Communication

Imidazolium-based phosphinite ionic liquid (IL-OPPh$_2$) as Pd ligand and solvent for selective dehalogenation or homocoupling of aryl halides

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ARTICLE INFO

ABSTRACT

The use of an imidazolium-based phosphinite ionic liquid (IL-OPPh$_2$) as ligand for Pd offers an efficient reagent system for the selective dehalogenation or homocoupling of aryl halides in the presence of NaO-Pr^i or Et$_3$N, respectively. This ionic liquid plays a dual role as both the reaction media and also as the potential complexing agent with Pd *via* its phosphinite carrying group. The ionic liquid containing its corresponding Pd complex can be easily recovered and reused in several runs.

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1. Introduction

Much study has been devoted to develop new methods for dehalogenation of aromatic halides from the synthetic [1] and environmental [2] points of view. Usually the systems which have been developed for the reduction of halogenated arenes employ inorganic hydrides as hydrogen source and a variety of transition-metals in DMF, dioxane, toluene and or methanol as solvent [3–12]. The use of ambient hydrogen pressure (balloon) as a source of hydrogen with Pd/C-Et$_3$N for the dehalogenation of aryl chlorides suffers from lack of chemoselectivity. With this system, the reduction of the nitro group has also been observed [13].

Cross-coupling reactions have also been widely used by chemists for the synthesis of biaryls *via* formation of carbon–carbon bonds [14]. Early researches have focused mainly on finding new coupling partners, however, attention during the last decade has turned towards the development of milder reaction conditions using new catalysts and reaction systems. In order to develop catalysts that can operate at very low metal loading, the complex of Pd with phosphines [15] and with *N*-heterocyclic carbenes (NHCs) [16] in organic solvents has been the subject of intensive studies. As part of the recent developments, ionic liquids as green solvents, have also been considered as potential media for this purpose [17].

2. Results and discussion

We have recently introduced an imidazolium-based phosphinite ionic liquid (Scheme 1, IL-OPPh$_2$) for the Heck reaction[18]. This ionic liquid plays a dual role both as a potential complexing agent *via* its phosphinite carrying group with Pd and also as the media. Here, we report a new application of this ionic liquid as solvent and ligand with catalytic amounts of PdCl$_2$ for the highly selective and efficient dehalogenation or homocoupling of aryl halides in the presence of NaOPr^i or Et$_3$N, respectively, at 80 °C (Scheme 1). This dual property provides the possibility of recycling of the ionic liquid along with its corresponding Pd complex as catalyst and eliminates the waste of the ligand and also the Pd compound.

The desired products were simply isolated by diethyl ether extraction. The use of this ionic liquid also offers avoiding the use of high boiling solvents, which their separation from the reaction mixtures is usually a tedious process.

Among the studied bases for dehalogenation of bromobenzene with PdCl$_2$ in this ionic liquid, NaOPr^i was found to be more suitable for dehalogenation, probably due to the presence of β-hydrogen which can be transferred to reduce the aryl halide (Table 1, Entry 1). Et$_3$N and NaOAc were found to be more efficient for homocoupling of bromobenzene. The more reactivity of Et$_3$N and NaOAc compared with sodium and cesium carbonates could be due to their more solubility in the reaction media (Table 1, Entries 4 and 5). We therefore selected NaOPr^i and Et$_3$N as the suitable

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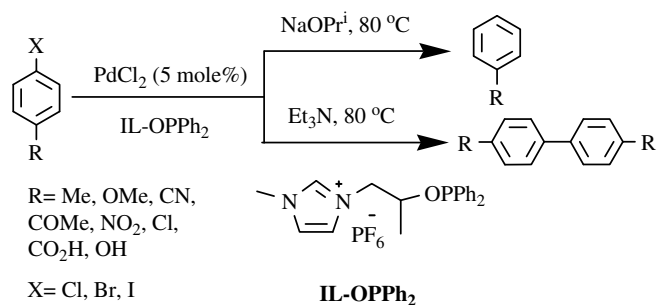
Scheme 1.

Table 1
Effect of different bases on dehalogenation and homocoupling of bromobenzene[a]

Entry	Base	Time (h)	Yield (%) [b]
1	NaOPr^i	1	100[c]
2	Na$_2$CO$_3$	8	50[d]
3	Cs$_2$CO$_3$	8	80[d]
4	NaOAc	5	100[d]
5	Et$_3$N	1	100[d]

[a] Reaction conditions: 0.5 mmole of IL-OPPh$_2$, 0.05 mmole of PdCl$_2$, 1.0 mmole of bromobenzene and 2.0 mmole of base.
[b] GC yield using *n*-octane as internal standard.
[c] Dehalogenation product.
[d] Homocoupling product.

bases for dehalogenation and homocoupling of aryl halides, respectively.

Under our optimized reaction conditions, 0.5 mmole IL-OPPh$_2$, 0.05 mmole of PdCl$_2$, and 2.0 mmole of NaOPr^i, the dehalogenated products were obtained in excellent yields for a wide array of aryl bromides and chlorides at 80 °C (Table 2). For example: a complete conversion was obtained for the reaction of bromobenzene and 4-

bromotoluene after 0.5 and 5 h, respectively (Table 2, Entries 1 and 2). For electron-deficient bromides, elongations of the reaction times along with the decrement of the yields of the products were observed (Table 2, Entries 3–5). This is most probably due to the less solubility of 4-bromobenzonitrile, 4-bromoacetophenone and 1-bromo-4-nitrobenzene in this ionic liquid. This method showed to be useful for dehalogenation of compounds carrying sensitive functional groups such as nitro, ketone and nitrile, so they remained intact in the reaction mixture and were not reduced. Also, we applied this PdCl$_2$/IL-OPPh$_2$ complex for the dehalogenation of heteroaryl halides. 3-Bromopyridine and 3-bromothiophene were dehalogenated satisfactorily and the desired products were isolated in 68% and 93% yields, respectively (Table 2, Entries 7 and 8). The use of this system for dehalogenation of aryl chlorides was also successful (Table 2, Entries 9–11). As the results shown in Table 2, Entries 10 and 11 demonstrate that the reaction is also applicable upon substrates carrying carboxylic and phenolic functionalities. The presented data in Table 2, Entries 5 and 6 also show the selective debromination reaction of 4-bromonitrobenzene and 4-chloro-bromobenzene without reduction of the reducible functional groups in the molecule. Aryl iodides under present conditions produce the coupling products rather than dehalogenation. This observation is in agreement with the reported methods in the literature for aryl iodides [3–5].

By changing the base from NaOPr^i to Et$_3$N, homocoupling was performed successfully for different substituted aryl halides. For this purpose, bromobenzene (Table 3, Entry 3) was treated as a model compound with 0.5 mmole IL-OPPh$_2$, 0.05 mmole of PdCl$_2$, and 2.0 mmole of Et$_3$N. The homocoupling product was obtained in high yield. The optimized conditions were then applied to other aryl halides to obtain homocoupling products. The results of this investigation are shown in Table 3.

Table 2
Dehalogenation of aryl halides with PdCl$_2$/IL-OPPh$_2$ system using NaOPr^i as base

Entry	Ar-X	Product	Time (h)	Yield (%)[a]
1			0.5	89
2			5	88
3			13	85
4			15	80
5			15	72
6			13	85
7			24	75
8			4	93
9			24	90
10			36	80
11			24	83

[a] In the case of volatile liquid products, the yields were determined by GC analysis using *n*-octane as internal standard.

Table 3
Homocoupling of aryl halides with PdCl$_2$/IL-OPPh$_2$ system using Et$_3$N as base

Entry	Ar-X	Product	Time (h)	Yield (%)[a]
1			0.25	95
2			1	90
3			0.25	90
4			15	75
5			15	62
6			15	69
7			15	58
8			12	80
9			15	60
10			5	94
11			18	78
12			20	80

[a] All products are known compounds and were identified by comparison of their physical or spectral data with those of known samples [20–27].

The recycling of the IL and its Pd complex can be achieved easily. After removal of the product by ether, the remaining mixture of ionic liquid and its corresponding Pd complex was washed with water to remove the produced triethylammonium halide in the homocoupling reaction, and or sodium halide and acetone in the dehalogenation reaction. Then the remained IL containing its Pd complex can be either dried in a vacuum oven, or extracted with dichloromethane followed by drying (Na_2SO_3) and evaporation of the solvent. The recycled IL and its Pd complex were reused for six runs in the reaction of bromobenzene for the dehalogenation or coupling reaction without losing its efficiency.

The use of mole ratio method for the complex formation between this IL and $PdCl_2$ in the presence of base is in good agreement with the ML_2 structure for this complex [18b]. The active catalyst can be formed by coordination of two molecules of phosphinite ionic liquid (IL-OPPh$_2$) through P atom to Pd(II) center followed by the reduction to Pd(0) by another molecule of IL-OPPh$_2$. This reduction is generally known for Pd(II) compounds [19].

3. Conclusion

In summary, we have shown the applicability of a imidazolium-based phosphinite ionic liquid (IL-OPPh$_2$) as both the reaction media and the ligand of Pd(II) for the efficient dehalogenation and homocoupling of a large variety of aryl halides. The use of this complex in the presence of NaOPr^i was shown to be selective for dehalogenation and with Et$_3$N was selective for homocoupling of aryl halides. The reusability of this phosphinite ionic liquid containing its Pd complex can also be considered as a strong practical advantageous of this method.

4. Experimental

The chemical were obtained from Fluka or Merck chemical companies and used without further purification. The progress of the reactions was followed with TLC using silica gel SILG/UV 254 plates or GLC on a Shimadzu model GC-10A instrument. IR spectra were run on a Shimadzu FTIR-8300 spectrophotometer. The ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker Avance DPX-250, FT-NMR spectrometer. Melting points were determined on a Buchi 510 in open capillary tubes and are uncorrected.

4.1. General procedure for the homocoupling of aryl halides

To a flask containing phosphinite ionic liquid (0.5 mmole, 0.23 g), $PdCl_2$ (0.05 mmole, 8.8 mg) and Et_3N (2 mmole, 0.20 g) were added at 80 °C and stirred for 15 min under nitrogen atmosphere. Then aryl halide (1.0 mmole) was added to the mixture. GC and TLC of the reaction mixture showed the completion of the reaction after 0.25–20 h. After completion of reaction, the mixture was cooled to room temperature and the coupled product was extracted with 3 × 5 ml of diethyl ether. (In the case of Table 3, Entries 12 and 13 dichloromethane was used.) Evaporation of the solvent followed by chromatography on a short column of silica gel gave the coupled product in 58–95% yield.

4.2. General procedure for the dehalogenation of aryl halides

$PdCl_2$ (0.05 mmole, 8.8 mg) and NaOPr^i (2.0 mmole, 0.13 g) were added to a flask containing phosphinite ionic liquid (0.5 mmole, 0.23 g) under nitrogen atmosphere. The flask was placed in an 80 °C oil bath and stirred for 15 min. Aryl halide (1.0 mmole) was then added to the mixture and stirred for 0.5–36 h. The reaction was monitored by gas chromatography. In the case of low boiling point products, GC yield was determined using

n-octane as internal standard. In other cases, the product was simply extracted with diethyl ether (3 × 5 ml). Evaporation of the solvent followed by chromatography on a short column of silica gel gave the desired product. All the products are known compounds and were identified by comparison of their physical and spectral data with the literature.

Physical and spectral data of the products:

4.3. Biphenyl

White solid, m.p. 70–71 °C (lit. 69–70 °C) (Ref. [20]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.63–7.31 (m, 10H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 145.5, 130.3, 127.4, 127.2.

4.4. 4,4′-Dimethylbiphenyl

White solid, m.p. 119–120.5 °C (lit. 118–120 °C) (Ref. [21]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.52 (d, J = 8.1 Hz, 4H), 7.23 (d, J = 8.0 Hz, 4H), 2.52 (s, 6H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 140.2, 138.6, 130.5, 124.4, 21.0.

4.5. 4,4′-Dimethoxybiphenyl

White solid, m.p. = 177–178 °C (lit. 178–179 °C) (Ref. [22]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.47 (d, J = 8.6, 4H), 7.12 (d, J = 8.6, 4H), 3.75 (s, 6H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 162.5, 135.4, 125.5, 118.7, 57.8.

4.6. 4,4′-Dichlorobiphenyl

White solid, m.p. 142–143 °C (lit. 142–145 °C) (Ref. [21]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.55 (d, J = 8.23 Hz, 2H), 7.41 (d, J = 8.23 Hz, 2H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 138.5, 135.5, 129.0, 128.2.

4.7. 4,4′-Dicyanobiphenyl

Colorless solid, m.p. 235–238 °C (lit. 236–240 °C) (Ref. [23]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.51 (d, J = 8.5 Hz, 4H), 7.75 (d, J = 8.5 Hz, 4H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 109.2, 120.2, 126.5, 133.4, 148.6.

4.8. 4,4′-Diacetylbiphenyl

White solid, m.p. 188–189 °C (lit. 189–190 °C) (Ref. [24]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.98 (d, J = 8.6 Hz, 4H), 7.70 (d, J = 8.6 Hz, 4H), 2.77 (s, 6H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 28.9, 125.5, 127.8, 138.2, 146.3, 195.8.

4.9. 4,4′-Dinitrobiphenyl

Yellow solid, m.p. 238–239 °C (lit. 240 °C) (Ref. [25]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.45 (d, J = 8.5 Hz, 4H), 7.85 (d, J = 8.5 Hz, 4H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 124.5, 126.3, 148.5, 150.5.

4.10. 3,3′-Bipyridyl

Orange oil, m.p. 231–232 °C (lit. 232 °C) (Ref. [26]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.45 (m, H5, 5′), 7.91 (d, H4, 4′), 8.6 (d, H6, 6′), 8.8 (s, H2, 2′), ^{13}C NMR (62.5 MHz, CDCl$_3$): 124.3, 133.5, 136.8, 149.5, 151.4.

4.11. 3,3′-Bithiophen

White solid, m.p. 130–132 °C (lit. 131–133 °C) (Ref. [27]), ^{1}H NMR (250 MHz, CDCl$_3$): 7.20 (d, 2 H), 7.30 (s, 1H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 93.3, 115.7, 118.2, 118.9.

4.12. Biphenyl-4,4′-dicarboxylic acid

Solid, m.p. 300 °C (lit. >300 °C) [27], ^{1}H NMR (250 MHz, CDCl$_3$): 7.75 (d, J = 8.5 Hz, 4H), 7.83 (d, J = 8.5 Hz, 4H), 12.5 (2H), ^{13}C NMR (62.5 MHz, CDCl$_3$): 127.5, 128.1, 135.6, 149.7, 170.4.

Acknowledgements

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