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Supporting Information

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# Pd Nanoclusters in Sonogashira Cross-Coupling: A True Catalytic Species?

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## *Supporting information*

### **Experimental Section**

**Materials and instrumentation.** GC analysis was performed using a Interscience Trace GC-8000 gas chromatograph with a 100% dimethylpolysiloxane capillary column (VB-1, 30 m × 0.325 mm). GC/MS analysis was performed using a Hewlett-Packard 5890/5971 GC/MS equipped with a ZB-5 (zebron) column (15 m × 0.25 mm). All products are known compounds and were identified by comparison of their GC retention times to those of authentic samples and by MS analysis. Samples for GC were added in equivalent amount of water, extracted with hexanes and filtered through an alumina plug prior to injection. GC conditions: isotherm at 110 °C (1 min); ramp at 30 °C min<sup>-1</sup> to 280 °C; isotherm at 280 °C (3 min). All the reactions were carried out under N<sub>2</sub> atmosphere in Schlenk-type glassware that was oven dried prior to reaction. Solutions were dispensed using a micropipette. Unless noted otherwise, chemicals were purchased from commercial firms and were used as received. Tetraoctylammonium glycolate was prepared according to the literature,<sup>1</sup> except that in the second stage of ion-exchange process glycolic acid was used instead of formic acid. TEM images were obtained with a JEOL-100 CXII instrument, operated at an accelerating voltage of 80 kV. At least four images were taken for each sample.

**Synthesis of Pd clusters.** A Schlenk-type vessel equipped with a rubber septum and a magnetic stirrer was evacuated and refilled with N<sub>2</sub>. The vessel was then charged with Pd precursor salt solution in DMF (20 mL, 10 mM) and 2.5 mL of a 0.2 M TOAG solution in DMF was added in one portion to the solution at 65 °C. The mixture was stirred for 6 h under a slight N<sub>2</sub> overpressure. The

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[1] M. B. Thathagar, J. Beckers, G. Rothenberg, *Adv. Synth. Catal.* **2003**, 345, 979.

color of the mixture changed from dark orange to black. The resulting Pd cluster suspension was then used as a catalyst stock solution in the Sonogashira cross-coupling.

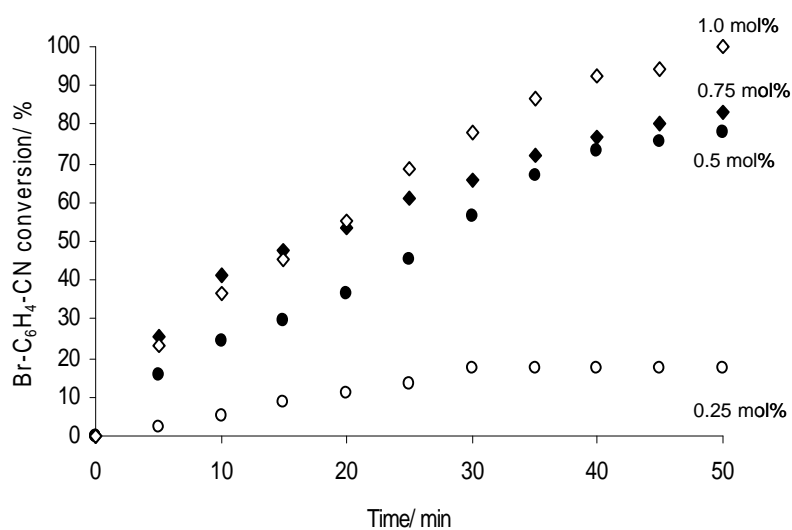
**Cross-coupling of phenylacetylene with 4-bromobenzonitrile using Pd clusters.** A Schlenk-type glass vessel equipped with a rubber septum and a magnetic stirrer was evacuated and refilled with N<sub>2</sub>. The vessel was then charged with a Pd cluster suspension prepared in DMF (1.0 mL, 10.0 mM, 1.0 mol%), phenylacetylene (2 ml, 750 mM, 1.5 mmol), TBAA (2 ml, 750 mM, 1.50 mmol) and 3 mL of DMF. 4-bromobenzonitrile (0.182 g, 1.00 mmol) was added and the mixture was stirred at 50 °C for 6 h under a slight overpressure of N<sub>2</sub>. Reaction samples were taken at regular intervals and monitored by GC (Pentadecane internal standard).

**Transmission electron microscopy (TEM) analysis.** TEM was used to determine the particle size and the morphology before, during and after the reaction. Samples were prepared by placing 150 µL of 1 mM Pd cluster suspension or the reaction mixture on carbon-coated copper grids. These were then placed in vacuum oven at 50 °C at 250 mm of Hg to evaporate the solvent. To see the effect of catalysis on the particle size the TEM samples were taken during and after the reaction.

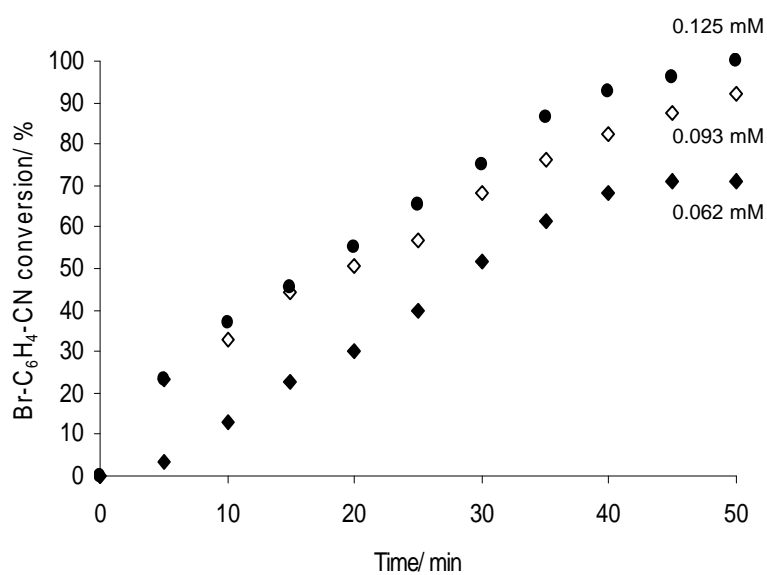
**Testing for {Pd + reagent} pre-activation.** To form the active Palladium complex 4-bromobenzonitrile (0.182 g, 1.0 mmol), DMF (7 ml) and Pd cluster suspension (1 ml, 10 mM, 1.0 mol%) were first stirred at 50 °C for 30 min. Phenylacetylene (0.152 g, 1.5 mmol), TBAA (0.44 g, 1.5 mmol) and internal standard were then added under slight N<sub>2</sub> over pressure. The samples were taken at regular intervals and analysed by GC. A similar experiment was performed wherein phenylacetylene was added before to form an inactive palladium complex.

**Pd cluster reuse in 2nd cycle.** A Schlenk-type glass vessel equipped with a rubber septum and a magnetic stirrer was evacuated and refilled with N<sub>2</sub>. The vessel was then charged with a Pd cluster suspension prepared in DMF (1.0 mL, 10.0 mM, 1.0 mol%), phenylacetylene (2 ml, 750 mM, 1.5 mmol), TBAA (2 ml, 750 mM, 1.50 mmol) and 3 mL of DMF. 4-bromobenzonitrile (0.182 g, 1.00 mmol) was added and the mixture was stirred at 50 °C for 6 h under a slight overpressure of N<sub>2</sub>. After complete conversion of 4-bromobenzonitrile same amount of fresh reactants were added to the reaction mixture. Reaction samples were taken at regular intervals and monitored by GC (Pentadecane internal standard).

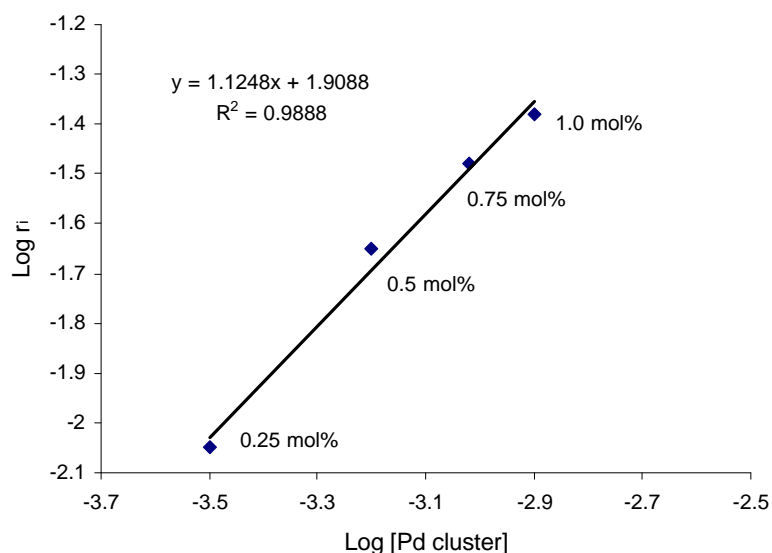
**Reaction profiles and kinetic analysis.** The reaction profiles obtained by varying concentration of Pd clusters and 4-bromobenzonitrile are shown in figures S1 and S2. Initial reaction rates ( $r_i$ ) were calculated from the slope of the conversion v/s time plot. The order of reaction was found by plotting  $\log(r_i)$  v/s  $\log(\text{concentration})$  as shown in figures S3 and S4.



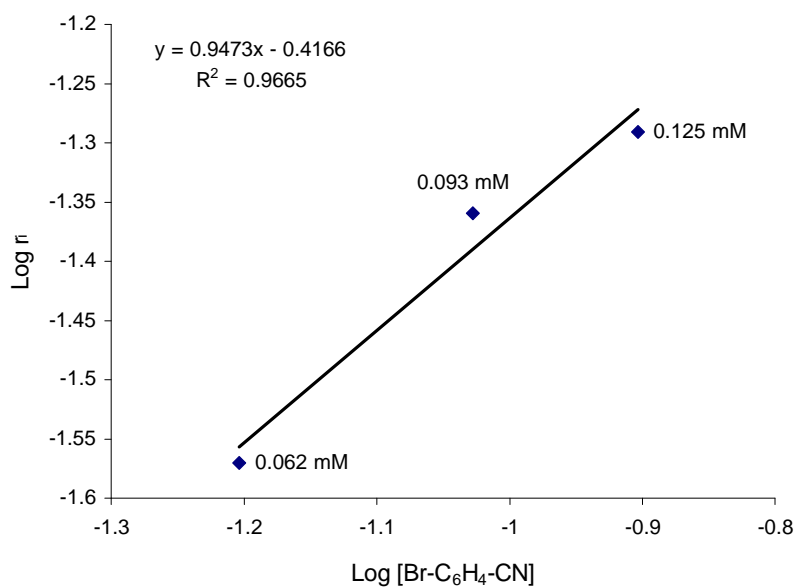
**Figure S1.** Sonogashira cross-coupling of phenylacetylene with 4-bromobenzonitrile using various concentrations of using Pd clusters as catalysts. The mol% of Pd clusters used is relative to 4-bromobenzonitrile concentration. Reaction conditions: 1.0 mmol Br-C<sub>6</sub>H<sub>4</sub>-CN, 1.5 mmol Phenylacetylene, 1.5 mmol TBAA, 8 mL DMF, 50 °C, N<sub>2</sub> atmosphere.



**Figure S2.** Sonogashira cross-coupling of phenylacetylene with various concentrations of 4-bromobenzonitrile using Pd clusters as catalysts. Reaction conditions: 1.5 mmol Phenylacetylene, 1.5 mmol TBAA, 1 mol% catalyst (total Pd clusters relative to Br-C<sub>6</sub>H<sub>4</sub>-CN), 8 mL DMF, 50 °C, N<sub>2</sub> atmosphere.

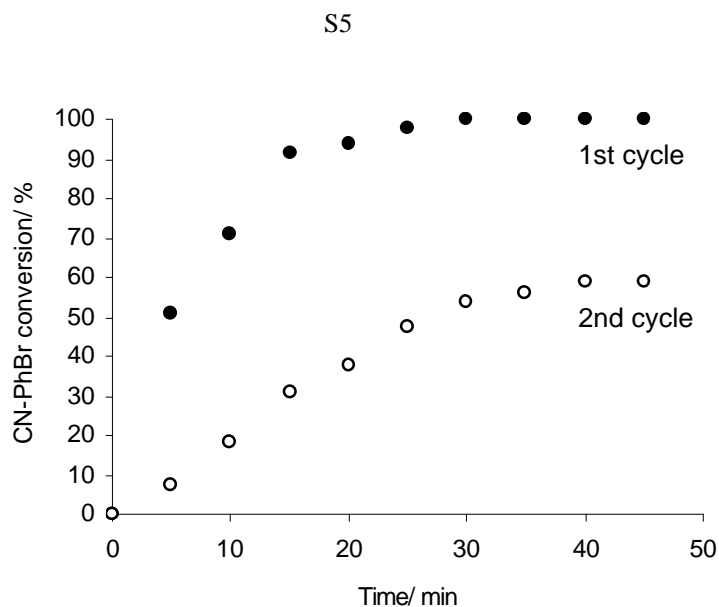


**Figure S3.** Log plot of the initial reaction rate dependence on concentration of Pd clusters with other parameters constant. Reaction conditions are the same as in Figure S1.



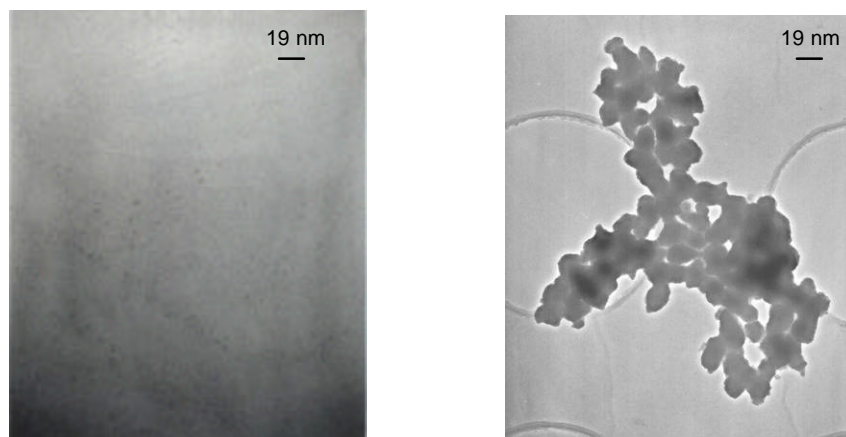
**Figure S4.** Log plot of the initial reaction rate dependence on concentration of 4-bromobenzonitrile, with other parameters constant. Reaction conditions are same as in Figure S2.

**Catalyst recycling experiment.** This experiment was carried out to check the activity of the newly formed smaller particles after the first run. We expected if reaction occurs on the surface of the clusters, the smaller particles with high surface area should give higher activity and/or reaction rate. However, this was not the case and reasons for this low activity in 2nd cycle might be either due to surface poisoning or because the smaller particles with tighter radii are less prone to leaching.



**Figure S5.** Activity of Pd clusters prepared using Pd(NO<sub>3</sub>)<sub>2</sub> in the 1st and 2nd cycle of Sonogashira reaction.

**Additional TEM results.** The TEM images taken during the reaction ( $t = 20$  min) show smaller particles (Figure S6, left) compared to that before the reaction. This is probably due to the stabilizing influence of TBAA used as a base. To check this hypothesis, we carried out a control experiment, with K<sub>2</sub>CO<sub>3</sub> as base. Indeed, the TEM image after the reaction showed very large particles (Figure S6, right) and also some aggregates were observed at the bottom of the reactor. This clearly indicates that TBAA plays an important role in preventing the growth of newly formed clusters after the reaction completion.



**Figure S6.** TEM image of the sample taken during the reaction when TBAA was used as a base (left) and image obtained after the reaction when K<sub>2</sub>CO<sub>3</sub> was used as a base (right). Reaction conditions: 1 mmol 4-bromobenzonitrile, 1.5 mmol Phenylacetylene, 1.5 mmol base, 1 mol% catalyst (total Pd clusters relative to 4-bromobenzonitrile), 8 mL DMF, 50 °C, N<sub>2</sub> atmosphere.