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Palladium on Calcium Carbonate Combined to 2-Hydroxypropyl-α/β-cyclodextrins: A Selective Catalytic System for Aqueous Heck Coupling and Hydroarylation

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Abstract: An efficient, selective and recoverable catalytic system for ligand-free aqueous Heck reactions using hydroxypropylated cyclodextrins (HPCDs) and palladium on calcium carbonate (Pd/$CaCO_3$) is highlighted. Remarkably, stereo- and chemoselectivities could be tuned by the cavity size of cyclodextrins, exploiting the relevance of host-guest interactions. UV-Vis experiments have led to strong evidence concerning an interplay between Pd(II) and α-HPCD, possibly ascribed to a reduction/stabilization effect of CDs. Unexpectedly, hydroarylation was the favored pathway with acrylonitrile which provided access to 3-phenylpropionitrile derivatives without usual hydride donors. Finally, determination of soluble Pd(0/II) *via* AAS enabled the definition of a predominant homogeneous mechanism in which TONs over 5000 were observed.

Keywords: aqueous-phase catalysis; cyclodextrins; Heck reaction; host-guest systems; hydroarylation

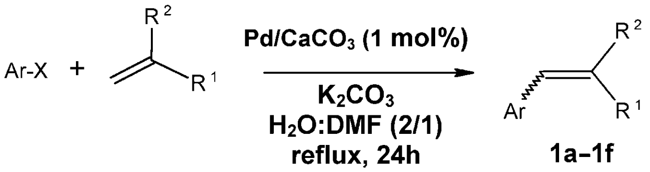
Introduction

Palladium-catalyzed cross-coupling reactions are one of the most straightforward methods for the formation of C–C bonds in organic synthesis.[1] In recent years, the Heck reaction, commonly the coupling between aryl halides and olefins, has found widespread use in many industrial processes, especially in the synthesis of fine chemicals and pharmaceutical intermediates.[2] However, efficient Heck reactions are usually carried out in organic solvents without catalyst recycle, which jeopardize their major industrial application in terms of costs and effluent treatment. In view of this, considerable efforts have been directed to the development of benign processes. With this emphasis, common strategies include the use of alternative ligands to phosphines,[3] non-classical solvents,[4] and phase-transfer conditions.[5] In particular, the use of aqueous medium continues to attract attention, in terms of cost, security and process conditions. Emerging conditions have involved biphasic catalytic systems,[6] in which the product can be cleanly separated from the catalyst, along covalently modified metal nanoparticles with supramolecular receptors[7] that can improve solubility and provide a range of interesting properties.

Catalytic systems on the basis of water-soluble supramolecular receptors, such as cyclodextrins, calixarenes and resorcinarenes, have drawn the attention of synthetic chemists due to their singular activities, especially in terms of substrate selectivity.[8] The design of such systems can combine properties of a metal core beyond a mass transfer effect, broadening the pallet of valuable and elegant approaches in the search for effective catalysts.[8c]

Cyclodextrins (CDs), cyclic oligosaccharides consisting of 6 (in α), 7 (in β) and 8 (in γ) D-glucopyranose units attached by α-1,4-linkages, are one of the most soluble supramolecular receptors and have gained increasing attention in contemporary chemistry.[9] Their hydrophobic internal cavity can include lipophilic molecules, causing significant increase of their solubility in polar solvents, e.g., water, a phenomenon well understood in the light of the host-

Table 1. Heck reactions catalyzed by the HPCD/Pd/$CaCO_3$ system in aqueous medium.[a]



Entry	Ar-X	R^1	R^2	Cyclodextrin (mol%)	Yield [%][b]; (*E*/*Z* ratio)[b]	Product
1	C_6H_5I	Ph	H	α-HPCD (1)	80; (89/11)	**1a**
2	C_6H_5I	Ph	H	No	61; (71/29)	**1a**
3	4-$MeOC_6H_4I$	Ph	H	α-HPCD (1)	97; (100/0)	**1b**
4	4-$O_2NC_6H_4I$	Ph	H	α-HPCD (1)/No	trace[c]	–
5	4-$O_2NC_6H_4I$	Ph	H	β-HPCD (1)	54; (62/38)[d]	**1c**
6	C_6H_5Br	Ph	H	α-HPCD (1)	67; (100/0)	**1a**
7	4-$MeCOC_6H_4Br$	CO_2Me	H	α-HPCD (1)	44; (100/0)[e]	**1d**
8	4-$MeCOC_6H_4Br$	CO_2Me	H	No	–[f]	–
9	C_6H_5I	CO_2Bu	CH_3	α-HPCD (1)	79; (94/16)	**1e**
10	C_6H_5I	CO_2Bu	CH_3	β-HPCD (1)	60; (68/32)	**1e**
11	C_6H_5I	CO_2Bu	CH_3	No	–	–
12	C_6H_5I	CO_2Me	H	α-HPCD (100)	41; (100/0)[g]	**1f**
13	C_6H_5I	CO_2Me	H	α-HPCD (1)	52; (100/0)[g]	**1f**

[a] *Reaction conditions:* aryl halide (1.0 mmol), alkene (1.2 mmol), K_2CO_3 (2.0 mmol), Pd/$CaCO_3$ (1 mol% based on Pd), H_2O/DMF (2:1, 15 mL), 110 °C.

[b] Determined by GC-MS.

[c] Biphenyl and nitrobenzene were detected in 15 and 40% yields.

[d] Nitrobenzene was obtained in 20% yield.

[e] 4,4′-Diacetyl-1,1′-biphenyl was also observed in 49%.

[f] 4,4′-Diacetyl-1,1′-biphenyl (82%) and acetophenone (17%) were the reaction products.

[g] Using neat water.

guest approach. Indeed, cyclodextrin itself can be used to discriminate between substrates, which provides a way for imparting selectivity[9d] to intrinsically non-selective reactions.

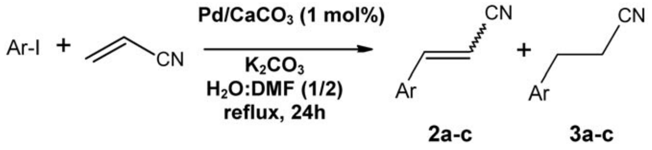
Because of our ongoing interest in the use of cyclodextrin derivatives in the study of inclusion phenomena and in catalysis,[10a–c] we have been attracted to explore aqueous cross-coupling reactions under supramolecular organometallic catalysis. Recently, we reported our first results on the use of hydroxypropylated cyclodextrins (HPCDs) in aqueous Heck reactions with aryl halides and methyl acrylate.[10b] This unprecedented catalytic system proved to be very effective using sub-stoichiometric amounts of α-HPCD in conjunction with Pd/$CaCO_3$[10d] as palladium source. In this work, we have enlarged our studies by examining HPCDs/Pd/$CaCO_3$ systems in Heck reactions with a range of aryl halides and olefins along with the effect in chemo- and stereoselectivities.

Results and Discussion

In our previous study, the use of 1 mol% of both α-HPCD and Pd/$CaCO_3$ in an aqueous mixture consisting of H_2O/DMF (2/1) contributed to a huge increase in the yield.[10b] Also, total regio- and stereoselectivities were achieved, showing the beneficial effect of CDs in this process.

A more extensive survey of Heck couplings under these conditions is presented in Table 1 and Table 2. For styrene, the reaction with iodobenzene in the presence of α-HPCD, using K_2CO_3 as base, provided stilbene in a good yield (80%), although a slight mixture of *Z/E* diastereomers was observed (Table 1, entry 1). As a reference, the reaction conducted in the absence of α-HPCD furnished a lower yield and decreased diastereoselectivity (Table 1, entry 2), suggesting the influence of the CD cavity. Application of the same conditions to activated and deactivated aryl iodides led to different reactivity patterns (Table 1, entries 3–8). In particular, the reaction between 4-iodoanisole and styrene, in the presence of α-HPCD, gave the corresponding product with complete conversion (Table 1, entry 3) but, surprisingly, the reaction failed when using the most active 4-iodonitrobenzene (Table 1, entry 4). In this case, the main product was nitrobenzene deriving from hydrodehalogenation of the substrate. However, under similar conditions a moderate yield of 4-nitrostilbene was observed in a β-HPCD medium (Table 1, entry 5).

Table 2. Heck coplings of iodoarenes with acrylonitrile.[a]



Entry	Ar	Cyclodextrin (mol%)	Yield [%];[b] (*E*/*Z* ratio);[b] (Product)	(Product)
1	C_6H_5	α-HPCD (1)	19; (59/41); (**2a**)	72 (**3a**)
2	C_6H_5	No	0[c]	0
3	C_6H_5	β-HPCD (1)	51; (52/48); (**2a**)	35 (**3a**)
4	C_6H_5	β-CD (1)	29; (51/49); (**2a**)	6 (**3a**)
5	4-MeO-C_6H_4	α-HPCD (1)	11; (67/33)[d]	57 (**3b**)
6	4-MeO-C_6H_4	No	0[e]	0
7	4-O_2N-C_6H_4	α-HPCD (1)/No	0[f]	0
8	4-O_2N-C_6H_4	β-HPCD (1)	42; (55/45); (**2c**)[g]	31 (**3c**)

[a] *Reaction conditions:* aryl iodide (1.0 mmol), acrylonitrile (1.2 mmol), K_2CO_3 (2.0 mmol), Pd/$CaCO_3$ (1 mol%), CD (1 mol%), H_2O/DMF (1:2, 15 mL), 110 °C.

[b] Determined by GC-MS.

[c] 10% biphenyl was detected.

[d] Not isolated.

[e] 15% 4,4′-dimethoxy-1,1′-biphenyl was detected.

[f] Nitrobenzene was the only product (30%).

[g] The crude material (obtained as a **2c/3c** mixture) was directly analyzed by ^{1}H NMR.

Based on our previous result on the arylation of methyl acrylate, we also attempted to couple aryl bromides using this aqueous protocol. Under the same conditions, the arylation of styrene with bromobenzene yielded the expected product in moderate yield (Table 1, entry 6). By contrast, when the reaction between the more reactive 4-bromoacetophenone and methyl acrylate was carried out, a substantial amount of the Ullmann product was observed (Table 1, entries 7 and 8), although a moderate yield of methyl 4-acetylcinnamate could be obtained in the presence of α-HPCD.

Since an analogous reactivity profile was displayed with 4-iodonitrobenzene (Table 1, entry 4), and from the standpoint of supramolecular catalysis, it is conceivable that molecular recognition processes constitute a decisive factor for the increase in (chemo)selectivity. In fact, these results are in line with the lower association constants α-CD/substrate involving acyl- and nitro-substituted arenes, when compared with β-CD.[11] Considering that α and β-HPCD are mixtures of closely related derivatives containing different degrees of substitutions and isomeric forms, the respective association constants would reflect an average effect which could explain the results in entries 4 and 5. Therefore, alternative pathways seem to be favored in a predominant aqueous medium. Indeed, this behavior suggests that the cavity is involved in the catalytic cycle.

Butyl methacrylate, a substituted α,β-unsaturated carbonyl compound, was also employed for the preparation of trisubstituted olefins. Under the same conditions as above described, α-HPCD led to butyl α-methylcinnamate in good yield and predominant *E*-diastereoselectivity (Table 1, entry 9). In comparison, α-HPCD-free medium was also applied but no significant yield was observed. Because of the more sterically demanding character of this olefin, we sought to evaluate the cavity effect on the stereoselectivity employing β-HPCD at similar conditions. Whereas a significant *E*/*Z* mixture was formed (Table 1, entry 10), this result clearly indicates that the stereochemistry of the product is induced by the cavity diameter, which represents a good evidence that β-H elimination is assisted by CD. This behavior has already been observed by Cassez and co-workers in a different CD system.[12]

Acrylonitrile was quite unreactive at this H_2O:DMF ratio, yielding cinnamonitriles only upon using a higher DMF ratio (1:2). In general, the presence of α-HPCD led to the desired cross-coupling derivative with an effective chemoselectivity (Table 2, entries 1 and 5) whereas biphenyl (Ullmann coupling) was the only product detected in its absence (Table 2, entries 2 and 6). Once again, Heck reactions with 4-iodonitrobenzene did not take place and hydrodehalogenation products were predominant in the presence/absence of α-HPCD (Table 2, entry 7). Most interestingly, hydrocinamonitriles were the major products in an α-HPCD medium using iodobenzene or 4-iodoanisole as the coupling partner (Table 2, entries 1 and 5). To the best of our knowledge, this result has not previously been observed in the context of Heck coupling. Further reactions employing β-HPCD and native β-CD (Table 2, entries 3, 4 and 8) afforded the Heck product in higher selectivity. So it could be presumed that the cavity diameter combined with the steric bulk/nature of the *O*-bound 2-hydroxypropyl groups play a significant role towards the hydroarylation pathway.

Beyond the experiments based on an aqueous-organic medium, we also have assayed the Heck reaction between methyl acrylate and iodobenzene applying pure water. In neat water, formation of inclusion complexes between iodobenzene-HPCD seems to be favored due to hydrophobic forces. This phenomenon was found to be critical, especially under stoichiometric amounts of CD (Table 1, entries 12 and 13). Combination with DMF provides significant solubility increase of aryl halides, which results in better diffusion and mass transfer of organic species. Assuming further, it is possible that the use of an organic modifier lowers the medium polarity, which partially disables the hydrophobic association between cyclodextrin and aryl halides, allowing the latter to interact with active palladium species.

To highlight the potential and simplicity of our catalytic system based on sub-stoichiometric HPCDs, we also compared it with the traditional micellar approach using classical ionic and non-ionic amphiphiles such as TBAB, Aliquat 336 and Triton X-100. As indicated in Table 3, only low to moderate yields were observed under the same conditions (1 mol% additive) by using the Heck reaction between iodobenzene and styrene as a model. Effective couplings required at least 15–20 mol%, suggesting the reaction rate was dependent on self-assembly into micelles.[13] Indeed, the lower *E*/*Z* ratios, when compared with α-HPCD (Table 1, entry 1), exploit the size and shape of the nanospace within which the reactions occur are decisive for boosting stereoselectivity.

As an effort to evaluate the actual turnover numbers of our CD system and to confirm our suspicions about a predominant homogeneous mechanism, determination of soluble Pd(0/II) species by using atomic absorption spectroscopy (AAS) was carried out. To address this issue, the Heck arylation of styrene was undertaken under the same general conditions.

Table 3. Heck reactions of iodobenzene with styrene using different amphiphiles[a]

Entry	Amphiphile	mol (%)	Yield [%][b]
1	TBAB	1	41 (62/38)
2	Aliquat 336	1	58 (74/26)
3	Triton X-100	1	34 (68/32)
4	TBAB	15	74 (79/21)
5	Aliquat 336	15	82 (80/20)
6	Triton X-100	20	80 (77/23)

[a] *Reaction conditions:* phenyl iodide (1.0 mmol), styrene (1.2 mmol), K_2CO_3 (2.0 mmol), Pd/$CaCO_3$ (1 mol%), amphiphile, H_2O/DMF (2:1, 15 mL), 110 °C, 24 h.

[b] Determined by GC-MS. The values in parentheses refer to *E*/*Z* ratio.

Analyzing the α-HPCD aqueous phase after 24 h, we obtained an estimation of the active palladium species from the Pd/$CaCO_3$ support. Pd(0/II) found in the solution at the end of the reaction corresponded to 1.4% of the total palladium. So, this aqueous phase was tested in three consecutive runs, after product extraction and, as expected, no appreciable loss of activity was observed. Subsequent analyses of the resultant filtrate by AAS pointed to 1.3–1.0% of the initial Pd load (1×10^{-2} mmol) which supports the idea that active Pd particles remain in solution, presumably due to a stabilization effect from CD units, as previously supposed by us.[10b] Therefore, significant TON values over 5000 could be obtained from the catalytic reactions (Figure 1).

For comparison, in a closely related study by Cassez et al.,[12] the increase in activity of Heck reactions catalyzed by Pd/C/randomly methylated β-CD was proposed to be related to the adsorption of cyclodextrin on the catalytic surface, in which the reaction takes place. Nevertheless, this idea contrasts with that prevailing here. Even though the reaction proceeding in the heterogeneous medium cannot be ruled out, our findings confirm the heterogeneous palladium is primarily the source of homogeneously active palladium species that actually perform the catalytic reactions.

Aiming at investigating the interaction between Pd and α-HPCD, we obtained UV-Vis absorption spectra of aqueous palladium chloride solutions in the presence of α-HPCD. As observed in Figure 2, the ligand-to-metal charge transfer band at 235 nm suffered a great increase in its absorbance after 24 h. This is probably addressed to the interaction between OH groups of cyclodextrin and Pd(II), similar to that described for a former Pd-dendrimer (G6-OH) interaction.[14] Also the pronounced absorption in the 310–375 nm range for the 24 h sample evidences the constitution of Pd(0) clusters,[15] which is reasonable by virtue of the microenvironment of CDs. Therefore, we presume that cyclodextrins present in excess with respect to Pd could act as capping agents for the Pd(0) species during and after catalysis and recycling, avoiding loss of activity through *hydrophobic-hydrophobic* stabilization.[16] On the basis of this reasoning, the inclusion phenomena of substrates inside CDs would allow a better interaction with Pd, resulting in a favorable effect on catalytic performance.

These results further contain interesting information about the role of HPCDs in the present system. Although our investigation did not focus on mechanistic aspects, some points regarding these findings

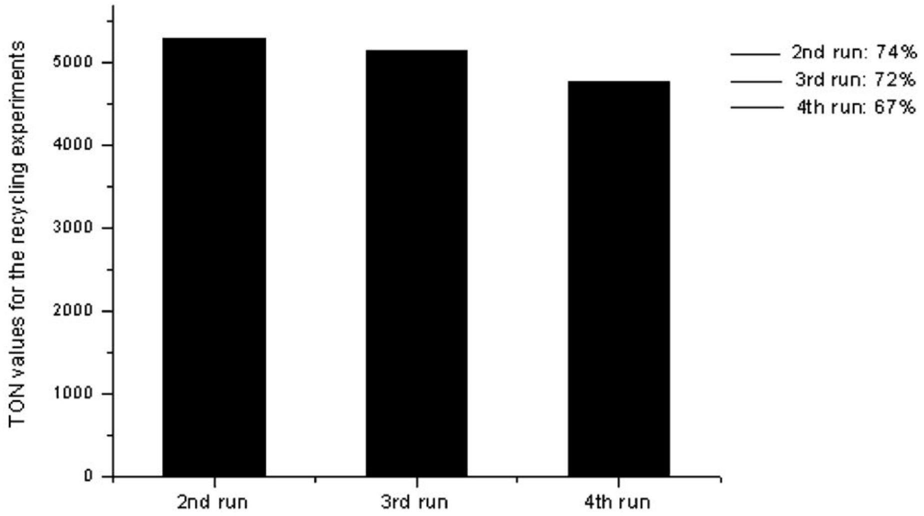


Figure 1. TON values obtained from the recycling experiments with α-HPCD. *Reaction conditions* (2nd–4th runs): phenyl iodide (1.0 mmol), styrene (1.3 mmol), K_2CO_3 (2.0 mmol), recovered aqueous phase, reflux, 24 h.

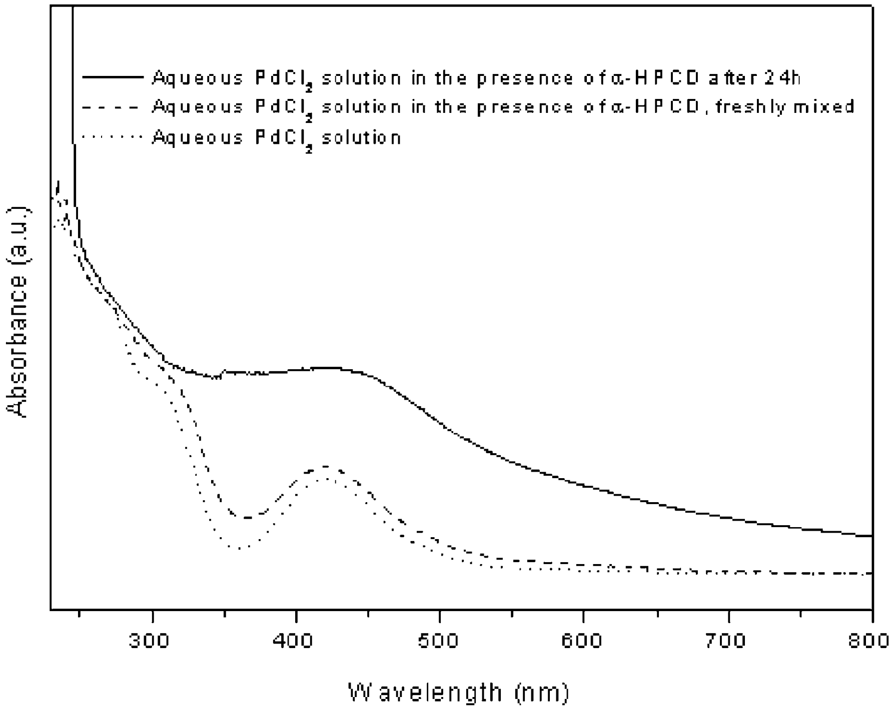


Figure 2. Absorption spectral of aqueous Pd(II) solutions observed upon UV-Vis light irradiation.

are worth noticing. First, the poorer chemoselectivity obtained when using electron-withdrawing groups substituted on aryl halides has already been observed in aqueous Heck reactions. Similarly to Perosa and co-workers,[17] hydrodehalogenation and homocoupling pathways were particularly pronounced in the presence of these reactive halides, which provide evidence that the respective intermediate from oxidative addition is the common one to competitive processes taking place in poorly dispersed aqueous systems. Indeed, this tendency suggests a slower rate preceding the migratory insertion step, in which fast reductive coupling and parallel reduction reactions could be favored. Upon CD complexation, however, these pathways have a considerable smaller preference and, thus, the reaction outcome is dictated by the Heck cycle.

Second, the catalytic hydroarylation of simple olefins is exceedingly rare. Related profiles are common in systems which are unable to reach the conforma-

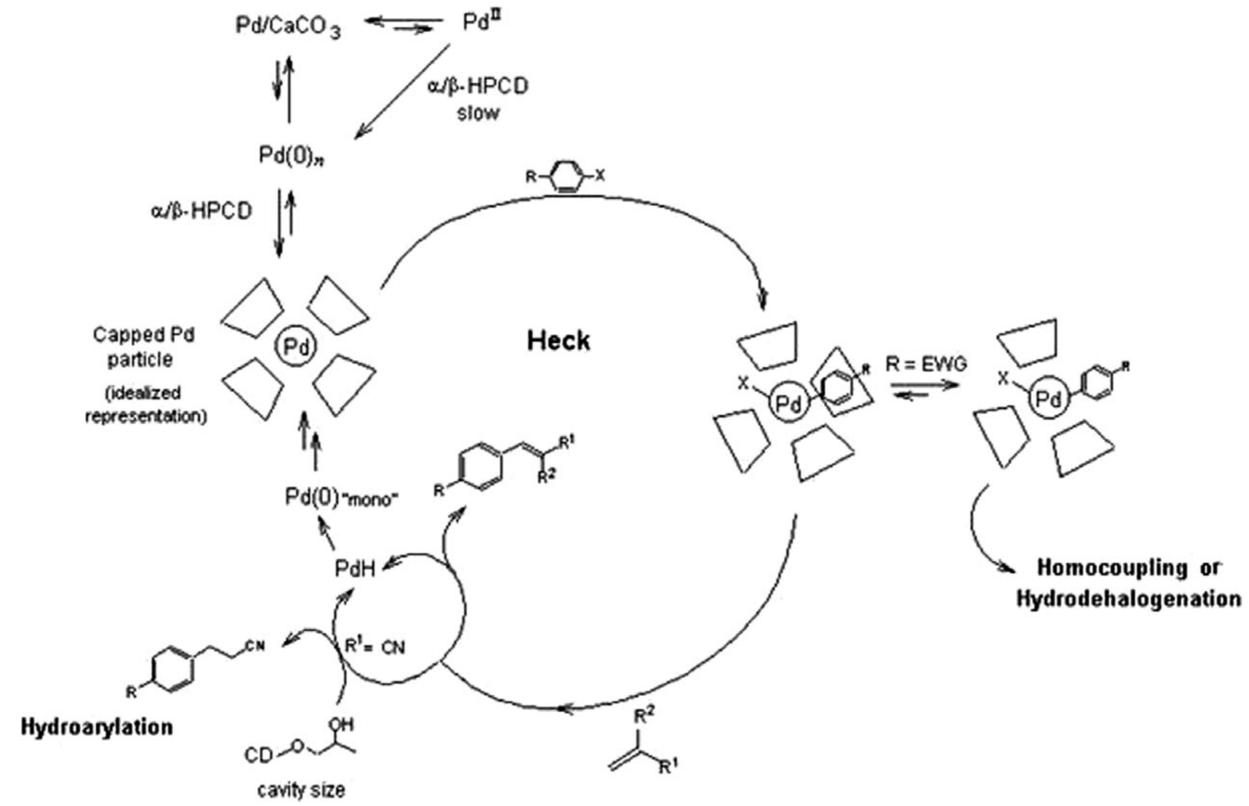


Figure 3. Proposed catalytic cycle in the presence of HPCDs.

tion required for *syn*-β-elimination of HPdX and, thus, the reaction with a hydride donor can occur.[18] Mainly due to the work of Wu,[19a] Hierso[19b] and Barros[19c] with alkyne protocols, it is known that alcohol functionalities provide an alternative route for hydrogenolysis of organopalladium intermediates through β-hydride elimination of palladium alcoholates. Acrylonitrile, a less activated Michael acceptor, reacted only in a CD medium to furnish a mixture of cinnamonitriles and their reduced product, whose ratio could be tuned to a far greater degree depending on the spatial restriction (cavity effect) and substituted groups on the primary macrocycle. Concerning the later factor, it is possible that Pd hydride species could mostly be generated by interactions between hydroxypropyl groups from CD and the σ-alkyl-Pd intermediate from acrylonitrile insertion, leading to Pd(0) species after one turnover. However, the reason for the outstanding selectivity towards acrylonitrile is not yet clear .

Third, as suggested by UV-Vis spectra and considering the significant number of hydroxy groups[21] present in the unique chemical environment of CDs, the reduction of Pd(II) species from the commercial $Pd/CaCO_3$ catalyst[20] could also be an additional role played by HPCDs even held down by a low kinetics. In this regard, subsequent reduction by the excess amount of α-HPCD, which also functions as a stabilizer, provides a means for reactivation and recycling.

A proposal in line with our results is depicted in Figure 3.

Conclusions

In conclusion, we have shown that the combination of $Pd/CaCO_3$ and α-HPCD, in sub-stoichiometric amounts, results in an efficient catalytic system for the arylation of activated olefins with aryl halides in aqueous medium. Even though using a heterogeneous catalyst, AAS measurements provided an insight into mechanistic aspects and evidence that the support acts as a reservoir of catalytically active Pd species. Indeed, the presence of 2-hydroxypropyl-α/β-cyclodextrins always contributed to enhancements in the yield along with a better diastereoselectivity profile (for α-HPCD), presumably induced by the cavity size. Central to supramolecular systems, molecular recognition processes seem to operate as an important effect for boosting selectivity.

Interestingly, hydroarylation was the favored pathway in the coupling with acrylonitrile, possibly a result of the CD cavity size along with interactions between 2-hydroxypropyl group and organopalladium intermediate. So far, hydroarylation has not been observed in common Heck systems which prompted us to investigate the operative mechanism and also provide an attractive protocol to access 3-phenylpropionitrile derivatives in the same pot without an additional hydrogen donor.

Furthermore, this catalytic system takes the advantage of using sub-stoichiometric amounts of the more soluble and cheaper HPCDs – compared with the micellar protocol – to achieve good activities in aqueous medium. Studies aimed at drawing on experimental data to currently understand the role of CD along with focusing on its application to the development of new methodologies are underway in our laboratory.

Experimental Section

General Methods

All reactions were carried out with previously distilled water using magnetic stirring. Reagents were obtained from commercial sources and used without previous purification. The α/β-HPCD were native α/β-CD partially *O*-2-hydroxypropylated with approximately 0.6 OH groups modified per glucopyranose unit. Purification of reaction products was carried out by flash chromatography using Merck silica gel 60 (230–400 mesh). Analytical thin layer chromatography was performed on Merck silica gel 60-F plates (0.25 mm). Visualization was accomplished with UV light. GC/MS analyses were carried out on a Shimadzu GC-2010 coupled to a quadrupole Shimadzu QP20105 network operating in a electron ionization mode at 70 eV. A DB-5 capillary column (30 m × 0.25 mm × 0.25 μm) was used for the separations. AAS measurements were performed on a Varian SpectrAA 220 FS employing a Varian Pd hollow cathode lamp. UV-Vis spectra were recorded in a double beam Varian model Cary 1E using an aqueous $PdCl_2$ solution (11.2 mM) or by the treatment of this solution with 2-hydroxypropyl-α-cyclodextrin at a ratio of 1:1 at 25 °C. Before UV measurements, samples were filtered through an Iso-Disc N-34 nylon membrane (0.45 μm × 3 mm) from Supelco. ^{1}H NMR spectra and proton-decoupled ^{13}C NMR spectra were recorded on a Fourier Transform Bruker AMX-200 spectrometer operating at 200 MHz (^{1}H) and at 50 MHz (^{13}C) using $CDCl_3$ or DMSO-d_6. ^{1}H NMR data are reported as s = singlet, d = doublet, dd = double doublet, t = triplet, m = multiplet.

Typical Procedure for Aqueous Heck Reactions with CDs

In a 50-mL reaction flask were placed potassium carbonate (276.4 mg, 2.0 mmol), CD (0.01 mmol), 10 mL distilled water, 5 mL *N,N*-dimethylformamide, aryl halide (1.0 mmol), alkene (1.2 mmol). and Pd/$CaCO_3$ powder (5% w/w, 21.3 mg, 1 mol% Pd). The mixture was heated and stirred at 110 °C for 24 h. It was then cooled, filtered through a thin pad of Celite and washed three times (3 × 10 mL) with chloroform. The organic phases were dried over Na_2SO_4, analyzed by GC/MS and the solvent evaporated under vacuum to afford the corresponding crude product. The isolated products were collected, purified by flash column chromatography and characterized by ^{1}H and ^{13}C NMR.

Recycling Experiments

The first run was carried out as described above. In a 50-mL flask containing the recovered aqueous phase were poured phenyl iodide (0.11 mL, 1.0 mmol), styrene (0.14 mL, 1.3 mmol), potassium carbonate (276.4 mg, 2.0 mmol) and 5 mL *N,N*-dimethylformamide. The resulting mixture was stirred and heated for 24 h at 110 °C.

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References

[1] a) R. F. Heck, *Org. React.* **1982**, *27*, 345; b) R. F. Heck, in: *Comprehensive Organic Synthesis*, Vol. 4, (Eds.: B. M. Trost, I. Fleming), Pergamon Press, Oxford, **1991**, Chapter 4.3; c) S. Bräse, A. de Meijere, in: *Metal-Catalyzed Cross-Coupling Reactions*, (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1998**; d) M. Beller, T. H. Riermeier, G. Stark, in: *Transition Metals for Organic Synthesis Building Blocks and Fine Chemicals*, Vol. 1, (Eds.: M. Beller, C. Bolm), Wiley-VCH: Weinheim, **1998**, p 208; e) I. P. Beletskaya, A. V. Cheprakov, *Chem. Rev.* **2000**, *100*, 3009–3066; f) N. J. Whitcombe, K. K. Hii, S. E. Gibson, *Tetrahedron* **2001**, *57*, 7449–7476; g) J. P. Knowles, A. Whiting, *Org. Biomol. Chem.* **2007**, 5, 31–44.

[2] a) J. G. de Vries, *Can. J. Chem.* **2001**, *79*, 1086–1092; b) J. G. de Vries, A. H. M. de Vries, *Eur. J. Org. Chem.* **2003**, 799–811; c) H.-U. Blaser, A. Indolese, F. Naud, U. Nettekoven, A. Schnyder, *Adv. Synth. Catal.* **2004**, *346*, 1583–1598; d) D. Schils, F. Stappers, G. Solberghe, R. van Heck, N. Coppens, D. Van den Heuvel, P. Van der Donck, T. Callewaert, F. Meeussen, É. De Bie, K. Eersels, E. Schouteden, *Org. Process Res. Dev.* **2008**, *12*, 530–536; e) G. O. D. Estrada, A. L. F. de Souza, J. F. M. da Silva, O. A. C. Antunes, *Catal. Commun.* **2008**, *9*, 1734–1738.

[3] a) D. A Alonso, C. Nájera, M. C. Pacheco, *Org. Lett.* **2000**, *2*, 1823–1826; b) X. Cui, Z. Li, C. Z. Tao, Y. Xu, J. Li, L. Liu, Q. X. Guo, *Org. Lett.* **2006**, *8*, 2467–2470; c) X. Cui, J. A. Li, Z. P. Zhang, Y. Fu, L. Liu, Q.-X. Guo, *J. Org. Chem.* **2007**, *72*, 9342–9345; d) W. X. Chen, C. J. Xi, Y. W. Wu, *J. Organomet. Chem.* **2007**, *692*, 4381–4388.

[4] a) H. C. Hailes, *Org. Process Res. Dev.* **2007**, *11*, 114–120; b) V. Polshettiwar, R. S. Varma, *Acc. Chem. Res.* **2008**, *41*, 629–639.

[5] a) C. Rabeyrin, D. Sinou, *J. Mol. Catal. A-Chem.* **2004**, *215*, 1–2, 89–93; b) S. Bhattacharya, S. Aasheesh, S. Saumitra, *Tetrahedron Lett.* **2005**, *46*, 3557–3560.

[6] a) D. E. Bergbreiter, P. L. Osburn, A. Wilson, E. M. Sink, *J. Am. Chem. Soc.* **2000**, *122*, 9058–9064; b) B. M. Bhanage, S. Fujita, M. Arai, *J. Organomet. Chem.* **2003**, *687*, 211–218; c) S. V. Jagtap, R. M. Deshpande, *Cat. Today* **2008**, *131*, 353–359.

[7] a) G. Cooke, *Angew. Chem. Int. Ed.* **2003**, *42*, 4860–4870; b) C. Ornelas, J. Ruiz, L. Salmon, D. Astruc, *Adv. Synth. Catal.* **2008**, *350*, 837–845.

[8] a) F. Hapiot, J. Lyskawa, H. Bricout, S. Tilloy, E. Monflier, *Adv. Synth. Catal.* **2004**, *346*, 83–89; b) A. L. Maksimov, D. A. Sakharov, T. Y. Filippova, A. Y. Zhuchikova, E. A. Kharakanov, *Ind. Eng. Chem. Res.* **2005**, *44*, 8644–8653; c) M. J. Wilkinson, P. W. N. M. van Leeuwen, J. N. H. Reek, *Org. Biomol. Chem.* **2005**, *3*, 2371–2383; d) E. A. Katayev, Y. A. Ustynyuk, J. L. Sessler, *Coord. Chem. Rev.* **2006**, *250*, 3004–3037; e) R. Zadmard, S. Taghvaei-Ganjali, B. Gorji, *Synth. Commun.* **2008**, 1830–1836.

[9] a) J. Liu, J. Alvarez, W. Ong, E. Roman, A. E. Kaifer, *Langmuir* **2001**, *17*, 6762–6764; b) L. Strimbu, J. Liu, A. E. Kaifer, *Langmuir* **2003**, *19*, 483–485; c) S. C. Mhadgut, K. Palaniappan, M. Thimmaiah, S. A. Hackney, B. Torok, J. Liu, *Chem. Commun.* **2005**, 3207–3209; d) F. Hapiot, S. Tilloy, E. Monflier, *Chem. Rev.* **2006**, *106*, 767–781; e) C. Machut, J. Patrigeon, S. Tilloy, H. Bricout, F. Hapiot, E. Monflier, *Angew. Chem. Int. Ed.* **2007**, *46*, 3040–3042; f) M. Ferreira, H. Bricout, A. Sayede, A. Ponchel, S. Fourmentin, S. Tilloy, E. Monflier, *Adv. Synth. Catal.* **2008**, *350*, 609–618.

[10] a) L. F. B. Malta, J. D. Senra, M. E. Medeiros, O. A. C. Antunes, *Supramol. Chem.* **2006**, *18*, 327–331; b) J. D. Senra, L. F. B. Malta, A. L. F. de Souza, M. E. Medeiros, L. C. S. Aguiar, O. A. C. Antunes, *Tetrahedron Lett.* **2007**, *48*, 8153–8156; c) L. F. B. Malta, Y. Cordeiro, L. W. Tinoco, C. C. Campos, M. E. Medeiros, O. A. C. Antunes, *Tetrahedron: Asymmetry* **2008**, *19*, 1182–1188; d) B. L. Oliveira, O. A. C. Antunes, *Lett. Org. Chem.* **2007**, *4*, 13–15.

[11] Q.-X. Guo, S.-H. Luo, Y.-C. Liu, *J. Incl. Phenom.* **1998**, *30*, 173–182.

[12] A. Cassez, N. Kania, F. Hapiot, S. Fourmentin, E. Monflier, A. Ponchel, *Catal. Commun.* **2008**, *9*, 1346–1351.

[13] a) G. Oehme, E. Paetzold, T. Dwars, *Angew. Chem. Int. Ed.* **2005**, *44*, 7174–7199; b) B. H. Lipshutz, B. R. Taft, *Org. Lett.* **2008**, *10*, 1329–1332.

[14] M. R. Knecht, M. G. Weir, A. I. Frenkel, R. M. Crooks, *Chem. Mater.* **2008**, *20*, 1019–1028.

[15] A. V. Gaikwad, G. Rothenberg, *Phys. Chem. Chem. Phys.* **2006**, *8*, 3669–3675.

[16] Y. Liu, K. B. Male, P. Bouvrette, J. H. T. Luong, *Chem. Mater.* **2003**, *15*, 4172–4180.

[17] A. Perosa, P. Tundo, M. Selva, S. Zinovyev, A. Testa, *Org. Biomol. Chem.* **2004**, *2*, 2249–2252.

[18] S. Cachi, *Pure Appl. Chem.* **1990**, *62*, 713–722.

[19] a) M.-J. Wu, L.-M. Wei, C.-F. Lee, S.-P. Leou, L. L. Wei, *Tetrahedron* **2001**, *57*, 7839–7844; b) J.-C. Hierso, M. Picquet, H. Cattey, P. Meunier, *Synlett* **2006**, 3005–3008; c) J. C. Barros, A. L. F. de Souza, P. G. de Lima, J. F. M. da Silva, O. A. C. Antunes, *Appl. Organomet. Chem.* **2008**, *22*, 249–252.

[20] Previous TPR measurements pointed to a considerable amount of Pd(II) species.

[21] a) P. Raveendran, J. Fu, S. L. Wallen, *J. Am. Chem. Soc.* **2003**, *125*, 13940–13941; b) P. Raveendran, J. Fu, S. L. Wallen, *Green Chem.* **2006**, *8*, 34–38; c) V. L. Budarin, J. H. Clark, R. Luque, D. J. Macquarrie, R. J. White, *Green Chem.* **2008**, *10*, 382–387.