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Pd on Surface-Modified $NiFe_2O_4$ Nanoparticles: A Magnetically Recoverable Catalyst for Suzuki and Heck Reactions

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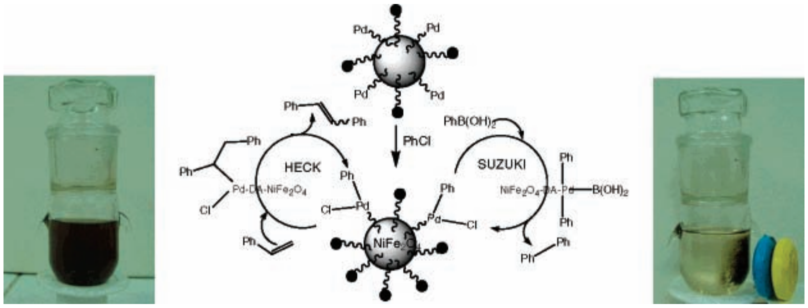
ABSTRACT



This communication reports on the use of $NiFe_2O_4$-DA-Pd, a complete magnetically separable catalyst for Suzuki and Heck coupling reactions of aromatic halide derivatives. The catalyst efficiency for the coupling of chloro derivatives is as good as bromo and iodo derivatives. Catalytic efficiency remains unaltered even after three repeated cycles.

One of the major areas of current research in the field of catalysis is the synthesis of surface-modified nanoparticles with appropriate surface-modifying agents and their application in specific catalytic reactions.[1,2] The high surface area combined with more active sites and a highly dispersed system because of the surface-modifying agents offers a particularly efficient catalyst for a wide variety of reactions. In addition, surface-modified nanoparticles can be used as noble metal supports to prepare heterogeneous catalysts that are more accessible to the reactants as compared to conventional heterogeneous systems.[1a,3] These surface-modified catalysts also take care of some of the routine problems associated with heterogeneous catalysis, such as leaching of metal ions, catalytic efficiency, etc. The primary formidable task in using such nanoparticle systems for heterogeneous catalysis is the problem associated with the separation of the catalyst after the reaction.

It is here that nanoparticles amenable for magnetic separation have an edge. There are many recent reports on the development of new catalysts using this property of magnetic separation.[4]

Surface-modified magnetic nanoparticles when used as catalyst supports ensure minimal loss, easy separation, and have the advantage of reusability in addition to taking care of the leaching problem as well as dispersion in the reaction medium. Thus surface modification with an appropriate capping agent makes the system more efficient than con-

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(1) (a) Mandal, S.; Roy, D.; Chaudhari, R. V.; Sastry, M. *Chem. Mater.* **2004**, *16*, 3714−3724. (b) Tatumi, R.; Akita, T.; Fujihara, H. *Chem. Commun.* **2006**, 3349−3351. (c) White, A. M.; Johnson, A. J.; Koberstein, T. J.; Turro, N. J. *J. Am. Chem. Soc.* **2006**, *128*, 11356. (d) Niu, Y.; Yeung, K. L.; Crooks, R. M. *J. Am. Chem. Soc.* **2001**, *123*, 6840−6846. (e) Lewis, L. N. *Chem. Rev.* **1993**, *93*, 2693−2730. (f) Underhill, R. S.; Liu, G. J. *Chem. Mater.* **2000**, *12*, 3633−3641.

(2) Tamura, M.; Fujihara, H. *J. Am. Chem. Soc.* **2003**, *125*, 15742−15743.

(3) (a) Tada, M.; Iwasawa, Y. *Chem. Commun.* **2006**, 2833−2844. (b) Wang, Z.; Shen, B.; Aihua, Z.; He, N. *Chem. Eng. J.* **2005**, *113*, 27−34.

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ventional heterogeneous catalyst systems. All these render the catalyst cost-effective, making it promising for industrial applications.

The Suzuki coupling reaction has become a main stay in modern synthetic organic chemistry for the preparation of biaryl compounds.[5] Similarly, the Heck coupling reaction is the most powerful and widely used method to couple alkenes with organic moieties bearing suitable leaving groups such as halide, triflate, or diazonium.[6] The coupling products of both the reactions have found good applications as intermediates in the preparation of materials, natural products, and bioactive compounds.[7] Despite the synthetic elegance and high turnover number, these coupling reactions suffer from the serious limitations of using expensive bromo- and iodoarenes that preclude their widespread industrial use.[8] Much recent work has been directed toward the development of new catalyst systems that efficiently process challenging substrates such as aryl chlorides[9] while still using relatively mild reaction conditions and low catalyst loadings.[10] With the intention of developing a new catalyst system that may take care of many of the above-mentioned inadequacies, namely, dispersion, leaching, separation, reusability, and catalytic efficiency toward various types of reactions, along with the added advantage of cost effectiveness, we have designed a novel catalyst system where Pd(0) nanoparticles have been anchored on the surface of dopamine-modified $NiFe_2O_4$ nanoparticles. The catalyst system is highly dispersible in various polar solvent systems, namely, water, ethanol, DMF, etc. Since the Pd(0) nanoparticles are stabilized by the amine groups of dopamine, leaching of Pd from the catalyst system is minimized. The superparamagnetic property of the $NiFe_2O_4$ nanoparticles facilitates the magnetic separation of the catalyst ensuring easy separation and reusability.

In our earlier publication,[11] we demonstrated the efficient use of our catalyst $NiFe_2O_4$-DA-Pd and Fe_3O_4-DA-Pd in the hydrogenation reaction for a range of compounds. In the present communication, we report on the use of $NiFe_2O_4$-DA-Pd for Heck and Suzuki coupling reactions of chloro, bromo, and iodo derivatives. We have observed that the catalyst exhibits very high efficiency for the coupling of chloro derivatives along with the bromo and iodo counterparts, thus making it a potentially important catalyst for industrial purposes. Another feature of our catalyst system is that we did not use any ligands to carry out the reactions. The catalyst is completely recoverable with the simple application of an external magnetic field, and the efficiency of the catalyst remains unaltered even after three repetitions in each of the reactions.

Procedures for the preparation and characterization of the catalyst are described in our earlier publication.[12]

In brief, the $NiFe_2O_4$ nanoparticles have been synthesized by a hydrothermal route at 225 °C. Anchoring of dopamine molecules on the surface of the as-synthesized $NiFe_2O_4$ nanoparticles has been achieved via refluxing for 12 h in aqueous medium. Pd(0) nanoparticles were then anchored onto the surface-modified $NiFe_2O_4$ nanoparticles by reducing Na_2PdCl_4 with hydrazine monohydrate.

Anchoring of the dopamine molecules has been confirmed with Fourier transformed infrared (FTIR) spectroscopy, while the weight percentage of Pd in the catalyst has been determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) analysis and was found to be 8.54 before reaction and 8.35 after three repetitions. ICP-AES studies confirmed the minimal loss of Pd during the reactions as the percentage of Pd in the catalyst before reaction is almost equal to the percentage of Pd after three repeated reactions.

X-ray photoelectron spectroscopy (XPS) studies confirmed the oxidation state of Pd nanoparticles where we have observed a single peak at the binding energy position of 334.42 eV with an fwhm of 1.6 eV that is attributed to the Pd in the zero oxidation state.

Vibrating sample magnetometer (VSM) studies confirmed the superparamagnetic behavior of the catalyst system. Results of FTIR, XPS, and VSM are presented in the Supporting Information.

Figure 1a shows the transmission electron microscope (TEM) micrographs of the $NiFe_2O_4$-DA-Pd, before reaction and (b) after three cycles. As the size of both $NiFe_2O_4$ and Pd are in the nanometer range, we were unable to distinguish

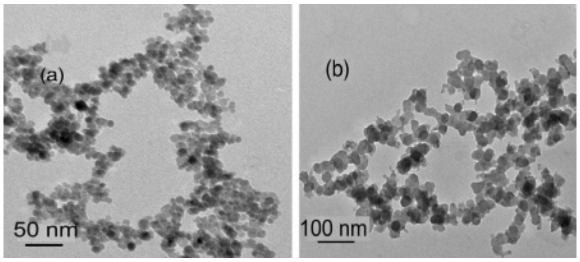

Figure 1. (a) $NiFe_2O_4$-DA-Pd before reaction and (b) after three reactions.

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[4] (a) Bönnemann, H.; Brijoux, W.; Brinkmann, R.; Dinjus, E.; Jouâen, T.; Korall, B. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1312−1314. (b) Lu, P.; Toshima, N. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 751−758. (c) Tsang, S. C.; Caps, V.; Paraskevas, I.; Chadwick, D.; Thompsett, D. *Angew. Chem., Int. Ed.* **2004**, *43*, 5645−5649. (d) Stevens, P. D.; Fan, J.; Gardimalla, H. M. R.; Yen, M.; Gao, Y. *Org. Lett.* **2005**, *7*, 2085−2088. (e) Lu, A.-H.; Li, W. C.; Kiefer, A.; Schmidt, W.; Bill, E.; Fink, G.; Schüth, F. *J. Am. Chem. Soc.* **2004**, *126*, 8616−8617. (f) Hu, A.; Yee, G. T.; Lin, W. *J. Am. Chem. Soc*. **2005**, *127*, 12486−12487. (g) Yi, K. D.; Lee, S. S.; Ying, Y. J. *Chem. Mater*. **2006**, *18*, 2459−2461. (h) Raja, R.; Glovko, B V.; Thomas, M. J.; Berenguer-Murcia, A.; Zhou, W.; Xie, S.; Johnson, G. F.B. *Chem. Commun*. **2005**, 2026−2028. (i) Kawamura, M.; Sato, K. *Chem. Commun*. **2006**, 4718−4719.

[5] (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (b) Suzuki, A. *J. Organomet. Chem.* **1999**, *576*, 147.

[6] Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic Press: London, 1985.

[7] Choudary, B. M.; Madhi, S.; Chowdari, N. S.; Kantam, M. L.; Sreedhar, B. *J. Am. Chem. Soc*. **2002**, *124*, 14127−14136.

[8] (a) Spencer, A. *J. Organomet. Chem.* **1984**, *270*, 115 (b) Spencer, A. *J. Organomet. Chem.* **1983**, *258*, 101.

[9] (a) Littke, A. F.; Fu, G. C. *Angew. Chem., Int. Ed.* **2002**, *41*, 4176−4211. (b) Lipshutz, B. H.; Sclafani, J.; Blomgren, P. A. *Tetrahedron* **2000**, *56*, 2139. (c) Churruca, F.: SanMartin, R.; Tellitu, R.; Domínguez, E. *Tetrahedron Lett.* **2003**, *44*, 5925−5929. (d) Churruca, F.; SanMartin, R.; Carril, M.; Tellitu, I.; Domínguez, E. *Tetrahedron* **2004**, *60*, 2393−2408. (e) Colacot, T. J.; Gore, E. S.; Kuber, A. *Organometallics* **2002**, *21*, 3301−3304. (f) Wang, Y.; Sauer, D. R. *Org. Lett*. **2004**, *6*, 2793−2796.

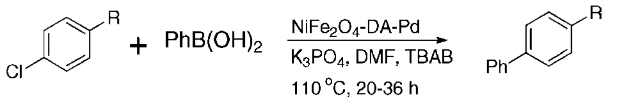
[10] Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685−4696. (b) Marion, N.; Navarro, O.; Mei, J.; Stevens, E. D.; Scott, N. M.; Nolan, S. P. *J. Am. Chem. Soc.* **2006**, *128*, 4101−4111.

between the two nanoparticles on the basis of their size, but because of the significant difference in the contrast, Pd particles could be easily identified as dark spots on $NiFe_2O_4$ nanoparticles.[13] From the TEM micrographs, it can be seen that the particles before the reaction are well-dispersed with an average size of 10 ± 2 nm. After three repeated reactions, we did not observe much change in the morphology and dispersion of the particles, but a slight increase in the particle size to about 15−20 nm was observed. This may be attributed to the growth of particles following repeated heat treatment of the catalyst while carrying out the reactions.

The synthesized catalyst system was then tested for the Suzuki cross-coupling reactions of aryl halides with phenyl boronic acid.

In a typical Suzuki experiment (Scheme 1), 0.5 mmol of the aryl chloride was taken in 5 mL of DMF. To this were added 1.2 equiv of phenyl boronic acid, 3 equiv of K_3PO_4, and 5 mg of tetrabutylammonium bromide (TBAB). The amount of catalyst used in each reaction was 50 mg, and temperature was maintained at 110 °C. Completion of the reaction was monitored by thin layer chromatography (TLC) after which the reaction mixture was cooled to room temperature. An excess amount of ether was added to the reaction mixture, and then a magnet was used to separate the catalyst from the reaction mixture. The pure product was isolated by column chromatography and confirmed with ^1H NMR and gas chromatographic mass spectrometry (GCMS) studies. The catalyst was then washed several times with chloroform and dried at room temperature under vacuum before being used again for the next reaction.

Scheme 1



The same reaction conditions and procedure were used for the bromo and iodo derivatives with temperatures maintained at 65 and 45 °C, respectively. Also, no TBAB was added into the mixture. Here it is observed that the reactions are faster and accomplished at comparatively lower temperatures than the chloro derivatives. Table 2 gives the summary of the Suzuki coupling reactions with bromo and iodo derivatives.

Table 1. Summary of the Suzuki Coupling Reactions with Chloro Derivatives

entry	R	X	yield[a] (%)	time (h)	temp (°C)
1	H	Cl	93 (90)[b]	36	110
2	NO_2	Cl	92	36	110
3	Me	Cl	80	36	110
4	COMe	Cl	88	36	110
5	OMe	Cl	76	36	110

[a] Isolated yield. [b] Yield after three reactions.

Table 2. Summary of the Suzuki Coupling Reactions with Bromo and Iodo Derivatives

entry	R	X	yield[a] (%)	time (h)	temp (°C)
1	H	Br	97 (96)[b]	30	65
2	NO_2	Br	98	30	65
3	Me	Br	82	30	65
4	COMe	Br	92	30	65
5	OMe	Br	74	30	65
6	NO_2	I	98	24	45
7	Me	I	97 (96)[b]	24	45
8	COMe	I	98	24	45
9	OMe	I	88	24	45

[a] Isolated yield. [b] Yield after three reactions.

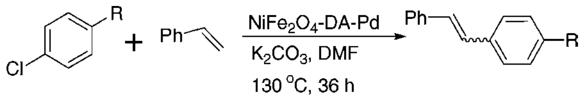
In standardizing the reaction conditions, we have used several bases and solvent systems to monitor the best possible combination. When we used DMA as the solvent while maintaining all other above-mentioned reaction conditions, we observed that the reactions were completed with very high yield, but the catalyst could not be reused. This is because the solvent forms a complex with the catalyst like a ferrofluid and gets dragged magnetically along with the particles. With dioxane and dioxane/water as solvent systems, the yield of the reactions was very low. When we used K_2CO_3 or triethylamine as the base instead of K_3PO_4, the yield was 10−20%, which is much less when compared to the standard reaction conditions employed.

Table 1 gives the summary of the Suzuki coupling reactions with chloro derivatives.

The catalyst system was also used for the Heck coupling reaction of aryl chlorides with styrene. Here also we have tried different solvents, reaction times, temperature, etc., for optimization of the reaction conditions to obtain maximum conversion and yield.

For Heck coupling reactions (Scheme 2), 0.5 mmol of the aryl chloride, 1.2 equiv of styrene, and 1.2 equiv of K_2CO_3 were taken in 5 mL of DMF and heated to 130 °C. This temperature was maintained until the completion of the reaction. The separation and product isolation procedures are the same as that adopted for the Suzuki coupling reactions.

Scheme 2



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(11) Guin, D.; Baruwati, B.; Manorama, S. V. *Org. Lett.* **2007**, *9*, 1491.

(12) Baruwati, B.; Reddy, K. M.; Manorama, S. V.; Singh, R. K.; Om, P. *Appl Phys. Lett.* **2004**, *85*, 2833−2835.

(13) Cozzoli, P. D.; Comparelli, R.; Fanizza, E.; Curri, M. L.; Agostiano, A.; Laub, D. *J. Am. Chem. Soc.* **2004**, *126*, 3868.

Table 3. Summary of Heck Reactions with Chloro Derivatives

entry	R	X	yield[a] (%)	time (h)	temp (°C)
1	H	Cl	95 (92)[b]	36	130
2	NO_2	Cl	88	36	130
3	Me	Cl	80	36	130
4	COMe	Cl	87	36	130
5	OMe	Cl	72	36	130

[a] Isolated yield. [b] Yield after three reactions.

Table 3 gives the summary of the Heck coupling reactions with chloro derivatives.

The Heck reaction with the bromo and iodo derivatives was carried out at 65 and 45 °C, respectively, following the same reaction procedure as that adopted for the chloro derivatives. The catalyst functions efficiently and gives nearly 95% product selectivity even under these mild conditions. Table 4 gives the summary of the Heck coupling reactions with bromo and iodo derivatives.

Table 4. Summary of Heck Reactions with Bromo and Iodo Derivatives

entry	R	X	yield[a] (%)	time (h)	temp (°C)
1	H	Br	97 (95)[b]	30	65
2	NO_2	Br	93	30	65
3	Me	Br	90	30	65
4	COMe	Br	92	30	65
5	OMe	Br	90	30	65
6	NO_2	I	95	24	45
7	Me	I	97 (94)[b]	24	45
8	COMe	I	97	24	45
9	OMe	I	95	24	45

[a] Isolated yield. [b] Yield after three reactions.

The reactions were repeated three times, reusing the catalyst for both Suzuki and Heck coupling reactions, and the yield remained almost the same.

The following observations are made from all the above studies. The catalyst system $NiFe_2O_4$-DA-Pd developed is highly effective for the C−C coupling reactions of aryl halides. The presence of dopamine in the $NiFe_2O_4$-DA-Pd catalytic system enhances the efficiency by acting as a ligand during the reactions. This may also be one of the reasons for the increased activity toward the C−C coupling of chloro derivatives.

In conclusion, we have developed a magnetically separable catalyst that is highly active toward Suzuki and Heck coupling reactions for a range of aryl halides. The catalyst is equally active toward the chloro derivatives when compared with the bromo and iodo derivatives of these aromatic halides. A highly dispersed catalyst system in DMF and the presence of more active sites in the nanosized Pd are the main reasons for the enhanced catalytic activity even for the chloro derivatives. The presence of dopamine acting as a ligand also adds to the merit of the catalytic system. The high activity, easy separation, and reusability are the salient features of the $NiFe_2O_4$-DA-Pd system that make it a competitive catalyst for scientifically and industrially important reactions.

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Supporting Information Available: Experimental methods, FTIR spectra, XPS, VSM plots, and GCMS spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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