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Communication

Halide-Enhanced Catalytic Activity of Palladium Nanoparticles Comes at the Expense of Catalyst Recovery

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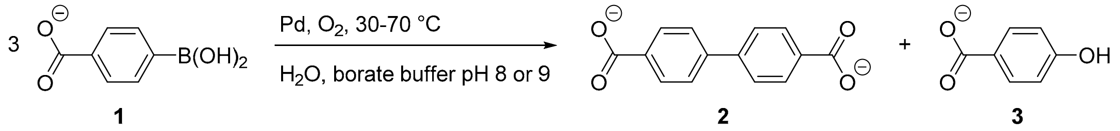
Abstract: In this communication, we present studies of the oxidative homocoupling of arylboronic acids catalyzed by immobilised palladium nanoparticles in aqueous solution. This reaction is of significant interest because it shares a key transmetallation step with the well-known Suzuki-Miyaura cross-coupling reaction. Additives can have significant effects on catalysis, both in terms of reaction mechanism and recovery of catalytic species, and our aim was to study the effect of added halides on catalytic efficiency and catalyst recovery. Using kinetic studies, we have shown that added halides (added as NaCl and NaBr) can increase the catalytic activity of the palladium nanoparticles more than 10-fold, allowing reactions to be completed in less than half a day at 30 °C. However, this increased activity comes at the expense of catalyst recovery. The results are in agreement with a reaction mechanism in which, under conditions involving high concentrations of chloride or bromide, palladium leaching plays an important role. Considering the evidence for analogous reactions occurring on the surface of palladium nanoparticles under different reaction conditions, we conclude that additives can exert a significant effect on the mechanism of reactions catalyzed by nanoparticles, including switching from a surface reaction to a solution reaction. The possibility of this switch in mechanism may also be the cause for the disagreement on this topic in the literature.

Keywords: catalysis; palladium; nanoparticles; boronic acid; polypyrrole; leaching; nanocomposite; halide; kinetics; reaction mechanism

1. Introduction

1.1. The Oxidative Homocoupling Reaction of Arylboronic Acids

The Suzuki-Miyaura cross-coupling reaction (SMXR) is one of the best-known C-C bond-forming reactions. Considerably less well-known is its mechanistic cousin, the oxidative homocoupling reaction (OHR) of arylboronic acids (illustrated for water-soluble reactants and products in Scheme 1). Where the SMXR involves an oxidative addition and a transmetallation of an arylboronic acid, the OHR involves two consecutive transmetallations [1,2]. The OHR is thus an ideal reaction to study the transmetallation step in separation.



Scheme 1. The palladium catalysed oxidative homocoupling reaction of 4-carboxyphenylboronic acid (**1**) to form 4,4′-dicarboxybiphenyl (**2**) and 4-hydroxybenzoic acid (**3**).

Of interest for the current study is the effect of added salts on the SMXR and the OHR. Added halides often exert a rate-retarding effect on the SMXR and the OHR. This rate-retarding effect has been attributed to the formation of unreactive halo-palladium complexes [3]. The effects of added chloride can be more complicated [4,5] including as a result of leveling the energy profile around the catalytic cycle [6]. The ability to study the transmetallation step in the absence of the halide-releasing oxidative addition step thus offers opportunities for improved mechanistic understanding. Although the OHR is often considered an unwanted side reaction of the SMXR, it can be usefully applied in synthesis as well (e.g., Ref. [7]).

1.2. Nanoparticle Catalysis

Catalysis by metal NPs) is a hot topic in chemical research because it offers tantalizing prospects of efficient reactions under mild environmentally friendly conditions [8]. NP catalysis rather literally occurs around the boundary between homogeneous and heterogeneous catalysis and has been referred to as "semi-heterogeneous catalysis" [9]. Catalysis by nanoparticles poses intriguing questions and gives rise to interesting ideas, such as the question whether reactions occur on the surface of the nanoparticles or in solution (*vide infra*) and the idea that reactions may be diffusion-limited or chemistry-limited depending on nanoparticle size [10]. Model reactions for studying catalysis by metallic nanoparticles have been proposed [11].

Because of the popularity of Pd chemistry, Pd NPs have been studied extensively [12,13]. Syntheses of these nanoparticles employ a variety of Pd precursors and stabilisers. For the current study, polymeric stabilisers [14,15] are of particular interest. The polymer most commonly used to stabilize NPs is poly-(*N*-vinyl-2-pyrollidone) (PVP), however, many other polymers have been used as well (see, e.g., Refs. [16–24]).

For catalyst recovery, heterogeneous catalysts tend to be recovered more readily than homogeneous catalysts. Nanoparticles, despite being much larger than individual atoms or molecules, are still not simple to separate completely from reaction mixtures. However, there are ways to increase the size of particles without having to sacrifice the high relative surface area of nanoparticles. By binding nanoparticles to a much larger support, the reactivity of the nanoparticles can be conserved while making recovery of the particles much easier. The main concern with immobilised nanoparticles in catalysis is whether the nanoparticles remain bound to the support under reaction conditions, since any particles, ions, or atoms detached from the surface will not be recovered. We have previously demonstrated how palladium nanoparticles can be immobilized on polystyrene microspheres [25] and on cellulose paper [26].

In addition to immobilizing nanoparticles, interactions with other materials may also be used to influence reactivity (for examples, see References [27–30] and references cited therein). In this context, nanocomposites are of significant interest. By forming a nanocomposite with Pd nanoparticles, the properties of the nanoparticles can be modulated to better suit their purpose. For example, we have previously shown how a thermoresponsive pNIPAM shell can be used to modulate diffusion of reactants to the catalytic surface of gold nanoparticles [31]. The use of a conductive polymer to confine metallic nanoparticles is of interest because the individual nanoparticles are electronically connected, which can affect the electronic state of the nanoparticle surfaces [32,33]. Such metal-conducting polymer nanocomposites can be synthesised using presynthesised polymers [34], but both components of the nanocomposite can also be synthesised conveniently in one-pot under appropriate conditions [35].

1.3. The Suzuki-Miyaura cross Coupling Reaction and the Oxidative Homocoupling Reaction or Arylboronic Acids Catalyzed by Pd NPs

Interest in Pd NPs in catalysis is immense [8,9,36–38], with the SMXR attracting particular interest (see examples in References [21–24,39–44]). Contrary to the situation for the SMXR, reports on the OHR of arylboronic acids catalyzed by Pd NPs are few and far between. Willis et al. [45] showed (heterogeneous) catalytic reactivity of Pd NPs supported on CeO_2, TiO_2, SiO_2, and ZrO_2 toward the OHR of phenylboronic acids in toluene at 60 °C under anhydrous conditions. The authors of this study suggest that individual Pd atoms leach from the solid NPs and these atoms cause the catalysis. Prastaro et al. [46] used palladium nanoparticles (Pd^0 NPs) stabilised in a protein cavity to catalyze the aqueous aerobic synthesis of symmetrical biaryls from arylboronic acids and from potassium aryltrifluoroborates.

1.4. The Mechanism of Catalysis by Nanoparticles—On the Surface or in Solution?

An ongoing debate is whether reactions catalyzed by NPs occur on the surface of the nanoparticles or in solution, catalyzed by leached palladium atoms or ions. Reviews of this debate include references [13,47–50].

Biffis [51] and Liu and Hu [52] attribute catalytic activity in the SMXR of microgel- and polymer-encapsulated Pd NPs, respectively, to leaching Pd^0 species. The leaching is suggested to occur following oxidative addition of the aryl halide leading to an X-Pd^{II}-Ar complex being released from the surface of the NPs into the solution. Following reductive elimination, Pd^0 atoms are then redeposited on the NPs [8]. Analogous mechanisms are supported by several further studies [53–55]. Alternative suggestions involve Pd atom leaching without involvement of the aryl halide. According to Gaikwad et al. [56] Pd^0 atom and Pd^{II} ion leach simultaneously and this simultaneous leaching underpins the catalysis in the SMXR. High-index surface facets have also been correlated with high catalytic activity as a result of increased Pd leaching [57,58].

Lee and coworkers [59], on the other hand, support the hypothesis that the SMXR occurs at the surface of Pd^0 NPs. *Operando* X-ray absorption spectroscopic studies of active Pd NPs in a SMXR showed that cross-coupling involved direct participation of palladium atoms at surface defect sites. This interpretation was supported by the effects of selective chemical and structural poisons. Shao et al. [60] also describe a surface-based process, but one which depends on the palladium dynamics. We have similarly shown that cellulose paper–immobilised Pd NPs form a catalyst for C-C bond-forming reactions providing outstanding catalyst recovery and no detectable (by ICP MS) Pd leaching [26]. These findings similarly suggest that the reaction occurs on the nanoparticle surface.

Finally, it has been suggested that the precise mechanism by which these reactions proceed may depend on the reaction conditions [61,62].

For the OHR of interest here, Prastaro et al. [46] suggest that the nanoparticle-catalyzed reaction proceeds via a Pd-peroxo complex, in analogy with the reaction mechanism for the OHR proposed by Adamo et al. [1,2] for molecular Pd catalysts.

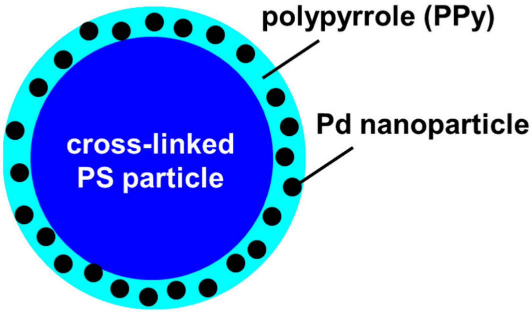
1.5. Catalysis in Aqueous Solutions

Water is a very attractive medium for synthetic reactions [63–67] as it is typically cheap and plentiful, non-flammable, non-toxic, and has a relatively low environmental impact (especially compared to dimethylformamide (DMF) or toluene, which are more typically used in palladium-catalysed coupling reactions). The challenge with using water as a solvent for palladium-catalysed reactions is that many palladium compounds and NPs are insoluble in water.

For cross-coupling reactions, the typically lower aqueous solubility of products compared to reactants can be used as an advantage, which we have shown for the SMXR where we achieved a pure product which crystallized directly from the predominantly aqueous reaction medium [26].

1.6. Aims

We have previously reported the synthesis and characterisation of a polypyrrole-palladium nanocomposite immobilised on polystyrene microspheres [25,67]. Oxidative polymerisation of pyrrole (Py) by $PdCl_2$ caused the formation of Pd nanoparticles in a nanocomposite with the polypyrrole (PPy). In the presence of micrometer-sized polystyrene (PS) particles, this oxidative polymerisation causes the PPy-Pd nanocomposite to form as a thin layer on the surface of the PS particles (Scheme 2).



Scheme 2. Schematic representation of PS-PPy-Pd nanocomposite consisting of a cross-linked polystyrene sphere (dark blue) with a surrounding layer of polypyrrole (light blue) containing palladium nanoparticles (black). Sphere, layer and nanoparticles have not been drawn to scale.

These PS-PPy-Pd particles have shown themselves to be an active catalyst for the SMXR reaction in aqueous conditions [68]. The catalyst has been shown to be recoverable, with loss of palladium <3% after five use cycles [67]. We have further shown that this system functions as a recoverable catalyst for the homocoupling reaction of arylboronic acids, allowing quantification of recovery of catalytic activity through the determination of reaction rate constants [25].

We were interested in exploring the scope of innovative solvents, including different water sources, that might be employed in aqueous palladium-catalysed reactions. Filtered seawater would constitute a readily available solvent if suitable. The reported rate-decreasing effect of added halide on palladium transmetallation reactions [3], however, would suggest that the salinity of seawater of approximately 600 mM would negatively affect reactivity. Our aim was therefore to study the effect of added chloride and bromide on the oxidative homocoupling reaction or arylboronic acids catalyzed by our polystyrene-polypyrrole-palladium nanocomposite. In this study, we again used rate constants to quantify catalytic activity because rate constants reflect the overall reactivity for the entire reaction duration; rate constants are therefore an even better measure of reactivity than the much-heralded partial conversions. To our surprise, the effect of added halide ions on the catalytic activity of our polystyrene-polypyrrole-palladium nanocomposite was two-fold. The added halide strongly increases the catalytic activity of the nanocomposite. This increase in catalytic activity comes at a cost, however. The addition of halide also leads to a significant decrease in recovery of catalytic activity. The increase in activity taken together with the poor recovery of activity between reaction cycles are in line with a mechanism where added halide leaches palladium from the nanoparticles in an aqueous environment. In an apparent contradiction to this, we and others have previously reported no detectable leaching of Pd for systems involving Pd NPs. We therefore propose that the mechanisms by which nanoparticle-catalysed reactions proceed depend on the solvent and additives of choice. Judicious choice of such additives allows rational optimization of reaction parameters to achieve desired outcomes through balancing reaction rates and catalyst recoverability.

2. Results and Discussion

2.1. Reaction Parameters

As in our previous study [25], we studied the homocoupling of 4-carboxyphenylboronic acid **1** (Scheme 1) because **1** is the most readily available arylboronic acid that forms a sufficiently water-soluble biaryl product, viz. **2**, allowing continuous reaction monitoring using UV-visible spectroscopy.

With the same aim of allowing us to follow the reaction by UV-visible spectroscopy, a concentration of 1.8 μM Pd was used because this produces a suitably low and stable baseline, while a concentration of 150 μM **1** creates clear changes in absorbance spectra upon reaction (Figure 1).

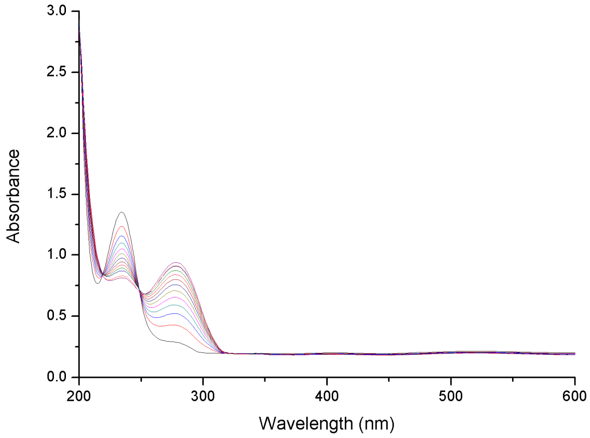


Figure 1. UV-visible spectra recorded during the homocoupling reaction of 150 μM **1** in aqueous pH 8 borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM, 1.2 mol·% Pd) over the course of 24 h at 70 °C.

Figure 1 shows that there is no appreciable reduction in the baseline absorbance over the course of the reaction, and there is a clear decrease in absorbance at 235 nm and an increase in absorbance at 278 nm (λ_{max} of **1** and **2**, respectively).

In order for the reaction to complete in a reasonable time frame, it was previously necessary to perform it at an elevated temperature of 70 °C [25]. To cover a range or reactivities, the reaction was followed using UV-visible spectroscopy at 278 nm at two different temperatures, in the absence of added halides in the first instance (Figure 2).

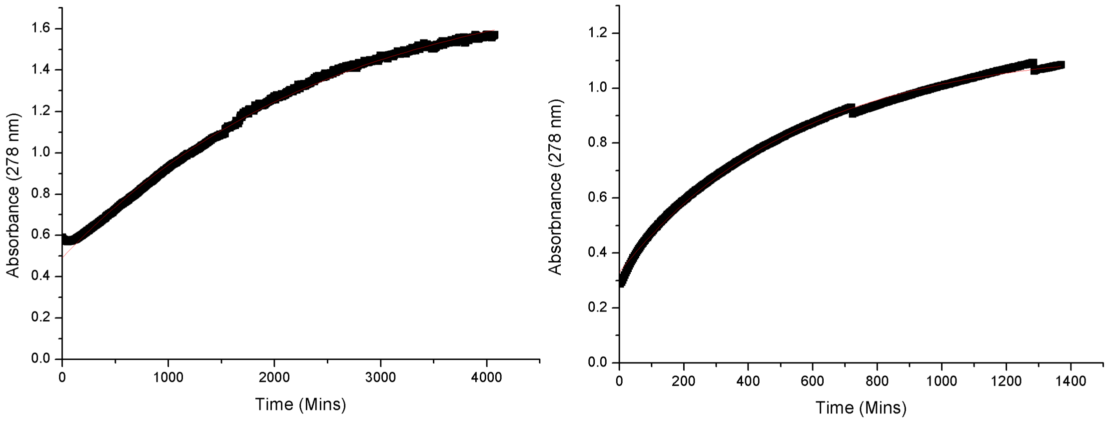


Figure 2. Absorbance at 278 nm recorded during the homocoupling reaction of 150 μM **1** in aqueous pH 8 borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM Pd) over the course of 72 h at 30 °C (**left**) and 70 °C (**right**).

Figure 2 shows that the homocoupling reaction takes nearly three days to complete at 30 °C, but raising the temperature to 70 °C causes the reaction to complete within 24 h.

2.2. Effect of Added Halide on the Catalytic Activity of Pd-PPy-PS Nanocomposites

As mentioned before, the addition of halide to reaction mixtures is known to slow down transmetallation reactions of palladium with arylboronic acids. We have shown that this is the result of a halide-hydroxo exchange reaction [69,70]. The Pd-PPy-PS nanocomposites as synthesized do not incorporate halide ions and the OHR does not lead to the release of halide ions during the reaction. In the absence of added halide ions, the halide-hydroxo exchange equilibrium is therefore not active under the reaction conditions. The addition of halide to the reaction mixture was expected to introduce the halide-hydroxo equilibrium. To test this hypothesis, the homocoupling reaction of **1** was carried out under the same conditions as before, but with the addition of various quantities of NaCl to the reaction mixture and under buffered conditions (Figure 3).

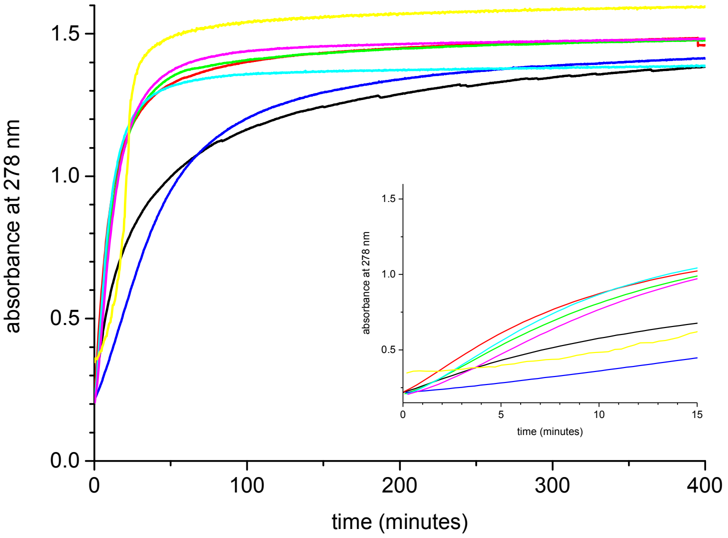


Figure 3. Examples of the absorbance at 278 nm recorded during the homocoupling reaction of 150 μM **1** in water with pH 9 borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM Pd) over the course of 7 h at 70 °C in the presence of 0 M (black), 0.05 M (red), 0.1 M (green), 0.25 M (blue), 0.5 M (cyan), 1 M (magenta), and 4.4 M (yellow) of NaCl. The first 15 min of the reaction are also shown as inset.

Remarkably, Figure 3 shows that the addition of chloride drastically increases the observed first-order rate constant (k_{obs}) for the OHR compared to the reaction in the absence of added halide. For example, at pH 9 and 1 M Cl^-, k_{obs} is 0.051 min^{-1} rather than 0.019 min^{-1} in the absence of halide. In fact, all reactions are essentially complete within three hours in the presence of chloride anion. Testing under the same conditions with the addition of NaBr instead of NaCl similarly gives rate accelerations (Figure 4).

The rate enhancement by bromide is even greater than the enhancement by chloride since all the reactions are over by 90 min. In terms of rate constants, at pH 9 and 0.1 M Br^- k_{obs} is 0.24 min^{-1} rather than 0.019 min^{-1} in the absence of halide, i.e., over ten-fold higher. Plotting k_{obs} as a function of halide concentration illustrates the effect of halide addition on the observed reaction rate constant (Figure 5).

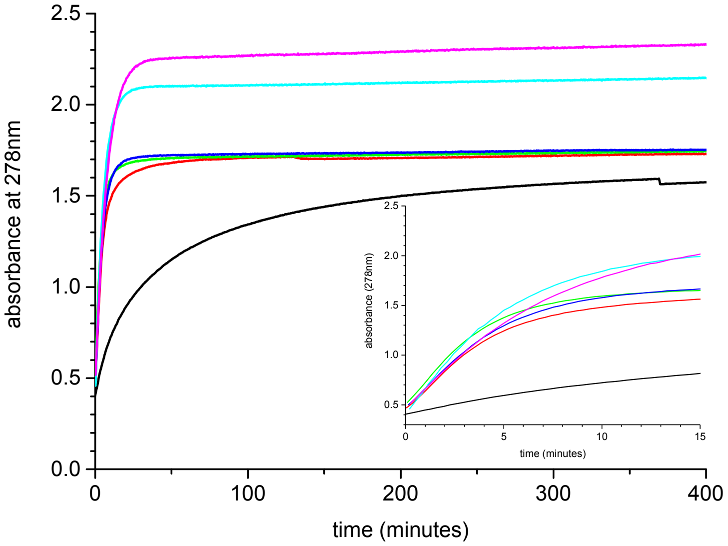


Figure 4. Examples of the absorbance at 278 nm recorded during the homocoupling reaction of 150 μM **1** in pH 9 aqueous borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM Pd) over the course of 7 h at 70 °C in the presence of 0 M (black), 0.05 M (red), 0.1 M (green), 0.25 M (blue), 0.5 M (cyan), and 1 M (magenta) NaBr with the first 15 min of the reaction as inset.

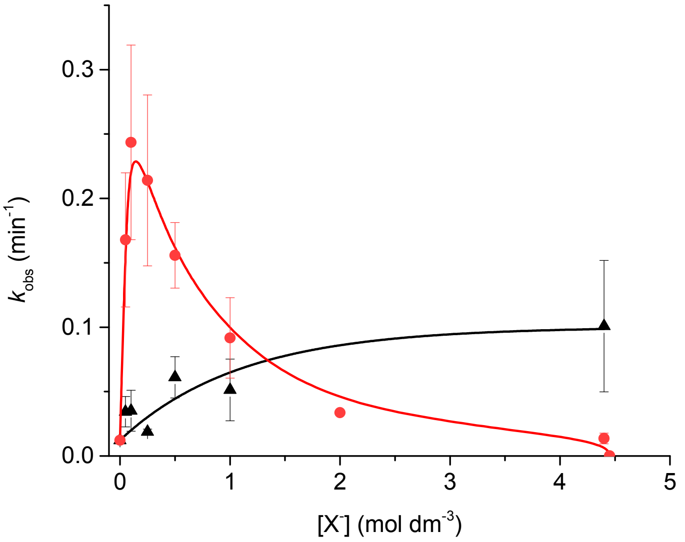


Figure 5. k_{obs} for the homocoupling reaction of 150 μM **1** in water with pH 9 borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM Pd) over the course of 7 h at 70 °C at varying [Cl^-] (▲) and [Br^-] (●). Lines are drawn to guide the eye, error bars represent standard deviations.

Figure 5 shows that for the addition of chloride, the trend is that k_{obs} increases as [Cl^-] increases all the way to a concentration of 4.4 M. In the presence of bromide, the rate constants also increase, but there is a turning point at 0.1 M bromide where the highest k_{obs} is found (0.244 min^{-1}), after which increasing the bromide concentration decreases the rate constant.

The observed acceleration upon addition of chloride can be exploited to perform the reaction in a reasonable time of around 5 h at a lower temperature of 30 °C (Figure 6).

The addition of 1 M chloride or more allows the reaction to reach completion by 12 h at 30 °C. The k_{obs} at 1 M Cl^- (0.014 min^{-1}) is of the same order of magnitude as for the reaction in the absence of halide at 70 °C (0.019 min^{-1}).

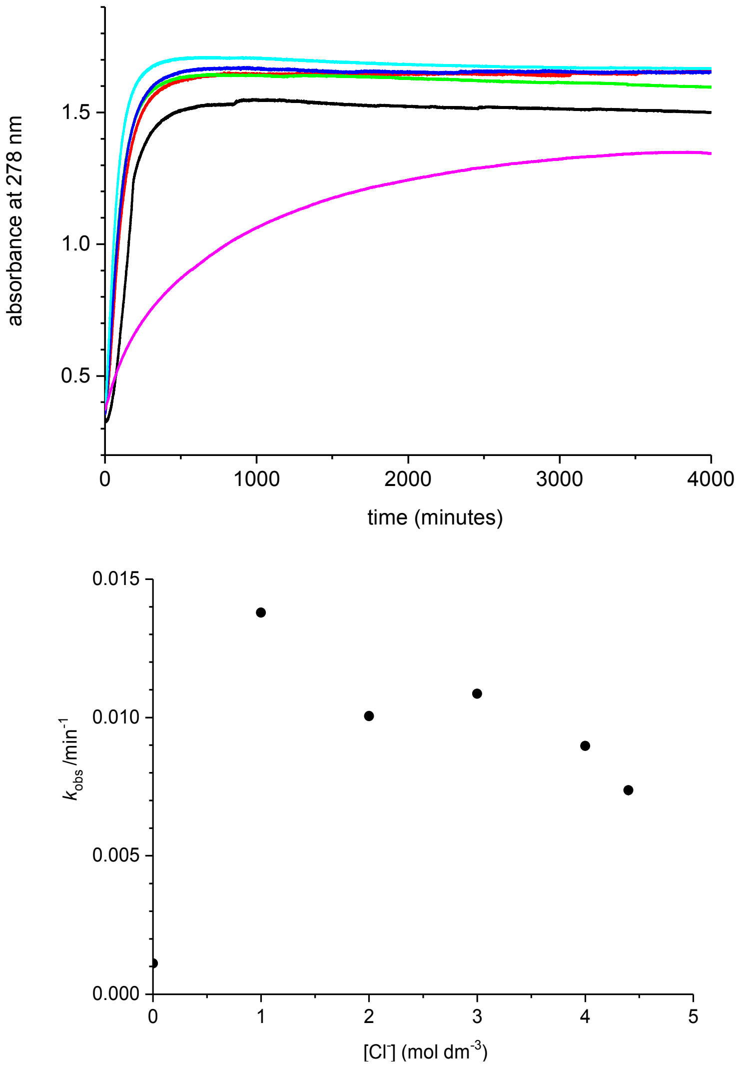


Figure 6. Examples of the absorbance at 278 nm recorded during the homocoupling reaction of 150 μM **1** in pH 9 borate buffer (10 mM) and catalyst Pd-PPy-PS (1.8 μM Pd) over the course of 64 h at 30 °C in the presence of 0 M (magenta), 1 M (light blue), 2 M (dark blue), 3 M (green), 4 M (red), and 4.4 M (black) NaCl (Left) and k_{obs} (●) plotted against [Cl$^-$] for the same reactions (Right).

The observed increase in rate constants upon addition of halide ions is unexpected since the proposed mechanism for the role of base in the SMXR and the OHR for molecular catalysts assumes that halide ions deactivate the palladium and need to be displaced by hydroxide prior to the transmetallation step. One would therefore expect addition of halide to slow down the homocoupling reaction by introducing an equilibrium that inactivates the palladium for the case of catalysis by Pd NPs as well.

There are three possible explanations for the observed increase in the rate constant for the homocoupling reaction upon the addition of halide ions. First, if the reaction occurs on the surface of the Pd NPs, the halide ions could have an activating effect on the Pd surface that is not observed in the molecular catalysts because of the different electronic properties of Pd atoms and Pd-PPy nanocomposites. A second explanation involves leaching of the Pd NPs themselves from the polypyrrole. In this scenario, the interactions between the Pd NPs and the polypyrrole are weakened by the increasing ionic strength or higher dielectric constant of the reaction medium at higher salt concentration. This cannot be the sole explanation for the data because of the observed difference in behaviour between systems with added NaCl and with added NaBr that have identical ionic strengths. Alternatively, the halide ions could be helping leach palladium atoms or ions into the solution where they are more available to catalyse the reaction and therefore lead to a faster overall reaction. The leaching could occur through aerobic oxidation of surface palladium atoms to Pd(II) after which these ions are either dissolved into bulk solution with the aid of the halide ions prior to the reaction or the leaching could be initiated by a first transmetallation reaction of a surface Pd(II) centre, after which the halide ions aid the dissolution of this centre into bulk solvent. In either case, the reaction would not be occurring on the surface of the nanoparticles, but rather in solution under these conditions.

If the explanation involving leaching of individual palladium ions applies, the deceleration at bromide concentrations in excess of 0.1 M can also be explained. At low bromide concentrations, the enhanced leaching outweighs the rate-retarding effect of bromide through the halide-hydroxo exchange process. At higher concentrations of bromide, however, the halide-hydroxo equilibrium on the leached Pd is driven in favour of the Pd-Br form and bromide has a greater effect inactivating the catalyst than increasing the availability of Pd centres in solution. For the case of added chloride, it appears as if leaching is less efficient, leading to a smaller rate enhancement, but the absence of a clear turning point in the rate effects also suggests that the chloride-hydroxo exchange equilibrium has a smaller rate-decreasing effect on the observed rate constant than the bromide-hydroxo exchange process. This is in line with the idea that transmetallations of palladium centres are faster for chlorides than for bromides.

2.3. Effect of Added Halide on the Recovery of Catalytic Activity

We have previously shown that our catalyst can be substantially recovered through centrifugation and we quantified the recovery of our catalyst in terms of the recovered catalytic activity [25]. Although it is obviously the catalyst that is recovered in its original or in a modified form, we present our data in terms of recovery of catalytic activity as quantified by reaction rate constants because this is, strictly seen, what we observe in our experiments. Here, the activity recovery was therefore studied at different concentrations of chloride at 30 °C (Figure 7).

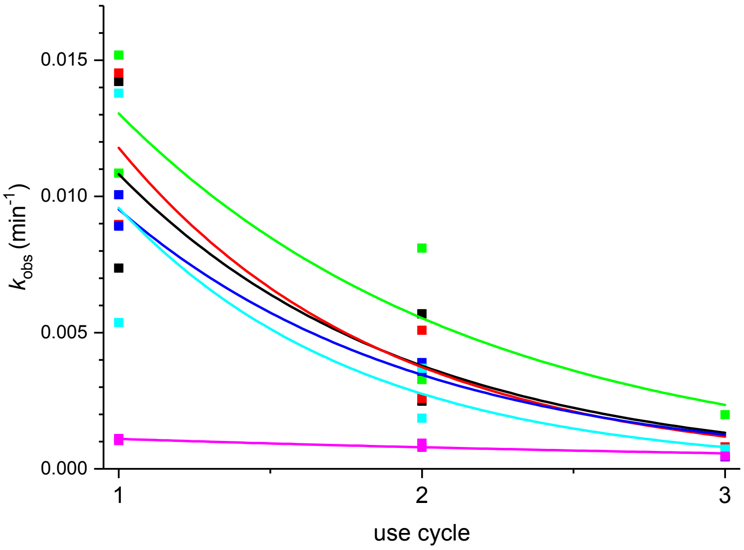


Figure 7. Observed first-order rate constants k_{obs} as a function of use cycle of the catalyst Pd-PPy-PS at initial catalyst Pd concentrations of 1.8 μM for the homocoupling reaction of 150 μM **1** in pH 9 borate buffer (10 mM) over the course of 72 h at 30 °C in the presence of 4.4 M (black), 4 M (red), 3 M (green), 2 M (blue), 1 M (cyan), and 0 M (magenta) chloride. Lines are fits of a first-order kinetic model to the data.

Figure 7 shows that catalytic activity is lost between use cycles under all experimental conditions. To quantify this loss of catalytic activity between use cycles, we analysed the kinetic data in Figure 7 in terms of a first-order rate law where the first-order rate law now describes the loss of catalytic activity. The rate constant of relative catalyst activity loss is higher in the presence of chloride (1.1 ± 0.2 cycle^{-1} for all NaCl concentrations used here) than it is in the absence of halide (0.3 cycle^{-1}), i.e., a loss of just over half the activity per cycle in the presence of chloride. In addition, unlike what was found for the reaction in the absence of chloride [25], the reactions in chloride-containing reaction mixtures trend towards rate constants of 0 min^{-1} rather than to a retained level of activity. This puts a finite limit on the reusability of the catalyst, since after three cycles, k_{obs} is essentially 0 min^{-1}, making the catalyst unusable. This observation agrees with the idea that, under these conditions, chloride is activating the catalyst by leaching particles or atoms into solution where they are more available to the reaction. This process is a double-edged sword, since the addition of halide to the system has drastically improved the rate constant for the reaction for the first cycle, but by the third cycle, the observed rate constant for the reaction was approaching that for the halide-free reaction.

Analogous studies of the recovery of catalytic activity by the Pd-PPy-PS particles in the presence of added bromide were carried out, but this time at 70 °C, to see if the catalytic activity as quantified by the reaction rate constant also decayed to 0 min^{-1} (Figure 8).

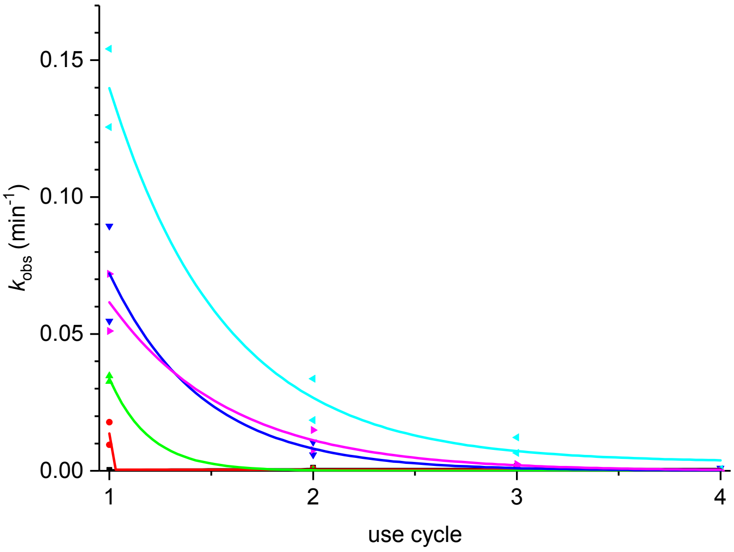


Figure 8. Observed first-order rate constants k_{obs} as a function of use cycle of the catalyst Pd-PPy-PS at initial catalyst Pd concentrations of 1.8 μM for the homocoupling reaction of 150 μM **1** in pH 9 borate buffer (10 mM) over the course of 21 h at 70 °C in the presence of 4.45 M (black), 4 M (red), 2 M (green), 1 M (blue), 0.5 M (cyan), and 0 M (magenta) bromide. Lines are fits of a first-order kinetic model to the data.

Figure 8 shows that catalytic activity is again lost between use cycles under all experimental conditions. In the presence of bromide, the trend is that the rate constant for loss of catalytic activity increases with increasing bromide concentration. From the above, it is clear that for both chloride and bromide, the recovery of catalytic activity decreases as halide concentration increases, with added bromide decreasing the retention of activity much more significantly than the chloride does. The increased loss of activity is clearly caused by the added halides, in agreement with our previous observation for SMXR and Heck reactions carried out in aqueous solutions in the absence of added halides where catalyst activity was retained and palladium loss was <3% after five reaction cycles [67].

2.4. Proposed Mechanism for Enhanced Catalysis and Increased Loss of Activity

Overall, the significant increase in catalytic activity accompanied by poor recovery of catalytic activity upon addition of chloride and bromide salts is in line with a mechanism in which the presence of halide ions leads to significant leaching of palladium from the nanocomposite. As discussed above, the Pd could be lost as either complexes of individual Pd ions or as Pd NPs. To explore this issue, we investigated the catalysis of the OHR by 1.8 μM Na_2PdCl_4. Na_2PdCl_4 was selected as a species that could be considered at the very least similar to leached palladium ions in the presence of high concentrations of chloride (Figure 9).

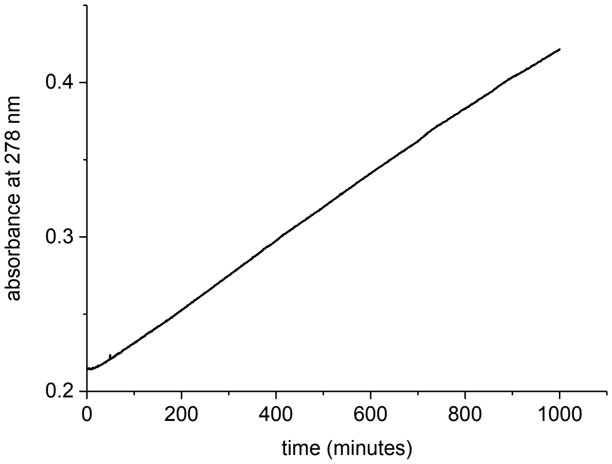
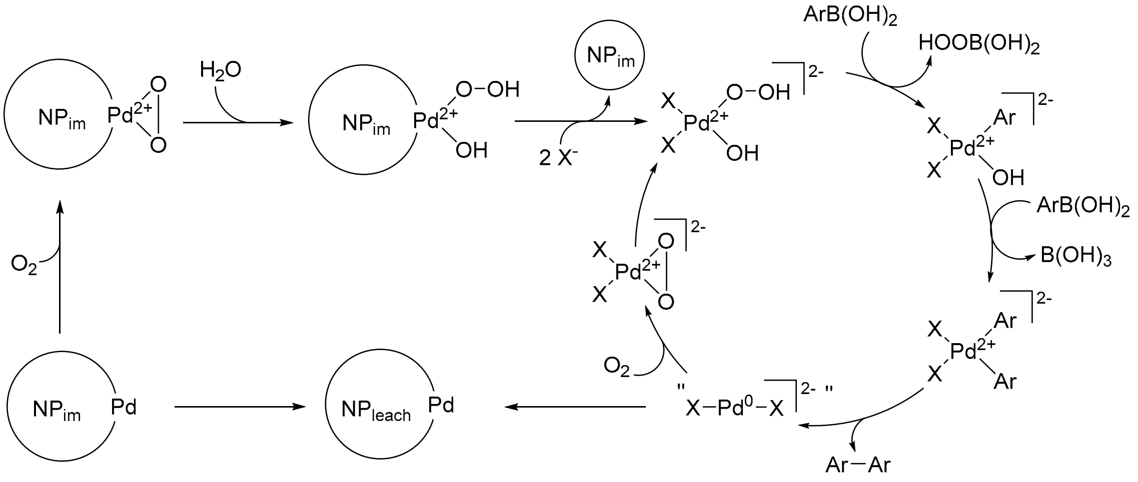


Figure 9. Absorbance at 278 nm recorded during the homocoupling reaction of 150 μM **1** in pH 9.1 borate buffer (10 mM) in the presence of 1.8 μM Na_2PdCl_4 at 30 °C.

Figure 9 shows that the OHR proceeds in the presence of 1.8 μM Na_2PdCl_4, indicating that leached Pd(II) species can indeed underpin the catalysis. Based on this observation, a possible catalytic cycle is proposed in Scheme 3.



Scheme 3. Mechanistic proposal for palladium leaching from nanoparticles and subsequent catalysis of the oxidative homocoupling reaction of arylboronic acids by dissolved palladium complexes.

Scheme 3 shows the initial oxidation of a Pd atom on the surface of the immobilized Pd NP (NPim) under aerobic conditions to form a palladium-peroxo complex, analogous to the mechanism previously proposed by Adamo et al. [1] for the OHR catalyzed by palladium complexes. In aqueous solution, this peroxo complex is likely hydrolysed quickly. The Pd^{2+} centre is subsequently dissolved with the aid of the halide anions. Two consecutive transmetallation steps followed by reductive elimination generate a Pd^0 species. Aerobic oxidation followed by hydrolysis then reforms the Pd^{2+} species. In Scheme 3, we have shown the catalytic cycle involving palladium dihalide species, but these may also be monohalide species, in line with literature reports [4–6] of such monoanionic species playing a key role in cross-coupling reactions. The formation of $HOOB(OH)_2$, which goes on the form H_2O_2, is supported by the observed formation of phenol as a side product in the reaction. A cruel mechanistic twist of the reaction, as shown in Scheme 3, is the possibility that leached palladium ions may form Pd NPs following reductive elimination. This constitutes a second pathway for the formation of leached NPs (NP_{leach}), which may themselves be catalytically active. This general mechanism is thus also in agreement with work by Saha et al. [71] who have shown that Pd NPs can be formed in aqueous solutions of Na_2PdCl_4 through reduction of the Pd^{2+} by aryl boronic acids; this reduction process is precisely the homocoupling reaction studied here but considered from the point of view of the palladium.

Overall, comparison with previous results (*vide supra*) and the variability of the observed effect with the nature and concentration of the added halide suggest that the importance of Pd leaching in catalysis, in terms of both catalyst activity and catalyst recovery, depends on the reaction conditions.

3. Materials and Methods

3.1. Chemicals

4-Carboxyphenylboronic acid was purchased from Acros Organics (Geel, Belgium). Sodium hydroxide and sulphuric acid were purchased from Fisher Scientific (Loughborough, UK). The Pd-PPy-PS nanocomposites were transported from Osaka to Cardiff in a sealed aqueous suspension and kept in the dark until use. All other chemicals were obtained from Sigma-Aldrich (Gillingham, UK) and were used as received unless noted. Water was purified using an ELGA option-R 7BP system. Borate buffers were prepared at a concentration of 0.1 M and adjusted to the appropriate pH using sodium hydroxide and sulphuric acid.

3.2. Kinetic Experiments

Reactions were followed using UV-visible spectroscopy employing a Jasco V-650 spectrophotometer with a PAC-743R Peltier thermostatted 6-cell changer (Jasco UK Ltd., Great Dunmow, UK). Quartz cuvettes (Hellma UK Ltd., Southend on Sea, UK) with a path length of 1 cm were used with a magnetic stirrer bar added to reduce sedimentation. pH of the samples was measured using a Hanna pH211 microprocessor pH meter equipped with a narrow VWR 662-1759 glass electrode (VWR, Lutterworth, UK). Equation (1) was used to analyse the kinetic data to derive the observed pseudo-first-order rate constant.

$$A = A_{\text{final}} - \Delta A e^{-k\text{obs} \times t} \tag{1}$$

In Equation (1), A is the absorbance at the λ_{max} of a given component (we used the absorbance at 278 nm for biphenyl **2**; phenol **3** has a λ_{max} of 253 nm), A_{final} is the final absorbance of the sample, ΔA is the change in absorbance of the sample, k_{obs} is the observed pseudo-first-order rate constant, and t is time.

The homocoupling reactions involving the nanocomposite were performed in 1 cm path length quartz cuvettes filled to a total volume of 2.5 mL (leaving approximately 1 mL head space above the solution). Deionised water and the volume of a 5 M solution of either NaCl or NaBr required to yield the desired final halide concentration were combined in the cuvette to a total volume of 2.2 mL using a 1–5 mL Gilson pipette. Next, 250 μL of the borate buffer stock solution were added using a 200–1000 μL Eppendorf micropipette, resulting in a buffer concentration of 10 mM and the UV spectrum was recorded to check the base line was suitably level. The stock catalyst suspension was shaken to disperse the nanoparticles and the required amount was then added using a 10–100 μL

Eppendorf micropipette (typically 25 μL, resulting in 1.8 μM [Pd]) and a spectrum was recorded again. Finally, an aliquot of the 4-carboxyphenylboronic acid stock solution was added using a 10–100 μL Eppendorf micropipette (typically 25 μL, resulting in a boronic acid concentration of 150 μM), and the kinetic measurements were started. Either a full spectrum was recorded every five minutes or, when performing simultaneous measurements, the absorbance of each cuvette at 278 ± 2 nm was measured every thirty seconds. Once the reaction reached its end point, a full spectrum for each cuvette was recorded.

The homocoupling reaction involving Na_2PdCl_4 was similarly studied in a 1 cm path length quartz cuvette filled to a total volume of 2.5 mL. The reaction solutions were prepared by mixing 942.5 μL of deionized water and 1250 μL of a 2 M aqueous solution of NaCl. To the resulting solution were then added 250 μL of a 100 mM borate buffer stock solution of pH 9.1, 37.5 μL of a 10 mM aqueous stock solution of 4-carboxyphenylboronic acid, and 20 μL of a 225 μM aqueous stock solution of Na_2PdCl_4.

All solutions were magnetically stirred during the reactions.

3.3. Catalyst Recovery

After each reaction cycle, the reaction mixture in the cuvette was divided into two aliquots of 1100 μL which were placed into two Eppendorf containers with 300 μL of the reaction mixture remaining in the cuvette. The aliquots in the Eppendorf containers were centrifuged at 13.3 K rpm for 10 min at 20 °C to recover the Pd-PPy-PS nanocomposite. From each Eppendorf container, 1000 μL of supernatant was removed and the sedimented nanocomposite were resuspended in 850 μL of a mixture of deionized water and the 5 M stock solution of NaCl or NaBr as required to achieve the desired final concentration of the halide. The resulting 950 μL of suspension from both Eppendorf containers were combined with the 300 μL of the reaction mixture that remained in the cuvette and 250 μL of buffer stock solution was added. The recovered nanocomposite was then reused in a subsequent reaction cycle.

4. Conclusions

The addition of chloride and bromide salts leads to (1) initial significant enhancement of catalytic activity and (2) poor recovery of catalytic activity. These observations are in line with a mechanism where added halides significantly enhance palladium leaching from the nanoparticles and where the leached palladium centres are responsible for most of the observed catalysis. The variability of these effects with the nature and concentration of the added halide indicates that reaction conditions play an important role in determining whether reactions proceed on the surface of the palladium nanoparticles or on leached palladium centres.

The implications from our findings are two-fold. In the aerobic oxidative homocoupling reaction of arylboronic acids, halide ions—and bromide ions in particular—may be used to generate highly active catalytic species from palladium nanoparticles if there is no need to recycle the catalyst. On the contrary, if high recyclability of the catalytic nanoparticles is required, for example in applications employing immobilized palladium nanoparticles in flow chemistry, halide ions in aqueous solutions should be avoided to prolong the catalyst life by avoiding leaching. The question of whether similar processes play a role under typically anaerobic Suzuki-Miyaura cross-coupling reactions, where Pd NPs are less likely to be oxidized other than by the reactants, is of current interest to us.

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