

# Applications of polydopamine in organic chemistry: from catalyst support to photoresponsive surfaces

*Theses of Ph.D. dissertation*

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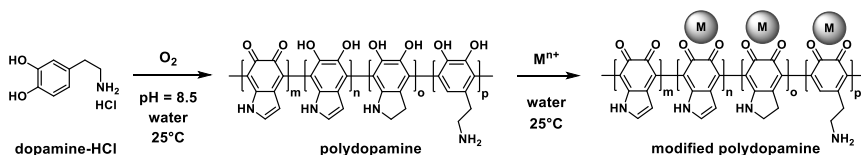
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## 1. Introduction and aims

Polydopamine (PDA), a polymer bearing similar functional groups as the natural adhesive mussel foot protein, can be synthesized in the laboratory via the autopolymerization of dopamine (Figure 1). Due to the universal adhesive property and redox activity of PDA, a growing number of publications appeared during the past decade proving its applicability as a catalyst support. Without additional reducing agent, transition metal nanoparticles can be formed on PDA surface that is adhered on any kind of support material, however only a limited number of model reactions (e.g. 4-nitrophenol reduction) were investigated with these metal/PDA/substrate composite systems and no comparative studies can be found. Therefore, our primary goal was to prepare a Pd nanoparticle doped PDA catalyst (Pd/PDA) and investigate its catalytic activity and reusability in transfer hydrogenation and C-C coupling reactions (Figure 2).



**Figure 1.** Synthesis of polydopamine (PDA), and its modification with metal nanoparticles.

It is a great challenge to immobilize photoresponsive molecules on macroscopic solid surfaces without the loss of their isomerizability. Therefore, our secondary goal was to harness the adhesive and reductive properties of PDA to prepare an Au nanoparticle doped PDA/quartz composite surface (Q-PDA-Au) that can be used to create photoresponsive surfaces. For this, we synthesized azobenzene derivatives that are possessed different UV-Vis absorption maxima (360/440 nm), alkyl chain lengths (propyl, hexyl), and terminal groups on the alkyl chain ( $NH_2$ , SH). We investigated the photochemical, and ligand exchange properties of these azobenzene photoswitches on Q-PDA-Au surface.

## 2. Experimental methods

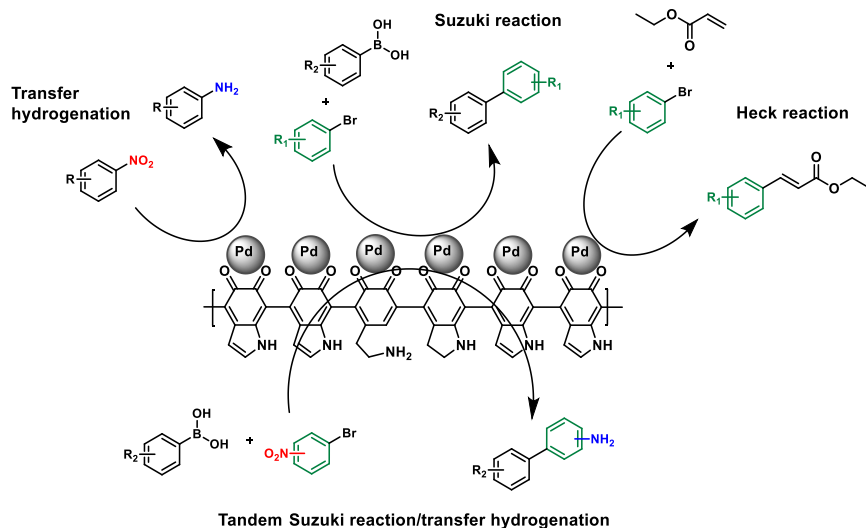
All of the reactions were performed on a millimolar scale, and were monitored by TLC, GC-MS, and LC-MS techniques. The crude products were purified by flash column chromatography and analysed by modern analytical methods (NMR, HR-MS, UV-Vis). The prepared catalysts and macroscopic surfaces were characterized by XPS, TEM, AFM, and water contact angle measurements with the help of our collaborators.

## 3. Novel scientific results

**3.1.** *We have prepared the smallest Pd nanoparticle containing Pd/PDA catalyst known in the PDA literature, with a Pd diameter of 1 – 3 nm.* To simplify the catalyst recycling procedure, we coated magnetite nanoparticles (MNP) with a PDA layer and modified it with Pd as well, however, in this case larger, 5 – 8 nm size Pd particles appeared on its surface. An explanation for this difference can be the mildly decreased Pd nanoparticle stabilizing capability of the surface due to the different polymer folding initiated by MNP – PDA interactions.

**3.2.** *The prepared Pd/PDA catalyst was found to be active and selective in transfer hydrogenation, Heck reaction, Suzuki reaction, and also in a one-pot tandem Suzuki reaction/transfer hydrogenation system.* Nitroaryl compounds were reduced to the corresponding anilines with high yields, however, the carbonyl reduction was not as general as the nitro reduction, and only aromatic ketones could be reduced to the corresponding alcohols. Molecules that contained aldehyde functions were unaffected in transfer hydrogenation, probably because of their imine formation with the amine moieties of PDA. This reaction is suggested to cause catalyst deactivation by creating a steric barrier around catalytically active centres. Another limitation of the system was the reaction of nitroaryl halides, where fast oxidative addition of Pd(0) to aryl halides obstructed the nitroreduction. Pd/PDA was found to be an active catalyst in the Heck reaction of aryl halides and ethyl acrylate. High yields were obtained in the presence of electron withdrawing groups in the *para* position of the aryl halide, while the yields decreased when electron donating groups were present. Exceptionally high catalytic activity of the Pd/PDA catalyst was observed in

the Suzuki reaction of aryl halides with arylboronic acids. Full conversions were detected at 80°C within 5 minutes, or at room temperature in 2 – 3 hours in many cases. However, in the case of heteroaryl halides prolonged, 1 hour reaction time was necessary for moderate yields at 80°C. A further limitation of the transformation was the hindering steric effect of *ortho* substituted aryl halides presumably in the oxidative addition step.



**Figure 2.** Pd/PDA catalysed organic transformations.

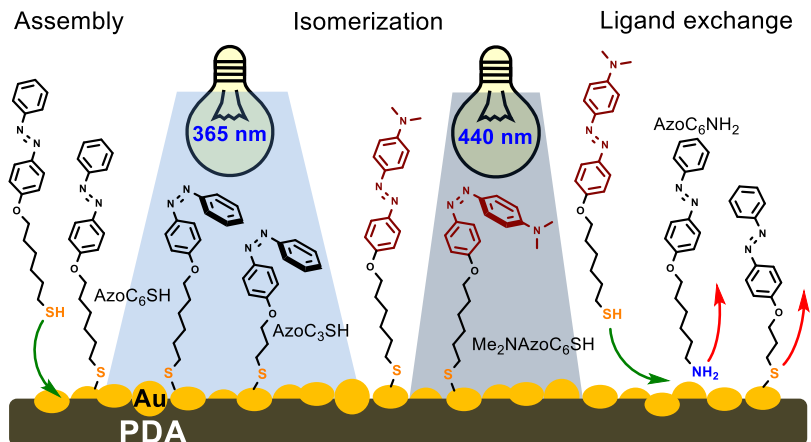
To capitalize on the similar conditions in the transfer hydrogenation and Suzuki reaction, we combined the two systems in a one-pot, tandem process. In this tandem Suzuki reaction/transfer hydrogenation reaction, aminobiphenyles were prepared from aryl boronic acids and nitroaryl halides in mostly good to high yields under a relatively short period of time (80°C, 1 h). However, decreased selectivities and low yields were observed in cases where the reaction rate of the Suzuki coupling was similar to that of the transfer hydrogenation. We were able to increase these yields by tuning the temperature during the two reaction steps (25°C, 2 h → 80°C, 1 h). One-pot Suzuki coupling and nitro reduction of heteroaryl halides with 3-nitrophenylboronic acid were conducted, however, in these cases

the delayed addition of the reducing agent (HCOONa) after the Suzuki step (80°C, 1 h before another 1 h at 80°C) was necessary to suppress side reactions. Successful large (gram) scale experiments were conducted with Pd/PDA in all four reactions, demonstrating its applicability in everyday laboratory practice. Moreover, because of the superior catalytic activity in Suzuki reaction, we were able to couple 4-bromo-nitrobenzene and phenylboronic acid in high yields in the presence of only 18 ppm ( $1.8 \times 10^{-3}$  mol%) Pd.

**3.3. Pd/PDA/MNP catalyst was recyclable in transfer hydrogenations and Suzuki reactions.** However, in the latter case, an elevated Pd leaching was observed, which resulted in decreased activity after the 4<sup>th</sup> run. We found that longer reaction time resulted in greater decrease of catalytic activity of the recycled catalyst, than higher reaction temperature. Decreased recyclability was observed in tandem Suzuki reaction/transfer hydrogenation, where the catalyst showed no activity after 2 cycles. On the other hand, Pd/PDA/MNP became inactive already after the first run in Heck reaction, probably because of the high Pd leaching, and nanoparticle aggregation.

**3.4. We found Pd particle size effect in the case of Suzuki reaction.** We observed similar activities of Pd nanoparticles with different sizes on Pd/PDA (1 – 3 nm) and Pd/PDA/MNP (5 – 8 nm) catalysts in transfer hydrogenations and Heck reactions, however, in Suzuki reactions we found decreased activity when Pd/PDA/MNP was used. Therefore, we synthesized a third Pd catalyst (Pd/PDA-13) with an average Pd diameter of 13 nm. In comparison with the previous two catalysts, we found further decrease in catalytic activity with increased Pd particle size in Suzuki reaction.

**3.5. By coating quartz slides with PDA and anchoring Au nanoparticles to its surface from an aqueous solution of  $\text{AuCl}_3 \times 3\text{H}_2\text{O}$ , we created a composite material (Q-PDA-Au).** High dispersity of 50 – 80 nm sized Au nanoparticles appeared on the PDA surface after 3 hours deposition time, which we expected to be able to bind photoisomerizable molecules and enable ligand exchange processes (Figure 3.)



**Figure 3.** Schematic representation of a Q-PDA-Au surface modified with photoisomerizable azobenzene derivatives capable to ligand exchange reactions.

**3.6. We created isomerizable molecular layers on Q-PDA-Au surface.** First, we synthesized azobenzene derivatives exhibiting different UV-Vis absorption maxima for their easier identification by UV-Vis spectrophotometry. We were able to modify Q-PDA-Au surfaces with all the synthesized azobenzene derivatives under the same condition (1 mM, EtOH solvent, 40°C, 24 h), which was monitored by UV-Vis and contact angle measurements. XPS analysis confirmed that the azobenzenes were attached to the Au nanoparticles. When azobenzene containing Q-PDA-Au surfaces were irradiated with light, a significant *trans* → *cis* isomerization occurred in all cases. The thermal reverse isomerization of *cis*-azobenzenes were slow (approx. 18 h), however, *trans* isomers were formed rapidly from *cis* upon visible light irradiation (AzoC<sub>6</sub>NH<sub>2</sub>, AzoC<sub>3</sub>SH, AzoC<sub>6</sub>SH). Only exception was the 4'-dimethylaminoazobenzene derivative Me<sub>2</sub>NAzoC<sub>6</sub>SH, which showed no *cis* → *trans* back isomerization in the presence of UV or visible light, and only a minor change in the absorption spectra appeared after thermal treatment (80°C, 18 h). This phenomenon can be explained either by the coordination of its tertiary nitrogen to the Au surface, or by the formation of hydrogen bond with the OH and NH<sub>2</sub> moieties of PDA. We demonstrated that the azobenzenes preserved not only their fast and reversible switching

property and thermal stability on Q-PDA-Au surface, but their photostability as well. AzoC<sub>6</sub>NH<sub>2</sub> and AzoC<sub>6</sub>SH modified surfaces were irradiated alternately with UV and visible light (10 cycles, 5 – 5 min/cycle). No considerable photodegradation was observed after 10 cycles.

**3.7. *The nature of the Q-PDA-Au surface enabled ligand exchange processes.*** In ligand exchange experiments we observed significant amine to thiol exchange capability, moreover, thiol to thiol exchange was also occurred on Q-PDA-Au surface. In this latter case, however, ligand exchange occurred with decreasing efficiency with increasing alkyl chain length of the exchanged ligand under identical conditions. A mixed Q-PDA-Au-„Azo” surface was created from AzoC<sub>3</sub>SH and Me<sub>2</sub>NAzoC<sub>6</sub>SH, where both ligands retained their photoisomerizability at the appropriate wavelength (365 nm or 440 nm). We need to note that the *cis* → *trans* reverse isomerization of Me<sub>2</sub>NAzoC<sub>6</sub>SH on the mixed surface was not observable in this case either.

#### 4. Scientific publications forming the basis of the thesis (MTMT ID: 10062652)

1. Attila Kunfi, Rita Bernadett Vloesková, Zsófia Keresztes, Miklós Mohai, Imre Bertóti, Ágnes Ábrahám, Éva Kiss, Gábor London  
Photoswitchable Macroscopic Solid Surfaces Based On Azobenzene-Functionalized Polydopamine/Gold Nanoparticle Composite Materials: Formation, Isomerization and Ligand Exchange  
*ChemPlusChem* **2020**, *85*, 797–805.  
I. F. (2018): 3.441
2. Attila Kunfi, Gábor London  
Polydopamine: An Emerging Material in the Catalysis of Organic Transformations  
*Synthesis* **2019**, *51*, 2829–2838.  
I. F. (2018): 2.867
3. Attila Kunfi, Zoltán May, Péter Németh, Gábor London  
Polydopamine supported palladium nanoparticles: highly efficient catalysts in Suzuki cross-coupling and tandem Suzuki cross-coupling/nitroarene reductions under green reaction conditions  
*J. Catal.* **2018**, *361*, 84–93.  
I. F. (2018): 7.723
4. Attila Kunfi, Vivien Szabó, Ágnes Mastalir, Imre Bucsi, Miklós Mohai, Péter Németh, Imre Bertóti, Gábor London  
Palladium on polydopamine: its true potential in catalytic transfer hydrogenations and Heck coupling reactions  
*ChemCatChem* **2017**, *9*, 3236–3244.  
I. F. (2017): 4.674  
 $\Sigma$  I. F. : 18,705



## 5. Scientific lectures and posters forming the basis of the thesis

### Lectures:

1. Attila Kunfi, Gábor London  
*Application of Polydopamine in the Construction of Efficient Heterogeneous Catalysts*  
2017. 05. 16. MTA Heterociklusos és Elemorganikus Kémiai Munkabizottság,  
Balatonszemes, Hungary
2. Attila Kunfi, Gábor London  
*Polydopamine – a Nature inspired material: applications in catalysis and materials chemistry*  
2016. 07. 11. 1<sup>st</sup> Hungarian-Norwegian Summer School on Bioactive Substance  
Research, University of Tromsø, Norway

### Posters:

1. Attila Kunfi, Rita Bernadett Vlocskó, Gábor London  
*Application of Polydopamine in the Construction of Efficient Heterogeneous Catalysts and Dynamic Interfaces*  
2019. 09. 09. – 09. 12. 1<sup>st</sup> International Conference on Adhesion in Aqueous Media:  
From Biology to Synthetic Materials, Dresden, Germany
2. Attila Kunfi, Gábor London  
*Construction of Heterogeneous Catalysts and Dynamic Interfaces on a Polydopamine Platform*  
2019. 07. 14. – 07. 18. 21<sup>st</sup> European Symposium on Organic Chemistry, Wien,  
Austria

## 6. Scientific publications not forming the basis of the thesis

1. Tamás Gazdag, Ádám Baróthi, Koppány Levente Juhász, Attila Kunfi, Péter Németh, András Sági, Ákos Kukovecz, Zoltán Kónya, Kornél Szőri, Gábor London  
Effect of particle restructuring during reduction processes over polydopamine-supported Pd nanoparticles  
*J. Nanosci. Nanotechnol.* **2019**, *19*, 484–491.  
I. F. (2018): 1.093
2. Tamás Gazdag, Attila Kunfi, Gábor London  
Cyanation of aryl bromides with  $K_4[Fe(CN)_6]$  using polydopamine supported Pd nanoparticle catalysis: formation of magnetite during the reaction  
*React. Kinet. Mech. Catal.* **2018**, *125*, 567–581.  
I. F. (2018): 1.428
3. Imre Bucsi, Ágnes Mastalir, Árpád Molnár, Koppány Levente Juhász, Attila Kunfi  
Heck coupling reactions catalysed by Pd particles generated in silica in the presence of an ionic liquid  
*Struct. Chem.* **2017**, *28*, 501–509.  
I. F. (2017): 2.019
4. Attila Kunfi, Ágnes Mastalir, Imre Bucsi, Gábor London  
Heck arylation of alkenes with aryl bromides by using supported Pd catalysts: a comparative study  
*React. Kinet. Mech. Catal.* **2016**, *119*, 165–178.  
I. F. (2016): 1.264  
 $\Sigma$  I. F. : 5,804  
Total I. F. : 24,509