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Suzuki and Heck Reactions Catalyzed by Preformed Palladium Clusters and Palladium/Nickel Bimetallic Clusters

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Abstract: Soluble palladium clusters and palladium/nickel bimetallic clusters stabilized by tetraalkylammonium salts or poly(vinylpyrrolidone) are effective catalysts in Suzuki and Heck reactions involving iodo-, bromo- or activated chloroaromatics, whereas chlorobenzene is not a suitable reaction partner.

It has been known for a long time that the chemical reduction of transition metal salts in the presence of tetraalkylammonium salts leads to nanostructured $R_4N^+X^-$-stabilized metal clusters.[1] Recently, we demonstrated that such materials are also accessible by electrochemical means and that the proper choice of current density and solvent allows for size selectivity.[2] On the basis of a study utilizing transmission electron microscopy (TEM) and scanning tunnel microscopy (STM) it was shown that each cluster is surrounded by a monomolecular layer of ammonium salt which thus functions as a stabilizer and prevents undesired metal powder formation.[3] Although these and related clusters have been shown to be hydrogenation catalysts,[1,2,4] there is no report of the use of such materials as catalysts of C-C bond forming processes such as Suzuki[5] or Heck[6] reactions in solution. Here we show for the first time that $R_4N^+X^-$-stabilized Pd clusters[2a-c] and Pd/Ni bimetallic clusters[2d] are active catalysts in both types of reactions. We also demonstrate that this type of catalysis is not restricted to $R_4N^+X^-$-stabilization, e. g., poly(vinylpyrrolidone) (PVP)-stabilized clusters[1,7] are also active catalysts.

The Suzuki reaction was tested using phenylboronic acid **1** and various chloro- and bromoaromatics **2** in the presence of catalytic amounts of $(C_8H_{17})_4N^+Br^-$-stabilized Pd clusters (size by TEM: 2 - 3 nm) or $(C_4H_9)_4N^+Br^-$-stabilized Pd/Ni bimetallic clusters (3 nm; Pd : Ni = 1 : 3)[2] (Table 1).

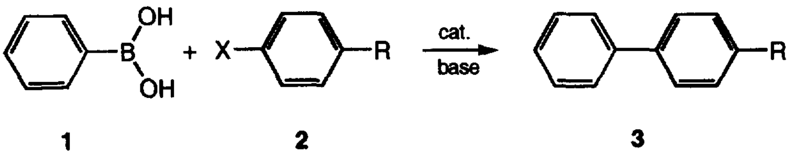


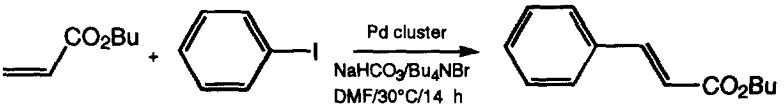
Table 1. Suzuki Coupling Reaction of **1** and **2** in N,N-Dimethylacetamide (DMA) (or as otherwise stated)

X	R	Cluster[a] (mol-% of metal)	Base (equiv.)	Temp. (°C)	Time (h)	Conversion[b]/ Yield (isolated) (%)
Br	H[c]	Pd (2%)	KOAc (2.5)	100	3.5	100/53
Br	H	Pd/Ni (2%)	KOAc (2.5)	100	3.5	100/47
Br	NO_2	Pd/Ni (2%)	KOAc (2.5)	120	2.5	100/92
Br	$COCH_3$	Pd/Ni (2%)	KOAc (2.5)	120	2.5	100/85
Br	CF_3	Pd/Ni (5%)	KOAc (2.5)	120	14	86/-
Br	CF_3	Pd/Ni (5%)	K_2CO_3 (2.0)	120	2	100/67
Br	CN	Pd/Ni (2%)	K_2CO_3 (2.0)	120	3	100/97
Br	OCH_3	Pd/Ni (5%)	KOAc (2.5)	120	23	47/-
Cl	NO_2	Pd/Ni (5%)	KOAc (2.5)	120	80	-/48
Cl	NO_2	Pd/Ni (5%)	KOAc/ nBu_4NBr (2.5/1)	120	14	82/-
Cl	NO_2	Pd/Ni (5%)	K_2CO_3/ nBu_4NBr (2.5/1)	120	14	92/-

[a] Pd clusters stabilized by $(C_8H_{17})_4N^+Br^-$; Pd/Ni bimetallic clusters stabilized by $(C_4H_9)_4N^+Br^-$.
[b] Estimated on the basis of GC or TLC. [c] Solvent: N,N-dimethylformamide (DMF).

Although optimization was not carried out, several trends are apparent. As in the normal Suzuki reaction,[5] bromoaromatics are better reaction partners than the chloro-analogs, and electron-withdrawing substituents facilitate the reaction. Bases such as KOAc or K_2CO_3 (as well as the Na salts) are well suited, whereas Hünig base results in poor yields. The Pd/Ni bimetallic clusters appear to be somewhat more efficient than the pure Pd clusters. It is currently not clear whether this is due to true bimetallic catalysis, or whether the presence of the nickel simply influences the morphology of the cluster. The reaction of bromobenzene with **1** was also carried out using 0.5 mol-% of a PVP-stabilized Pd cluster[7] (2.5 equiv. KOAc/DMA/100°C/3.5 h). Conversion was complete, although isolation of the product **3** (R = H) caused some problems (23%). The use of PPh_3 in these reactions leads to a reduction of the rate. Phosphine-free Suzuki reactions have been reported recently in a heterogeneous system[8] and in solution[9] using catalysts derived from $Pd(OAc)_2$, $Pd_2(dba)_3 \cdot C_6H_6$ (dba = dibenzylideneacetone) or $[(\eta^3\text{-}C_3H_5)PdCl]_2$.

Several experiments were also carried out using the Pd clusters in Heck reactions. For example, acrylic acid *n*-butyl ester **4** was reacted with iodobenzene **5** in the presence of $(C_8H_{17})_4N^+Br^-$-stabilized Pd clusters (size: 3 nm; amount of total Pd: 1 mol-%) overnight, affording cinnamic acid ester with nearly quantitative conversion.



4 **5** **6**

The system is unsuitable for chlorobenzene. Phosphine-free Heck reactions have been reported in other systems.[10] Although in our reactions solutions of metal clusters function as catalysts, these systems cannot be viewed as homogeneous catalysis in the classical sense.[11] Rather, colloidal solutions are involved in which catalysis occurs at active sites on the surface of the clusters. In this sense it is more like heterogeneous catalysis.

In summary, we have shown for the first time that solutions of ammonium salt stabilized Pd or Pd/Ni clusters are useful catalysts for phosphine-free Suzuki[12] and Heck reactions.[13] Polymer (e. g., PVP) stabilized Pd clusters are also active catalysts. A general limitation is the fact that non-activated chloroaromatics do not react. Indeed, a general solution to this problem remains a challenge in organic chemistry, despite several interesting developments.[5,6,10,14]

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12. Typical procedure: To a solution of a $(C_8H_{17})_4N^+Br^-$-stabilized Pd cluster (2 - 3 nm)[2] (2 mol-%) in 5 ml of dry DMA are added phenylboronic acid **1** (1.1 mmol), an aryl halide **2** (1 mmol) and potassium acetate (2.5 mmol) under argon. The mixture is heated up to the reaction temperature and stirred for the time given in Table 1. The solution is diluted with CH_2Cl_2 (50 ml) and washed twice with half-sat. NaCl solution. After washing with H_2O, the solvent is stripped off and the crude material is purified by flash chromatography (SiO_2).
13. Dr. M. Beller (Hoechst AG) has informed us that they have made similar observations (Heck reactions).
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