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Poly(4-vinylpyridine) and Quadrapure TU as Selective Poisons for Soluble Catalytic Species in Palladium-Catalyzed Coupling Reactions – Application to Leaching from Polymer-Entrapped Palladium

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Abstract: Poly(4-vinylpyridine) and Quadrapure TU were successfully used as poisons for palladium-catalyzed Heck couplings of iodoarenes and *n*-butyl acrylate using a poly(urea) entrapped palladium precatalyst, Pd-EnCat 40, in a variety of reaction solvents and conditions. These results suggest that all of the Heck coupling takes place outside the poly(urea) matrix *via* a soluble palladium species leached from the solid. This observation is consistent with previous conclusions that leached species are also solely active when using other supported catalysts such as Pd/C or with supported palladacycles. Control experiments including poisoning by Hg(0), hot filtration, 3-phase tests, and monitoring of reaction kinetics after recycle support this conclusion. The quantity of PVPy or Quadrapure TU needed for quenching depends on the amount of palladium that is leached and thus applying these poisons to other palladium catalysts in which the amount of soluble palladium is unknown requires an initial trial and error approach.

Keywords: Heck reaction; leaching; palladium; selective catalyst poisons; supported catalysts

Introduction

The ability to recycle and recover palladium catalysts for coupling reactions such as the Heck reaction is of great interest. Traditional heterogeneous precatalysts such as palladium on carbon (Pd/C)[1–4] or palladium on oxides[4–6] have been used effectively, although it has been conclusively shown in essentially all cases they operate by a release and capture mechanism, whereby soluble palladium that is the active catalyst is leached from the solid.[4–8] After all the aryl halide is consumed, the soluble palladium can in some cases redeposit on the support. Despite numerous reports claiming palladium surface-catalyzed Heck reactions, there is no conclusive proof in the literature to support them.[8] Many other types of heterogeneous precatalysts have been prepared with a goal of achieving catalyst recovery and recycle, including Pd-loaded zeolites,[4,5,9–11] silane-functionalized oxides,[12–15] and immobilized Pd(II) complexes.[16–24] In most cases where the authors carefully test for homogeneous vs. heterogeneous catalysis, the nature of the true active palladium species is clear,[3–7,8–10,12,13,19–24] with it usually[25] being leached, soluble palladium species, not supported palladium sites. However, in the vast majority of cases (primarily those not cited here), the identity of the true active species remains unclear, and routinely, only a few (often non-conclusive[8]) control experiments are done to probe potential leaching of active or inactive palladium. Nonetheless, more often than not, new supported forms of palladium continue to be erroneously reported as recoverable, recyclable solid catalysts.

A variety of different control experiments has been applied to palladium-catalyzed coupling reactions to assess the nature of the true active species. Use of only a single test can lead to incorrect conclusions about the nature of the active species and, therefore, numerous complimentary tests must be used together to gain an accurate picture of the catalysis.[8,26] Most often, a filtration or split test is used to analyze for palladium leaching from solid catalysts.[27] In this case, the reaction is filtered, for example, midway through a reaction and the solid-free filtrate is monitored for reaction. This test alone, when positive (i.e., the filtrate is shown to have activity) is strong evidence that soluble species that were able to pass through the filter are active catalysts. However, a negative result from a filtration test, when conducted alone, is not sufficient proof that there are no leached

active species when coupling reactions are probed. This is because of the possibility of the soluble species redepositing on the support during the filtration, a behavior that has been observed by Lipshutz in related chemistries.[28] Thus, while split tests or hot filtration tests are valuable tools in the chemist's arsenal for characterizing catalyst leaching, they should not be used as a sole test for heterogeneity in coupling chemistry.[8,26]

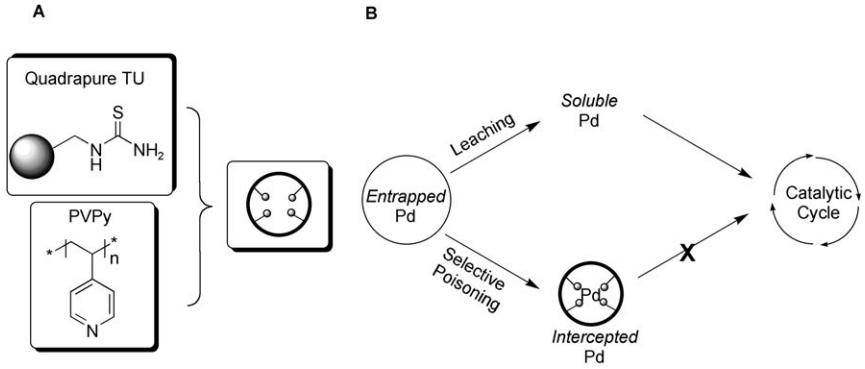
Elemental analysis (EA) of the filtered reaction solution by ICP-MS is another common technique to measure the amount of leached palladium, but it too is complicated by the same reasons as noted for hot filtration. Additionally, elemental analysis of the support before and after reaction is often used to quantify the amount of palladium lost, but the catalyst is often recovered *via* filtration and some or all of the previously soluble palladium can potentially redeposit back onto the solid during this process, thereby lowering the amount of lost palladium determined by EA. Furthermore, in many cases, the amount of leaching necessary to create soluble active species is so low[29,30] that the loss would not be detected by elemental analysis of the solid precatalyst before and after use in a reaction. It should be noted that, for practical application, the amount of leached palladium as determined by elemental analysis might be an extremely important parameter. However, for catalysis science, understanding of the location of the active site is critical and thus additional tests beyond EA are needed in fundamental investigations.

Similarly, recycling and reuse of a catalyst several times without loss in final *yield* is often given as proof that the catalyst is sufficiently recyclable.[8,31] However, it is often the case that reaction kinetics are not reported and although the final conversion might be the same for each reuse (given enough time), the catalyst *activity* is often significantly lower due to degradation or loss of metal. Average turnover frequencies (TOFs) can be useful for comparison, although as Beletskaya[32] points out, these can be potentially misleading if induction periods of differing lengths exist for different samples or different runs.

Poisoning of Pd(0) by elemental mercury is often used as a test for heterogeneous catalysis. If addition of Hg(0) to a reaction extinguishes activity, this is often viewed as a conclusive test for catalysis by metal surfaces, because this is the way the historic literature describes the test.[33,34] This is often the case *in the context of the original studies*. Indeed, the historic literature with the Hg(0) test focuses on hydrogenation reactions with metal complexes in elevated formal oxidation states bound by protective ligands. Certainly, these catalysts are not affected by Hg(0), as they are not M(0) species and they are protected by strong ligands. However, we hypothesize that the "naked" molecular Pd(0) species, that have been postulated to be the true active catalytic species in many cases,[35,36] are an example of *homogeneous catalysts that should be affected by Hg(0)*, as a consequence of their lack of protecting strong ligands and their M(0) state. This effect could be associated with interactions with molecular Pd(0) species, or more likely *via* amalgamation of the soluble palladium nanoparticles that are often present in equilibrium with active molecular palladium. Thus, we do not feel that, in the context of palladium-catalyzed coupling chemistries, poisoning by Hg(0) can be taken as proof of catalysis by macroscopic or colloidal palladium particles.[8]

The so called "three phase" test[37–39] can be used to detect the presence of soluble catalytic palladium, whereby one of the reagents is anchored on a different solid from the catalyst and can only react if a soluble, catalytic palladium source is present (assuming negligible background reaction). This can be a powerful test, although it must be used carefully, as often one or several of the reagents are required to induce leaching of the palladium. Thus, if the immobilized reagent is the one required to cause leaching from the precatalyst, one must be sure to add a soluble component as well,[12] which can cloud the experimental results. For example, if an aryl halide is needed for leaching of palladium (as is often but not always the case), a soluble aryl halide must be added to the system.

It is noteworthy that all of the tests described above are capable of elucidating whether there is soluble catalysis, but none of them are capable of conclusively indicating if there is catalysis by immobilized catalytic species or a solid surface. Thus, in many contributions, authors have identified catalysis by soluble species but could not rule out some catalysis by supported sites. The Hg(0) test is capable of extinguishing catalysis by free Pd(0),[8,22–24,26,40,41] although it is not believed that it can discriminate between heterogeneous, macroscopic palladium particles, soluble palladium nanoparticles, or homeopathic[35,36,42,43] palladium (*vide supra*).[8] What is needed is a poison that is selective for leached, homogeneous species. Here we report on the use of insoluble, cross-linked poly(4-vinylpyridine) (PVPy) and a thiourea functionalized polymer (Quadrapure TU) as selective traps for soluble catalytic palladium species (Scheme 1). These poisons are applied to the study of a relatively new catalyst system that has recently been reported as a recoverable, recyclable Pd catalyst for coupling reactions, Pd-EnCat, a poly(urea) entrapped $Pd(OAc)_2$ material.[44–49]



Scheme 1. Selective poisons, Quadrapure TU and PVPy, used in this study (**A**) and an illustration of leaching of Pd from an entrapped matrix and then either entering the catalytic cycle or being intercepted by selective poisons (**B**).

Results and Discussion

Poly(4-vinylpyridine) as a Poison

In our recent work on the nature of the active species using soluble and immobilized Pd(II) SCS and PCP pincer coupling catalysts, it was necessary to devise a poison that could selectively quench catalysis by soluble catalytic species while leaving immobilized sites within the pores of a silica support or on a polymer backbone unaffected.[22–24] Recalling the use of bulky or polymeric amines as basic poisons for accessible acid sites (soluble sites or insoluble sites on the external surface of solids),[50,51] we surmised that such materials might work equally well for removing free Pd species from solution in coupling reactions. Indeed, we found literature reports describing that addition of a large excess of copolymers of PVPy effectively extinguished any activity associated with palladium nanoparticle precatalysts in the Heck reaction of styrene and 4-bromoacetophenone.[52] In contrast, addition of molecular pyridine merely slowed the reaction rate. Thus, the poisoning effect of PVPy was ascribed to its ability to pull soluble Pd out of solution, binding it tightly in a multidentate manner. Another nice example of an insoluble metal poison is polymer-bound thiophenol, which was effectively used by Ley to show that palladium-containing perovskites were actually sources of active, soluble palladium species.[53]

In our work characterizing SCS and PCP Pd(II) complexes in Heck couplings, we utilized an array of tests to conclusively show that all catalysis in these systems was associated with leached Pd(0) species.[22–24] Whereas it had been reported previously that palladacycles like the half-pincer Herrmann–Beller complex decompose to give active Pd(0) species,[20,32,54–58] it had never been possible to conclusively rule out small amounts of catalysis by Pd(II) or Pd(0) species that still retained the Pd-C palladacycle bond [operating in Pd(0)-Pd(II) or Pd(II)-Pd(IV) cycles].[59] Similar results were obtained on phosphite PCP pincers at the same time we reported on decomposition in SCS pincers.[41] Again, it was not possible to rule out small amounts of catalysis by intact metal-ligand complexes in that work, although it was clear that the vast majority of catalysis was promoted by Pd(0) species (nanoparticles, it was suggested). In contrast, by immobilizing SCS and PCP pincer complexes onto insoluble porous silica supports and soluble poly(norbornenes), it was possible to conclusively show for the first time that there was effectively no catalysis by intact pincer species.[22–24] Essentially complete poisoning of catalysis by Hg(0) and PVPy showed that only leached Pd(0) species were active. Generation of such species necessarily required breaking of the Pd–C palladacycle bond, and these supported systems were found to be simply another source of homeopathic palladium.[35–36,42–43]

Entrapped Pd Catalysts in Coupling Reactions

Palladium acetate entrapped in a polyurea matrix is commercially available as a series of catalysts sold as Pd-EnCat. It has been described as a recyclable, immobilized catalyst system that simplifies removal of Pd in C–C bond forming and reduction processes.[44,48,60] As it has generally been accepted that solid precatalysts operate at high temperatures by releasing soluble palladium into solution, it was of interest to see if this precatalyst also behaved the same way. Thus, Pd-EnCat represented an interesting system for study using PVPy and Quadrapure TU as poisons. In particular, we focused on elucidating whether the catalysis occurs at palladium sites entrapped within the solid matrix or whether, like other supported catalysts (Pd/C, Pd/SiO_2, etc.), these systems represented solids that released Pd into solution, where the catalysis could ultimately occur.

Catalytic Studies

Palladium immobilized on carbon is widely known to be a source of soluble palladium for Heck couplings of iodoarenes.[3,6–8] We selected this as a model precatalyst to verify that PVPy and Quadrapure TU will quench catalysis from leached palladium species from solid sources under our reaction conditions. Figure 1 displays the results of the effect of PVPy and Quadrapure TU on the Heck coupling of iodobenzene with butyl acrylate in DMF (Scheme 2). Reactions were conducted at 110 °C and activated by addition of triethylamine at an iodobenzene to palladium ratio of 40:1. When 300 equivalents of PVPy *to total palladium content* were added after 15 min (50 % conversion) the reaction slowed but did not immediately cease. When Quadrapure TU was used, a complete loss of activity was observed. This is consistent with their use as efficient palladium scavengers. The amount of Quadrapure used was twice that required to bind all the added palladium based on the manufacturer's reported scavenging limit, 0.19 mmol Pd per gram polymer. In our previous studies, the PVPy was applied to systems where only a fraction of the total palladium content was leached into solution and thus 300 equivalents *to total palladium content* were found to be sufficient for complete quenching. However, the fact that the Pd/C reaction is slowed upon addition of this much PVPy may suggest that the amount added was not sufficient to bind all the leached palladium. A subsequent reaction was performed in which the amount of PVPy added at 15 min was raised to 450 equivalents (Figure 1). Complete cessation of activity was observed in this case, but not until several hours after addition of the PVPy. Thus, these initial studies confirmed that both PVPy and Quadrapure TU are effective poisons that can completely shut down reactivity using solid precatalysts that are known to operate by leaching of active, soluble species.

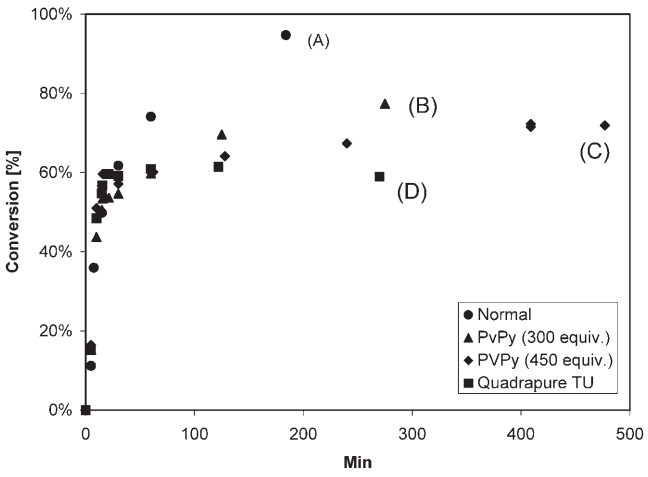
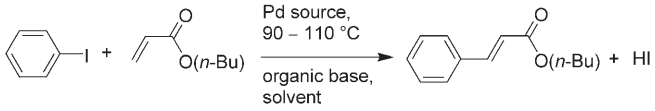


Figure 1. Conversion of iodobenzene as a function of time *via* Heck catalysis by Pd-C under normal conditions (**A**), with 300 equivalents of PVPy added at 15 minutes (**B**), with 450 equivalents of PVPy added at 15 min (**C**), and with Quadrapure TU added at 15 min (**D**). Reaction (**A**) reached full conversion by 750 min.



Scheme 2. General depiction of Heck coupling of iodobenzene with *n*-butyl acrylate. Listed conditions encompass those used in this study. Pd sources included Pd/C or Pd-EnCat 40 and solvents used were either DMF, isopropyl alcohol, or toluene.

Next, we shifted our focus to Pd-EnCat 40 as a precatalyst for the Heck couplings. If leaching occurs with Pd-EnCat 40, it was expected to be less than that for the Pd/C and so the 300 equivalents of PVPy were kept constant across all reactions unless otherwise noted. Pd-EnCat 40 was purchased from Aldrich and used without further modification in the Heck coupling of iodobenzene or iodopyridine and butyl acrylate in either isopropyl alcohol (IPA) at 90 °C, toluene at 110 °C, or DMF at 110 °C. In all experiments with Pd-EnCat 40, a 40:1 ratio of aryl halide to palladium was used. Elemental analysis (Desert Analytics, Tucson Arizona) of the Pd-EnCat 40 showed a 4.8 % atomic mass percent palladium corresponding to a palladium loading of 0.45 mmol per gram catalyst which is comparable to the 0.4 mmol per gram reported by the manufacturer. The makers of Pd-EnCat 40, Reaxa Ltd., report leaching tests of various solvents in which they stir the Pd-EnCat 40 at 80 °C for two days, cool to room temperature, then filter off the catalyst, after which only ppm levels of palladium in the filtrate were measured.[60] In the same report they also described the ability of various solvents to swell the polymer matrix of Pd-EnCat 40 at room temperature over two hours. These previous results indicated that, among the three solvents selected for this study, DMF has the greatest percentage of polymer swelling and gives the most palladium in solution at 110 % and 7 ppm, respectively. IPA and toluene cause significantly less swelling at 5 % and 0 %, respectively, and both have <1 ppm of palladium detected in solution. As the reported leaching tests were not performed under Heck reaction conditions it was difficult to determine, based on these results, how much palladium might leach during a Heck coupling. Also, it is possible that the amount of palladium in solution during the 80 °C treatment was higher than that reported at the end, as the cooling step could cause palladium deposition on the Pd-EnCat 40 (*via* a release and recapture process akin to those observed with Pd/C) and/or formation of palladium black that is removed

during the filtering process. In a separate report by Smith, it was suggested that, when using Pd-EnCat 40 for Heck couplings in DMF at 200 °C, the catalyst acts as a slow reservoir of soluble Pd(0) nanoparticles.[61] Other reports described reactions performed in either IPA, supercritical carbon dioxide, or toluene as solvents.[48,49] When reacting in IPA, the palladium content of the crude reaction solution was the only measurement for detection of palladium leaching and a loss of 2.8 % of the original palladium was reported. No other tests for leaching or tests to determine whether the reaction truly happens inside the polyurea matrix were performed, although it appears that this is a general hypothesis about how the Pd-EnCat catalyst line operates.[60,61]

Based on the previously mentioned results in the literature, DMF is the most likely reaction solvent to promote leaching of palladium from Pd-EnCat 40 as compared to toluene or IPA. A number of tests under varying reaction conditions were performed to verify this hypothesis. Figure 2 displays the results of the Heck coupling of iodobenzene and *n*-butyl acrylate in DMF. Two types of experiments were done, some with preheating of the catalyst and reaction solution (without base) for twenty-five minutes, followed by addition of base to initiate catalysis, and one where the catalyst and all reagents were added together and the reaction was initiated *via* immersion in an oil bath. Results from experiments with addition of PVPy, Quadrapure TU or Hg(0) at different points during the reaction are also shown. The preheated reaction progressed rapidly upon the addition of base, whereas the reaction proceeded slightly slower with a slight induction time without preheating of the solution. In every case in which a known poison was used, the reaction was rapidly stopped after the addition of the poison, except for when Quadrapure TU was added at 3.5 min (10 % conversion). This reaction continued until it ceased sometime between 7.5 and 10 min (30 % conversion) and this was most likely due to a competition between the rate of reaction, which is quite fast under these conditions, and the rate of quenching by the Quadrapure TU. We hypothesize that once all of the leached palladium is finally bound the Quadrapure TU, the reaction no longer progresses. An argument could be made that in this case some amount of reaction is still occurring inside the Pd-EnCat 40 matrix, but considering that the other reactions using PVPy essentially stop after addition of the poison, it is highly unlikely that this is occurring.

Other tests were conducted in DMF to further probe whether or not leaching occurred. Reaction kinetics after one recycle were monitored and after a hot filtration test was performed in which the preheated solution was filtered while hot and base was immediately added to the filtrate to initiate reaction (Figure 3). The decrease in reaction rate using recycled Pd-EnCat 40 indicates that some of the palladium was lost during reaction and/or was in some way deactivated. Reaction after hot filtration of the preheated solution indicates that some form of soluble palladium species was leached from the Pd-EnCat 40 and was active for Heck coupling. Elemental analysis of Pd-EnCat 40 after one reaction in DMF showed a decrease in atomic weight percent of palladium from 4.80 % to 2.84 %, a 41 % loss of palladium. Given that some of the soluble palladium may have precipitated onto the polymer, this value should be viewed as a lower boundary for leached palladium. A 3-phase test

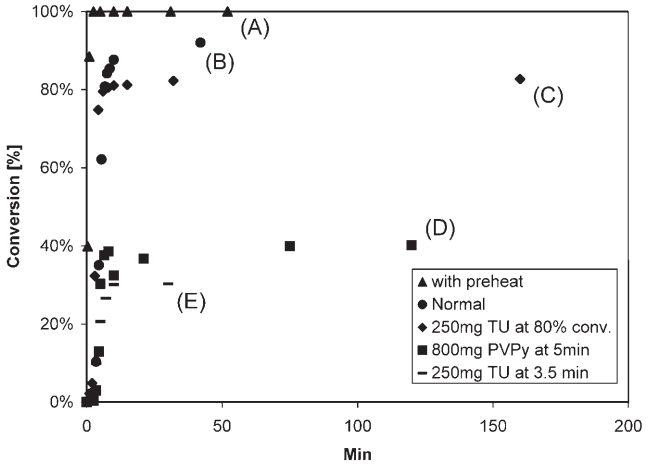


Figure 2. Conversion of iodobenzene as a function of time *via* Heck catalysis by Pd-EnCat 40 in DMF with preheating (**A**), under normal conditions (**B**), with Quadrapure TU added at 6 min (**C**), with 300 equivalents PVPy added at 5 min (**D**), and with Quadrapure TU added at 3.5 min (**E**).

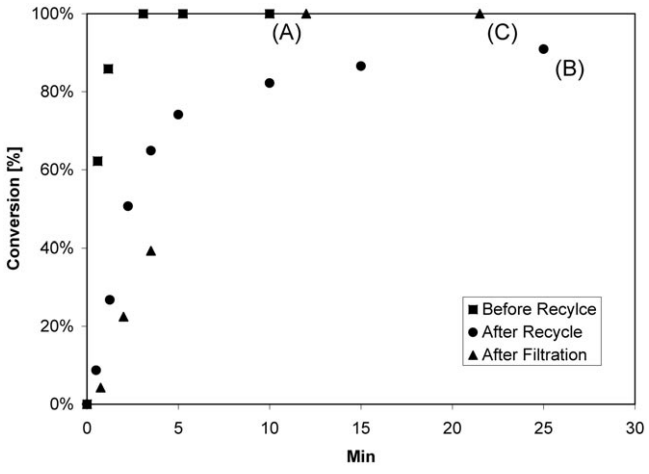
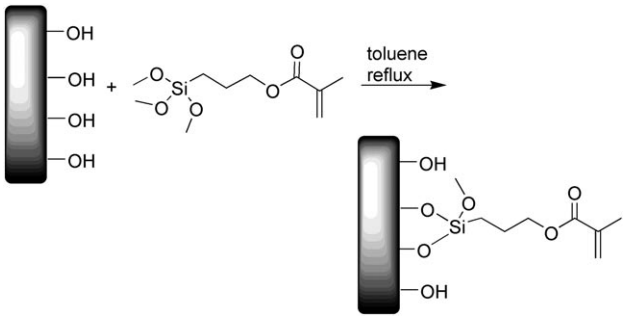


Figure 3. Conversion of iodobenzene as a function of time *via* Heck catalysis by Pd-EnCat 40 in DMF with preheated normal reaction (**A**), after recycle of same catalyst used for **A** (**B**), and after hot filtration of the preheated solution (**C**).



Scheme 3. Immobilization of methacroyloxypropyltrimethoxysilane on SBA-15 for use as 3-phase material in Heck catalysis.

was conducted in which an acrylate, methacroyloxypropyltrimethoxysilane, was immobilized on a porous silicate (Scheme 3). After 6.5 h, 0.22 mmol of the iodobenzene were consumed, consistent with 73% of the initial 0.3 mmol of immobilized acrylate reacted. No presence of coupled product was detected in solution indicating negligible leaching of the acrylate from the silica. An attempt to identify the solid-bound coupling product *via* FT-Raman analysis of the silica after reaction was inconclusive due to the low loading of organic on the silica and the difficulty in separating out the Pd-EnCat 40 from the silica particles after reaction.

Some additional observations of the Heck reactions in DMF also indicate the presence of soluble palladium. During the pre-heating of the solution (before activation by base) a significant color change of the solution was observed in DMF from clear to dark pinkish (also observed with Pd/C). Additionally, the Pd-EnCat 40 particles changed from reddish-orange to black. In contrast, no solution color change was observed in most reactions involving IPA, although the catalyst particles changed color as they did in DMF.[62] The solution color changes attributed to Pd-EnCat 40 may be due to leaching of a significant amount of entrapped palladium during the pre-heat in DMF.[63] In the case of IPA, either not enough palladium is leached to cause a noticeable color change, the leached palladium is quickly deactivated by formation of palladium black, or no palladium is leached during the preheat step. The blackish color change of the particles, which remains after the reaction and recovery of the particles, is consistent with formation of Pd(0). As this might be indicative of formation of palladium black on or inside the particles, a potential deactivation pathway, preheating the solution was only used for a limited number of reactions. After addition of either PVPy or Quadrapure TU to reactions in DMF using either Pd-EnCat 40 or Pd/C, the pinkish tinge disappeared, signifying removal of most if not all palladium from solution.

As noted previously, Heck couplings of various substrates with *n*-butyl acrylate in IPA were reported previously[48] and leaching was reported to be more limited in this solvent than in DMF.[60] To this end, poisoning tests using Hg(0) and PVPy in IPA were performed on this system. Similar to the results reported above for reactions in DMF, the activity in IPA ceased after either Hg(0) or PVPy was added to the reaction (Figure 4). Additional Heck couplings in IPA were performed with iodobenzene and *n*-butyl acrylate using two different bases, triethylamine or tri-*n*-propylamine. Addition of PVPy or Quadrapure TU to these reactions also resulted in a cessation of activity (Figure 4). The results from these reactions performed in IPA indicate that all of the catalysis is performed *via* leached palladium. A hot filtration test (as was previously described for a pre-heated DMF solution), was performed with IPA as the solvent and iodobenzene as the aryl halide. Unlike in the case of DMF, where significant activity was observed in solution after addition of base, no reaction was observed in IPA. Since the filtration was of the preheated solution that was missing base, it is likely that the leaching only likely takes place after addition of base in this case, as leaching of Pd upon heating with pure IPA[60] or with solvent and some reagents did not seem to occur. However, the reaction poisoning by Quadrupre TU or PVPy is interpreted as being consistent with all catalysis occurring *via* leached active palladium species.

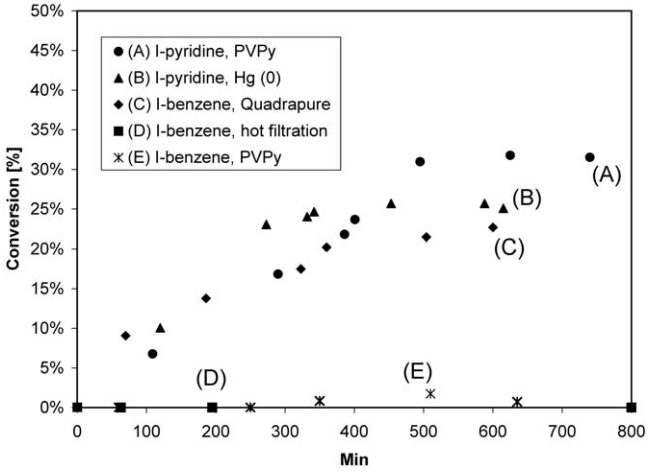


Figure 4. Conversion of iodopyridine as a function of time *via* Heck catalysis by Pd-EnCat 40 in isopropyl alcohol with 300 equivalents of PVPy added at 400 min (**A**), with 300 equivalents of Hg(0) added at 342 min (**B**). Conversion of iodobenzene as a function of time *via* Heck catalysis by Pd-EnCat 40 in isopropyl alcohol after adding Quadrapure TU at 350 min (**C**), after filtration of preheated solution (**D**), with 300 equivalents of PVPy added prior to start of reaction (**E**).

A series of reactions was also performed using toluene as a solvent. Reaction data with and without use of poisons are shown in Figure 5. Similar to when IPA was used, the reactions in toluene proceeded significantly slower than reactions performed under similar conditions in DMF. Observations regarding quenching by PVPy, Quadrapure TU, or Hg(0) are the same in toluene as was noted for DMF and thus the same conclusions apply, that all of the catalysis occurs *via* soluble palladium outside of the Pd-EnCat 40 matrix. This is further supported by a 3-phase test in which 0.12 mmol of iodobenzene were consumed in 6.5 h when using the immobilized acrylate.

Thus, in all solvents tested, Pd-EnCat 40 appears to be a reservoir for soluble, active palladium species that catalyze the reaction in solution under these conditions. Essentially no reaction appears to occur in the polymer matrix. These results are wholly consistent with those seen with more traditional palladium metal particle precatalysts such as Pd/C or Pd/SiO_2.[3–10] Furthermore, it appears that the rate of reaction may correlate with the amount of palladium that is leached and stabilized in solution. Significant palladium leaching occurred using DMF, which gave by far the highest rates. Use of IPA or toluene did appear to cut down on palladium leaching, making these potentially useful precatalysts as was previously reported,[60] but these solvents severely reduced the reaction rate as well. Indeed, the averaged TOFs in IPA and toluene were 50-fold lower than in those in DMF. These lower reaction rates may be a consequence of limited stabilization of leached palladium in IPA and toluene, or perhaps due to low levels of leaching in these solvents. It should also be noted that the substrate:catalyst ratio has a strong impact on the reaction rates and the relatively low substrate:catalyst ratio used here (40:1) may account for the markedly lower rates seen here in all solvents compared to previous reports.[36]

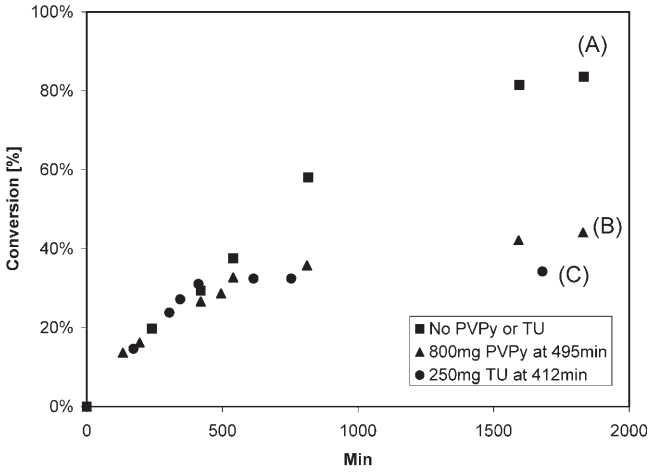


Figure 5. Conversion of iodobenzene as a function of time *via* Heck catalysis by Pd-EnCat 40 in toluene under normal conditions (**A**), with 300 equivalents of PVPy added at 400 min (**B**), and with Quadrapure TU added at 15 min (**C**).

The Pd-EnCat line has been reported to mediate a variety of different catalytic reactions while facilitating recovery of the palladium after reaction.[44,48,60] While this report suggests that the activity associated with this precatalyst is completely derived from leached palladium species in the Heck reaction (and likely in other coupling reactions involving aryl halides as well), it does not necessarily imply that for other chemistries, the reaction cannot or does not occur within the polymer particles.

Conclusions

Under the reaction conditions studied, both crosslinked poly(4-vinylpyridine) and Quadrapure TU are effective poisons of active soluble palladium species in Heck reactions. They have been successfully used for the detection of leached, active palladium from both Pd/C and from a polyurea encapsulated Pd-$(OAc)_2$ during the catalysis. Results of this study also indicate that in the case of the polyurea encapsulated palladium, negligible reaction occurs inside the matrix as compared to that in solution from leached palladium when either DMF, IPA, or toluene is used as the solvent. As noted in previous works,[48,49,60,61] careful choice of solvent allows Pd-EnCat 40 to be an effective *precatalyst* in Heck coupling reactions, as it limits the amount of soluble palladium that is generated, leading to reaction products potentially containing very little palladium. However, in doing so, the reaction rates are suppressed, as it appears that only leached palladium participates in the catalysis. It should be noted that, after submission of this work, a careful, comprehensive study by Broadwater and McQuade appeared that reached similar conclusions with regard to leaching of palladium from other Pd-EnCat catalysts under Heck and Suzuki conditions.[64] Using 3-phase tests and TEM analysis they showed that leaching of catalytically active palladium was occurring, but they could not determine whether any catalysis was occurring inside the Pd-EnCat matrices. The absence of such activity was demonstrated here. We suggest that other metal scavengers could be similarly applied as selective poisons to other heterogeneous precatalysts for distinguishing whether or not leaching is occurring. However, it should be pointed out that a range of tests is needed to probe how much poison is required in each case, as catalysis can still occur if an insufficient amount of poison is added. Performing complimentary tests such as studying kinetics after recycle, hot filtration, and 3-phase analysis is advised as well.[8] Ultimately, the reactivity of the Pd-EnCat 40 fits perfectly the trends described previ-

ously in the literature, with essentially all precatalysts (whether they be supported[3–6], soluble[32,35,42], or "entrapped"[47,48]) giving active soluble ligand-free palladium when using high temperatures and aryl iodides as reagents[8,36,65] in the Heck reaction.

Experimental Section

General Remarks

Pd-EnCat 40 (Aldrich) was purchased and used without further modification. *N,N*-Dmethylformamide and *n*-butyl acrylate were dried by stirring with CaH_2 for 24 h, distilled and stored at < 4°until use. Isopropyl alcohol (< 50 ppm H_2O, ACROS) was used as received and syringed under argon pressure. Elemental analyses were performed by Desert Analytics (Tucson, Arizona). All other reagents were used as received from commercial sources.

Heck Reactions

In general, iodobenzene was coupled with *n*-butyl acrylate in 5.0 mL of solvent at either 110 °C for DMF and toluene or 90 °C for isopropyl alcohol. Molar ratios of aryl halide, acrylate and base were 1.0:1.5:3.0, respectively, and all reactions were conducted under an argon atmosphere using standard Schlenk line techniques. Typically 60 mg of Pd-EnCat 40 or 85 mg of Pd-C were added to a 50 mL three-necked flask and 5.0 mL of a solution of the reagents (40:1 molar ratio of aryl halide to palladium) were added and the entire system was purged with argon. To initiate reaction the solution was immersed in a temperature-controlled oil bath followed immediately by addition of a solution of base (0.5 mL of solvent) into the reaction mixture. Triethylamine was used as the base in reactions in which the solvent was DMF or toluene and tetra-*n*-butylammonium acetate was used as a base for reactions in isopropyl alcohol unless indicated otherwise. Time zero samples were taken just prior to base addition and conversions of iodobenzene or iodopyridine were monitored by gas chromatography and referenced to an internal standard, dodecane.[24] A slightly different procedure was used for reactions involving iodopyridine. In reactions in which iodopyridine was used, all reagents and base were stirred overnight at room temperature under argon to insure adequate dissolution of iodopyridine. Pd-EnCat 40 was then added under positive argon pressure and the solution was immediately immersed in a 90 °C oil bath to initiate reaction.

Poisoning Studies

Poisons were either introduced prior to initiation of reactions by the addition of base or were added during the reaction sequence. Amounts of PVPy were adjusted to give 300 equivalents of pyridine units to total palladium content. The reported palladium scavenging of Quadrapure TU is 0.19 mmol $g.^{-1}$ Amounts of Quadrapure TU were adjusted such that double the amount required for complete scavenging all of the palladium introduced into the reaction was present. For example, when 60 mg (0.025 mmol of Pd) of Pd-EnCat 40 were used an amount of 250 mg of Quadrapure TU was added to quench the reaction. Enough Hg(0) was added to provide 300 equivalents of mercury to total palladium content and stirring was inspected to insure adequate breakup of mercury.

3-Phase Test

Methacroyloxypropyltrimethoxysilane was immobilized on hexagonal mesoporous silica SBA-15 with 100 Å diameter pores by mixing 25 g of the silane with 4.5 g of SBA-15 in dry toluene under argon and refluxing for 24 h, at which point 0.4 mL of DI water were added. Reflux was continued for 4 h, then the reaction was allowed to cool, was filtered and washed with approximately 750 mL of toluene and 500 mL of hexane. Filtered solids were then Soxhlet extracted for 72 h with dichloromethane. Solids were then dried under high vacuum for 16 h. Loading of organic material was determined by TGA (NETZSCH STA 409) and found to be 0.66 mmol g^{-1}. For the synthesis of 100 Å SBA-15 refer to Galarneau et al.[66] 3-Phase tests were then conducted using the acrylate-functionalized silica by simply adding 500 mg of 3-phase material to a Heck reaction, similar as that described above, before the addition of base. *n*-Butyl acrylate was excluded from all 3-phase tests.

Recycling and Reuse of Catalysts

Recovery of Pd-EnCat 40 was done by simple filtration under slight vacuum. Recovered solids were extensively washed with dichloromethane, THF and acetone, until GC analysis of the filtrate indicated no detectable amounts of reagents or products, followed by drying under high vacuum overnight. Recovered materials were stored in sealed sample vials until use.

Hot Filtration

Hot filtration tests were conducted in which a reaction solution consisting of 163 mg of iodobenzene, 155 mg of *n*-butyl acrylate, 50 mg of Pd-EnCat 40, 136 mg of dodecane and 5.0 mL of solvent was preheated in an oil bath at the reaction temperature for 25 min (90 °C for IPA and 110 °C for DMF). The hot solution was then quickly filtered under static vacuum in an inert atmosphere of argon by use of a swivel frit attached to a Schlenk line. Next, 131 mg of tri-*n*-propylamine, 1.2 equivalents to iodobenzene, was added to the catalyst-free filtrate to initiate the reaction, which was monitored by GC.

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