–90.
6. Deshmukh, R. R.; Rajagopal, R.; Srinivasan, K. V. *Chem. Commun.* **2001**, 1544–1545.
7. (a) Koehler, K.; Djakovitch, L. *J. Mol. Catal. A: Chem.* **1999**, *142*, 275–284; (b) Heidenreich, R. G.; Krauter, J. G. E.; Pietsch, J.; Koehler, K. *J. Mol. Catal. A: Chem.* **2002**, *182–183*, 499–509.
8. Typical experimental procedure: An aryl halide (10 mmol), methyl acrylate (10 mmol), triethylamine (10 mmol) were added to NMP (15 mL) in a 50 mL flat bottomed flask. The catalyst (0.2 g, 10% Pd/C) was added and the mixture was sonicated and stirred for the specified time at rt in air. Samples were withdrawn at various time intervals and analysed by gas chromatography. The product was identified by comparison with an authentic sample. The ultrasonic bath used for reactions had a frequency of 35 kHz and electric power rating of 85 W.
9. DeSouza-Barboza, J. C.; Petrier, C.; Luche, J. L. *J. Org. Chem.* **1988**, *53*, 1212–1218.
10. The catalyst $Pd(OAc)_2$–NaY was prepared as reported in Djakovitch, L.; Koehler, K. *J. Am. Chem. Soc.* **2001**, *123*, 5990–5999.
11. Typical experimental procedure for the redeposition of dissolved Pd onto the carbon support: The filtrate from the above reaction was reduced with sodium formate (3 g) under sonication for 10 h. Redeposition was monitored using ICP-AES analysis for Pd content in solution. The catalyst was filtered off and used for successive recycles.