

# Palladium Nanoparticles Stabilized by a Copolymer of *N*-Vinylimidazole with *N*-Vinylcaprolactam as Efficient Recyclable Catalyst of Aromatic Cyanation

I. P. Beletskaya<sup>b</sup>, A. V. Selivanova<sup>a</sup>, V. S. Tyurin<sup>a</sup>, V. V. Matveev<sup>a</sup>, and A. R. Khokhlov<sup>b</sup>

<sup>a</sup>*Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow, 119991 Russia*  
*e-mail: beletska@org.chem.msu.ru*

<sup>b</sup>*Lomonosov Moscow State University, Moscow, Russia*

Received May 22, 2009

**Abstract**—A new recyclable catalytic system was developed based on palladium nanoparticles and a copolymer of *N*-vinylimidazole and *N*-vinylcaprolactam for cyanation of aromatic bromides. The source of the cyanide ion was a nontoxic potassium hexacyanoferrate.

**DOI:** 10.1134/S1070428010020016

Aromatic nitriles are an important class of organic compounds used in the production of dyes, pharmaceuticals, agricultural reagents [1, 2]. They often are intermediate products in the organic synthesis for the cyano group is easily transformed into other functional groups [3]. The aryl cyanides are commonly obtained from aryl halides by Rosenmund–von Braun reaction [4] or from diazonium salts by Sandmeyer reaction [5]. Both these reactions proceed under stringent conditions and require employing stoichiometric or even larger quantity of copper compounds. However it is possible at present to perform the catalytic cyanation under mild conditions (see, e.g., [6]). The transformation of aryl halides into nitriles was investigated with the use of various sources of the cyanide ion under the catalysis with complexes of nickel [7], palladium [8], and copper [9]. The cheapest source of the cyanide ion are simple salts like KCN, but they are toxic, and moreover, they are poisons for the palladium catalyst [10]. The poisoning is prevented by adding chelating diamines, for instance, *N,N,N',N'*-tetramethylethylenediamine (TMEDA) [2, 11], or by applying as catalyst the combination Pd(0)–Cu(I) [12]. Another widely used source of the cyanide ion is Zn(CN)<sub>2</sub> [13, 14], the application has been described also of Me<sub>3</sub>SiCN [15], a combination KCN–Me<sub>3</sub>SnCl [16], of acetone cyanohydrine [17], and (RO)<sub>2</sub>BCN [18]. ArI, ArBr, ArOTf, and even ArCl containing electron-acceptor substituents were brought into the reaction. The nonactivated aryl chlorides are involved into the reaction at the use of strongly

donor and sterically hindered phosphine ligands [19], even at relatively low temperature (80–95°C) [20]. A cyanation reaction with a palladium catalyst with a grafted phosphine ligand was reported, but the recyclization possibility of this catalyst was not mentioned [21].

Recently the potassium hexacyanoferrate(II) was used again as a cheap and nontoxic source of the cyanide ion [22]. The reaction with aryl bromides was carried out with palladium-phosphine catalyst [23], in the presence of diamines in ionic liquids [24], and at higher temperatures also with “ligand-free” palladium [25]. The reaction with an immobilized palladium was performed with aryl iodides [26], and with activated aryl bromides and Pd/C it was carried out in the presence of inorganic bases and Bu<sub>3</sub>N. The possibility was shown to recyclize the catalyst (four cycles), but the yield in this case gradually decreased [27]. It proved that at high temperature (140–160°C) even the nonactivated aryl chlorides were involved into the reaction [28]. The great interest is attracted by the possibility of the cyanation in water, under the microwave irradiation, and without ligands. As catalyst Pd/C [29] or palladium acetate [30] were used, both aryl iodides and aryl bromides were brought into the reaction.

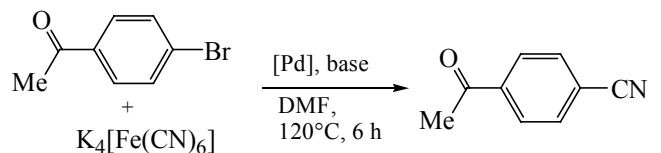
In extension of the research on recyclizable catalytic systems based on soluble polymers [31, 32] we carried out the cyanation of aryl bromides with potassium hexacyanoferrate(II) using for a catalyst the palladium immobilized on a random copolymer poly(*N*-vinylimidazole)–poly(*N*-vinylcaprolactam) (the content of *N*-vinyl-

caprolactam 30 mol%) that previously had been shown to be efficient and recyclizable catalyst in Heck reaction [32].

The effect of the nature of the base on the yield of the reaction product was studied by an example of the reaction of 4-bromoacetophenone in DMF at 120°C. The function of the base apparently consists in driving the cyanide ion from  $K_4[Fe(CN)_6]$ . The reaction failed to proceed at the use as the base of  $K_2CO_3$  evidently because of the high solubility of  $K_2CO_3$  resulting consequently in a higher concentration of the cyanide ions in the solution leading to the poisoning of the catalyst. The use of  $Na_3PO_4$ ,  $K_3PO_4$ , and  $Na_2CO_3$  made it possible at the concentration of Pd 1 mol% to bring the reaction to completion in 6 h (Table 1). The quantity of the catalyst can be considerably reduced (to 0.1 mol%), but it leads to the longer reaction time. Inasmuch as the recycling of the catalyst permitted avoiding the loss of palladium we applied further the concentration of Pd 1 mol%.

Under the optimized conditions (1 mol% Pd and  $Na_3PO_4$ ) reaction was performed with aryl and heteroaryl bromides. All aryl bromides containing both electron-acceptor and electron-donor substituents reacted to 100% conversion of aryl bromide (by the data of NMR and GLC), but the selectivity of the reaction varied in the

**Table 1.** Cyanation of 4-bromoacetophenone with potassium hexacyanoferrate (II) in the presence of various bases<sup>a</sup>



Run number	Base	Yield, % <sup>b</sup>
1	$Na_2CO_3$	80
2	NaOAc	24
3	$K_2CO_3$	No reaction
4	$Na_2CO_3$ – $K_2CO_3$ , 1:1	58
5	$Na_3PO_4$ <sup>c</sup>	93
6	$K_3PO_4$ <sup>c</sup>	92
7	$Na_2CO_3$ <sup>d</sup>	98 <sup>e</sup>

<sup>a</sup> Reaction conditions: 1 mol% of  $PdCl_2$ /copolymer 1 : 5 (with respect to monomer unit), 0.2 mmol of 4-bromoacetophenone, 0.044 mmol of  $K_4[Fe(CN)_6] \cdot 3H_2O$ , 0.2 mmol of base, 0.5 ml of DMF, 120°C, 6 h.

<sup>b</sup> Yield by <sup>1</sup>H NMR data, dimethyl terephthalate used as reference.

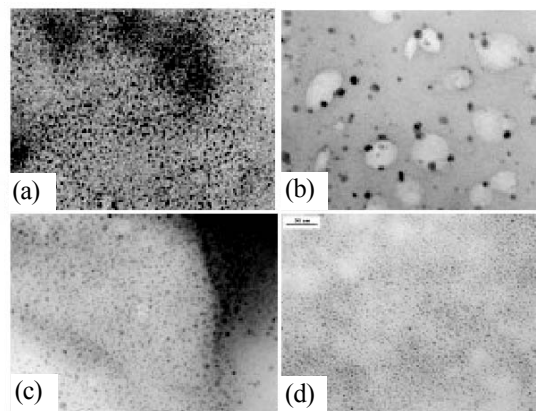
<sup>c</sup> 0.1 mmol of base.

<sup>d</sup> 0.1 mol% of Pd, 10 h. <sup>e</sup>Yield of the isolated reaction product.

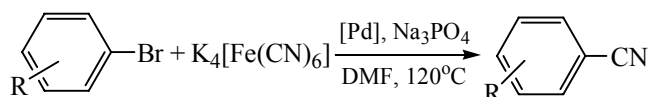
range 60–99%, likely due to the reduction processes. In going from electron-deficient aryl bromides to electron-rich compounds the time of the reaction grew. Due to the volatility of some compounds the yield measured by NMR spectra after concentration was underestimated; similar case had been previously observed [14]. We yet have not found the reason of the formation from *p*-bromochlorobenzene alongside the *p*-chlorobenzonitrile also of 1,4-dicyanobenzene (Table 2, run no. 6), and therewith as the main reaction product, whereas the *p*-chlorobenzonitrile proper did not react under the given conditions.

2-Bromopyridine failed to react even at 140°C. We presume that the reason was the difficulty of the reductive elimination from the complex 2-PyPdCN in the absence of strong donor ligands (Table 2, run no. 11). Although we failed to bring into the reaction the *p*-chlorobenzonitrile the more activated *p*-chloroacetophenone reacted at 140°C but the yield was low (conversion 37%) (Table 2, run no. 14).

By the example of the 4-bromoacetophenone cyanation we studied the possibility of the catalyst recyclization. On completion of the reaction in each cycle the catalyst was precipitated by ethyl ether, it was isolated, washed, and to the solid residue the solvent and the required amounts of the reaction components were added. The yields in the ten successive cycles varied from 93 and 99% in the first cycles to 89% in the last (Table 3), i.e., the catalyst activity changed within the limits of the measurement error. The investigation of catalyst samples after the fourth and the tenth cycles by transmission electro microscopy showed that the size distribution of palladium nanoparticles altered insignificantly. The



The images obtained by transmission electron microscopy of catalytic system  $PdCl_2$ /copolymer 1:5 after a blank run (a), after the 1st (b), 4th (c), and 10th (d) cycle of 4-bromoacetophenone cyanation (scale 50 nm).

**Table 2.** Cyanation of aryl bromides<sup>a</sup>

Run no.	Aryl bromide	Time, h	Reaction product	Yield, % <sup>b</sup>	Run no.	Aryl bromide	Time, h	Reaction product	Yield, % <sup>b</sup>
1 <sup>c</sup>		11		77	8		8		80
2 <sup>c</sup>		18		70	9		8		65
3		18		70	10		11		>99
4		6		93	11 <sup>c</sup>		16		no reaction
5		8		71	12 <sup>c</sup>		16		61
6 <sup>d</sup>		8	 	22 60	13		10		72
7		8		75	14 <sup>c</sup>		16		21

<sup>a</sup> Reaction conditions: 1 mol% of PdCl<sub>2</sub>/copolymer 1 : 5 (with respect to monomer unit), 0.2 mmol of aryl bromide-, 0.044 mmol of K<sub>4</sub>[Fe(CN)<sub>6</sub>]·3H<sub>2</sub>O, 0.2 mmol of base, 0.5 ml of DMF, 120°C, 6 h.

<sup>b</sup> Yield by <sup>1</sup>H NMR data, dimethyl terephthalate used as reference.

<sup>c</sup> 140°C.

<sup>d</sup> 0.088 mmol of K<sub>4</sub>[Fe(CN)<sub>6</sub>]·3H<sub>2</sub>O.

dimensions of the formed nanoparticles lie in the range 2–15 nm, and the distribution maximum corresponds to 7 nm (see the figure, b–d). Regrettably, the resolution of the electron microscope did not allow more precise

measurements, and it was not possible to explain the reason of the visible change in the nanoparticles after the tenth cycle.

**Table 3.** Recycling of catalyst, 10 cycles

Cycle no.	Yield, %	Cycle no.	Yield, %
1	93	6	>99
2	93	7	97
3	90	8	93
4	>99	9	95
5	90	10	89

The palladium nanoparticles evidently form by reduction of palladium(II) chloride with dimethylamine contained in the solvent or arising on heating DMF. It is shown by the blank experiment that the palladium nanoparticles formed at heating PdCl<sub>2</sub> in DMF for 2 h 120°C (see the figure, a).

Therefore the catalytic system we developed makes it possible to replace efficiently bromine atoms by the cyano group in aryl bromides both with electron-acceptor and electron-donor substituents. It was established that in the course of this reaction the bivalent palladium is reduced to zero-valent with the subsequent formation of

stable palladium nanoparticles stabilized by the polymer. The polymer system with the nanoparticles is easily isolated from the low-molecular reaction products by precipitation and can be used repeatedly with the retention of its activity.

## EXPERIMENTAL

NMR spectra were registered on a spectrometer Bruker AMX-400 with operating frequency 400 MHz from solutions in deuterochloroform. The quantitative analysis by  $^1\text{H}$  NMR method was carried out using dimethyl tetrphthalate as internal reference. The images by transmission electron spectroscopy were obtained on an instrument EM 301 Philips. The solvents used in the synthesis were purified by standard procedures. The most reagents purchased from Aldrich were used without further purification. The copolymer poly(*N*-vinylimidazole)–poly(*N*-vinylcaprolactam), M20000, was prepared by method [32]. Palladium chloride was taken as an ethanol solution of  $\text{H}_2\text{PdCl}_4$ . The reactions were carried out in an argon atmosphere, the reaction progress was monitored by TLC on Alugram SilG/UV<sub>254</sub> plates (Macherey-Nagel).

**Cyanation of aryl halides with potassium hexacyanoferrate(II), General procedure.** 1 ml of a solution of  $\text{H}_2\text{PdCl}_4$  in ethanol (*C* 0.002 mmol/ml) was evaporated in a vacuum to dryness, and thereto was added 0.2 mmol of aryl halide, 18.6 mg (0.044 mmol) of  $\text{K}_4[\text{Fe}(\text{CN})_6] \cdot 3\text{H}_2\text{O}$ , 16.4 mg (0.1 mmol) of  $\text{Na}_3\text{PO}_4$ , 1.0 mg (5 mol% with respect to one monomer unit) of copolymer poly(*N*-vinylimidazole)–poly(*N*-vinylcaprolactam) (content of *N*-vinylcaprolactam 30 mol%), and 0.5 ml of DMF. The reaction mixture was heated at constant stirring at 120°C for a time required for the completion of the reaction. On cooling the mixture to room temperature the catalyst was precipitated by adding 4 ml of ethyl ether, the solution was separated, the precipitate was washed with ethyl ether (2×2 ml). The combined ether solutions were passed through a small bed of silica gel, elution with 4 ml of dichloromethane. The obtained reaction mixture was studied by  $^1\text{H}$  NMR.

**Recycling of catalyst.** To the separated precipitate of catalyst twice washed with ethyl ether and dried in a vacuum was added 39.8 mg (0.2 mmol) of *p*-bromoacetophenone, 18.6 mg (0.044 mmol) of  $\text{K}_4[\text{Fe}(\text{CN})_6] \cdot 3\text{H}_2\text{O}$ , 12.3 mg (0.075 mmol) of  $\text{Na}_3\text{PO}_4$ , 0.5 ml of DMF, and the reaction was performed by the general procedure.

**Preparation of ethanol solution of  $\text{H}_2\text{PdCl}_4$ .** To 3.6 mg of  $\text{PdCl}_2$  in 6 ml of anhydrous ethanol was added 0.3 ml of 4 M solution of HCl in dioxane, the mixture was stirred at room temperature till the complete dissolution of  $\text{PdCl}_2$ . The solution was transferred into a volumetric flask of 10.0 ml, and ethanol was added to the mark. Thus the solution of  $\text{H}_2\text{PdCl}_4$  was obtained of the concentration 0.002 mmol/ml.

The authors are grateful for the financial support to the Russian Academy of Sciences (program of basic research of the Department of Chemistry and Material Science of the Russian Academy of Sciences no. 4 “Creation and investigation of macromolecules and macromolecular structures of new generations”).

## REFERENCES

- Schareina, T., Zapf, A., and Beller, M., *J. Organometal. Chem.*, 2004, vol. 689, p. 4576.
- Sundermeier, M., Zapf, A., Mutyala, S., Baumann, W., Sans, J., Weiss, S., and Beller, M., *Chem. Eur. J.*, 2003, vol. 9, p. 1828.
- Larock, R.C., *Comprehensive Organic Transformations: A Guide To Functional Group Preparations*, New York: VCH, 1989.
- Mowry, D.F., *Chem. Rev.*, 1948, vol. 42, p. 189; Rosenmund, K.W. and Struck, E., *Chem. Ber.*, 1919, vol. 52, p. 1749.
- Ellis, G.P. and Romney-Alexander, T.M., *Chem. Rev.*, 1987, vol. 87, p. 779.
- Beletskaya, I.P., Sigeev, A.S., Peregudov, A.S., Petrovskii, P.V., *J. Organometal. Chem.*, 2004, vol. 689, p. 3810; Hatsudaa, M., and Seki, M., *Tetrahedron*, 2005, vol. 61, p. 9908.
- Cassar, L., Foa, M., Montanari, F., and Marinelli, G. P., *J. Organometal. Chem.*, 1979, vol. 173, p. 335; Sakakibara, Y., Okuda, F., Shimoyabashi, A., Kirino, K., Sakai, M., Uchino, N., and Takagi, K., *Bull. Chem. Soc. Jpn.*, 1988, vol. 61, p. 1985; Sakakibara, Y., Ido, Y., Sasaki, K., Sakai, M., and Uchino, N., *Bull. Chem. Soc. Jpn.*, 1993, vol. 66, p. 2776.
- Takagi, K., Okamoto, T., Sakakibara, Y., Ohno, A., Oka, S., and Hayama, N. *Bull. Chem. Soc. Jpn.*, 1975, vol. 48, p. 3298; Takagi, K., Okamoto, T., Sakakibara, Y., Ohno, A., Oka, S., and Hayama, N., *Bull. Chem. Soc. Jpn.*, 1976, vol. 49, p. 3177; Dalton, J.R. and Regen, S.L., *J. Org. Chem.*, 1979, vol. 44, 4443; Akita, Y., Shimazaki, M. and Ohta, A. *Synthesis*, 1981, p. 974; Anderson, Y. and Lengstrom, B., *J. Chem. Soc., Perkin Trans. 1*, 1994, p. 1395; Anderson, B.A., Bell, E.C., Ginah, F.O., Harn, N.K., Pagh, L.M., and Wepsiec, J.P., *J. Org. Chem.*, 1998, vol. 63, p. 8224.
- Wu, J.X., Beck, B., and Ren, R.X., *Tetrahedron Lett.*, 2002,

- vol. 43, p. 387; Zanon, J., Klapars, A., and Buchwald, S.L., *J. Am. Chem. Soc.*, 2003, vol. 125, p. 2890; Schareina, T., Zapf, A., and Beller, M., *Tetrahedron Lett.*, 2005, vol. 46, p. 2585; Schareina, T., Zapf, A., Magerlein, W., Müller, N., and Beller, M., *Synlett.*, 2007, p. 555; Schareina, T., Zapf, A., Magerlein, W., Müller, N., and Beller, M., *Chem. Eur. J.*, 2007, vol. 3, p. 6249; Schareina, T., Zapf, A., Cotte, A., Müller, N., and Beller, M., *Synthesis*, 2008, vol. 20, p. 3351.
10. Nakamura, M. and Fujiwara, S., *J. Coord. Chem.*, 1972, vol. 1, p. 221.
  11. Sundermeier, M., Zapf, A., Beller, M., and Sans, J., *Tetrahedron Lett.*, 2001, vol. 42, p. 6707.
  12. Anderson, B.A., Bell, E.C., Ginah, F.O., Harn, N.K., Pagh, L.M., and Wepsiec, J.P., *J. Org. Chem.*, 1998, vol. 63, p. 8224.
  13. Tschaen, D.M., Desmond, R., King, A.O., Fortin, M.C., Pipik, B., King, S., and Verhoeven, T.R. *Synth. Commun.*, 1994, vol. 24, p. 887; Maligres, P.E., Waters, M.S., Fleitz, F., and Askin, D., *Tetrahedron Lett.*, 1999, vol. 40, p. 8193; Jin, F. and Confalone, P.N., *Tetrahedron Lett.*, 2000, vol. 41, p. 3271; Chidambaram, R., *Tetrahedron Lett.*, 2004, vol. 45, p. 1441; Stazi, F., Palmisano, G., Turconib, M., and Santagostino, M., *Tetrahedron Lett.*, 2005, vol. 46, p. 1815; Chobanian, H.R., Fors, B.P., and Lin, L.S., *Tetrahedron Lett.*, 2006, vol. 47, p. 3303; Littke, A., Soumeillant, M., Kaltenbach, R., Cherney, R., Tarby, C., and Kiau, S., *Org. Lett.*, 2007, vol. 9, p. 1711.
  14. Martin, M.T., Liu, B., Cooley, B.E. Jr., and Eaddy, J.F., *Tetrahedron Lett.*, 2007, vol. 48, p. 2555.
  15. Chatani, N. and Hanafusa, T., *J. Org. Chem.*, 1986, vol. 51, p. 4714; Sundermeier, M., Mutyala, S., Zapf, A., Spannenberg, A., and Beller, M., *J. Organometal. Chem.*, 2003, vol. 684, p. 50.
  16. Yang, C. and Williams, M.J., *Org. Lett.*, 2004, vol. 6, p. 2837.
  17. Sundermeier, M., Zapf, A., and Beller, M., *Angew. Chem., Int. Ed.*, 2003, vol. 42, p. 1661.
  18. Jiang, B., Kan, Y., and Zhang, A., *Tetrahedron*, 2001, vol. 57, p. 1581.
  19. Sundermeier, M., Zapf, A., Beller, M., and Sans, J., *Tetrahedron, Lett.*, 2001, vol. 42, p. 6707; Jin, F. and Confalone, P.N. *Tetrahedron, Lett.*, 2000, 41, p. 3271; Chobanian, H.R., Fors, B.P., and Lin, L.S., *Tetrahedron Lett.*, 2006, vol. 47, p. 3303.
  20. Littke, A., Soumeillant, M., Kaltenbach, R.F., Cherney, R.G., Tarby, C.M., and Kiau, S., *Org. Lett.*, 2007, vol. 9, p. 1711.
  21. Hatsuda, M. and Seki, M., *Tetrahedron Lett.*, 2005, vol. 46, p. 1849; Hatsuda, M. and Seki, M., *Tetrahedron*, 2005, vol. 61, p. 9908; Srivastava, R.R., and Collibee, S.E., *Tetrahedron Lett.*, 2004, vol. 45, p. 8895.
  22. Schareina, T., Zapf, A., and Beller, M., *Chem. Commun.*, 2004, vol. 12, p. 1388.
  23. Grossman, O. and Gelman, D., *Org. Lett.*, 2006, vol. 8, p. 1189.
  24. Li, L.-H., Pan, Z.-L., Duan, X.-H., and Liang, Y.-M., *Synlett.*, 2006, p. 2094.
  25. Schareina, T., Zapf, A., and Beller, M., *J. Organometal. Chem.*, 2004, vol. 689, p. 4576; Weissman, S.A., Zewge, D., and Chen, C., *J. Org. Chem.*, 2005, vol. 79, p. 1508.
  26. Polshettiwar, V., Hesemann, P., and Moreau, J.J.E., *Tetrahedron*, 2007, vol. 45, p. 6784.
  27. Zhu, Y.-Z. and Cai, C., *Eur. J. Org. Chem.*, 2007, p. 2401.
  28. Cheng, Y., Duan, Z., Li, T., and Wu, Y., *Synlett.*, 2007, p. 543; Schareina, T., Zapf, A., Magerlein, W., Müller, N., and Beller, M., *Tetrahedron Lett.*, 2007, vol. 48, p. 1087; Schareina, T., Jackstell, R., Schulz, T., Zapf, A., Cotte, A., Gotta, M., and Beller, M., *Adv. Synth. Catal.*, 2009, vol. 351, p. 643.
  29. Chen, G., Weng, J., Zheng, Z., Zhu, X., Cai, Y., Cai, J., and Wan, Y., *Eur. J. Org. Chem.*, 2008, p. 3524.
  30. Velmathi, S. and Leadbeater, N.E., *Tetrahedron Lett.*, 2008, vol. 49, p. 4693.
  31. Beletskaya, I.P., Kashin, A.N., Litvinov, A.E., Tyurin, V.S., Valetsky, P.M., and van Koten, G., *Organometallics*, 2006, vol. 25, p. 154; Beletskaya, I.P., Tarasenko, E.A., Khokhlov, A.R., and Tyurin, V.S., *Zh. Org. Khim.*, 2007, vol. 43, p. 1733; Beletskaya, I.P., Kashin, A.N., Khotina, I.A., and Khokhlov, A.R., *Synlett.*, 2008, p. 1547.
  32. Beletskaya, I.P., Khokhlov, A.R., Tarasenko, E.A., and Tyurin, V.S., *J. Organometal. Chem.*, 2007, vol. 692, p. 4402.