

Communication

Highly efficient reduction of ferrocenyl aldehyde and ketones in ionic liquids

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Abstract

For the first time ferrocenyl aldehyde and ketones were effectively reduced to alkylferrocene using sodium borohydride and aluminum chloride in an ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIm]BF₄). Mild reaction conditions, enhanced rates, improved yields, and recyclable ionic liquid are the remarkable features exhibited in this process.

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1. Introduction

Owing to their interesting optical, thermal and redox properties, ferrocene derivatives have emerged as strong candidates for materials and catalysts [1]. Alkylferrocenes are important intermediates in organometallic synthesis. Consequently, alkylferrocenes are normally prepared via reduction acylferrocenes [2]. The classical methods for this transformation include catalytic hydrogenolysis, Clemmenson reduction and reductive deoxygenation employing lithium aluminum hydride under anhydrous conditions [3]. However, the usage of zinc amalgam made this process non-eco-friendly. In addition, the possibility of some functional groups existing in the molecule is limited under the conventional reaction conditions and excess amount of toxic solvents such as CH₂Cl₂, ClCH₂CH₂Cl was also required.

In recent years, room temperature ionic liquids (RTILs) have attracted much interest as a new kind of possible “green” solvents and catalyst media. In comparison with conventional organic solvents currently being used in the industry, RTILs have several benefits, for example, they are tunable polarity, high thermal stability, negligible

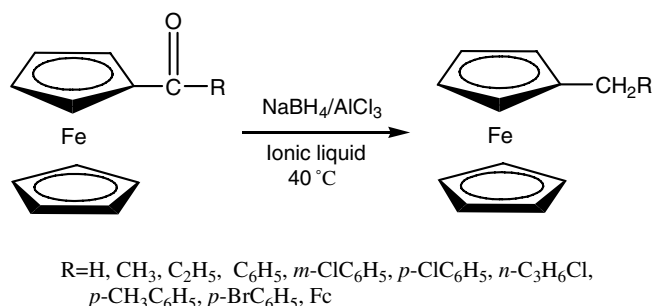
vapor pressure, nonflammable, recyclability, etc. [4]. Based on these outstanding characteristics, the potential industrial applications of RTILs in organic synthesis, gas separations, liquid–liquid extractions, electrochemical studies, and catalytic reactions, have been extensively studied [5–8]. Herein, we report an efficient and environmentally benign method for the synthesis of alkylferrocenes by reduction of corresponding ferrocenyl (Fc) aldehyde and ketones using NaBH₄/AlCl₃ in ionic liquids without any other organic solvents (Scheme 1).

2. Results and discussion

Firstly, 10 different solvents, including nine ionic liquids, were investigated to find out the most suitable one for this process in which acetylferrocene was used as the substrate. The results are summarized in Table 1. Under comparable experimental conditions, the yield was low if THF were used as solvent, while 94% yield could be obtained in the presence of [BMIm]BF₄. In other words, [BMIm]BF₄ can effectively accelerate this reaction. To our surprise, when [BMIm]PF₆, [HMIm]PF₆, [BMIm]NO₃, [BMIm]ClO₄ and [Bpy]PF₆ were applied, respectively, no product was detected. However, we found that the ionic liquids including BF₄[−] are only effective mediums (entries 3–5) for the formation of ethylferrocene, although the mechanism was

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Scheme 1. Reduction of ferrocenyl aldehyde and ketones in the presence of ionic liquids.

Table 1
Reduction of acetylferrocene by NaBH₄/AlCl₃ in different solvents^a

Entry	Solvents	Temp. (°C)	Time (min)	Yield (%) ^b
1	THF	40	55	57
2	[EMIm]BF ₄	40	55	86
3	[BMIm]BF ₄	40	55	94
4	[HMIm]BF ₄	40	55	92
5	[BMIm]PF ₆	40	300	
6	[HMIm]PF ₆	40	300	
7	[BMIm]NO ₃	40	300	
8	[BMIm]ClO ₄	40	300	
9	[Bpy]BF ₄	40	55	40
10	[Bpy]PF ₆	40	300	

^a The products were characterized by ¹H NMR and IR.

^b Isolated yield.

not clear. On the other hand, the performance of [EMIm]BF₄, [HMIm]BF₄ and [BMIm]BF₄ is very similar, although the latter shows slightly higher yield. Subsequent studies were, therefore, carried out in [BMIm]BF₄.

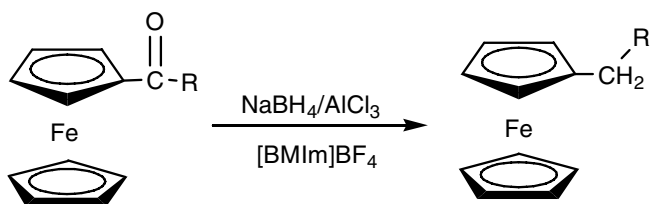


Table 2
Reduction of ferrocenyl aldehyde and ketone in ionic liquid [BMIm]BF₄^a

Entry	R	Product	Temp. (°C)	Time (min)	Yield (%) ^b
1	H	FcCH ₃	35	60	95
2	CH ₃	FcCH ₂ CH ₃	40	55	94
3	C ₂ H ₅	FcCH ₂ CH ₂ CH ₃	40	70	92
4	C ₃ H ₇	FcCH ₂ Ph	40	55	98
5	<i>m</i> -ClC ₆ H ₅	FcCH ₂ PhCl- <i>m</i>	40	35	98
6	<i>p</i> -ClC ₆ H ₅	FcCH ₂ PhCl- <i>p</i>	40	35	98
7	<i>n</i> -C ₃ H ₇ Cl	Fc(CH ₂) ₄ Cl	35	35	90
8	<i>p</i> -CH ₃ C ₆ H ₅	FcCH ₂ PhCH ₃	40	60	96
9	<i>p</i> -BrC ₆ H ₅	FcCH ₂ PhBr- <i>p</i>	50	70	96
10	Fc	FcCH ₂ Fc.	50	110	80

^a The products were characterized by ¹H NMR and IR.

^b Isolated yield.

Table 3
Recycling of the [BMIm]BF₄ in the synthesis of ethylferrocene^a

Run	Temp. (°C)	Time (min)	Yield (%) ^b
1	40	55	94
2	40	55	94
3	40	55	93
4	40	60	92
5	40	60	92
6	45	75	93
7	45	75	93

^a The products were characterized by ¹H NMR and IR.

^b Isolated yield.

With these results we extended our study to other aldehyde and ketones. Fortunately, the results obtained in [BMIm]BF₄ show, for all the compounds under study, excellent yields (see Table 2).

One of the most attractive properties of ionic liquids is that they can provide good to excellent performance in terms of product separation and reusability when they are used as either catalysts or reaction medium in synthetic chemistry. In this transformation, it is also observed that when the reaction is complete and the product were extracted, [BMIm]BF₄ could be reused once again in the synthesis of ethylferrocene without a significant decrease in yield at least seven times except for a small mechanical loss. The results are shown in Table 3.

3. Conclusions

In conclusion, we have demonstrated the reduction of acetylferrocene to alkylferrocene using NaBH₄/AlCl₃ in ionic liquid under mild conditions in excellent yield. The experimental procedure is very simple and convenient. The products can be recovered by extraction with ether and the ionic liquid reused at least seven times.

4. Experimental

All reagents were of AR grade and used without further purification. Following ionic liquids were used in these reactions: [BMIm]BF₄ (BMIm = 1-butyl-3-methyl imidazole); [BMIm]PF₆; [BMIm]NO₃; [BMIm]ClO₄; [EMIm]BF₄ (EMIm = 1-ethyl-3-methyl imidazole); [HMIm]BF₄ (HMIm = 1-hexyl-3-methyl imidazole); [HMIm]PF₆; [Bpy]BF₄; [Bpy]PF₆ (Bpy = 1-butyl-pyridinium). All ionic liquids used in this work were synthesized according to the previous papers [9] and were dried in vacuo at 90 °C before use.

4.1. The general procedure for the reaction

To a solution of acetylferrocene (0.114 g, 0.5 mmol) in preheated [BMIm]BF₄ (25 ml) in a 50 ml common flask set was slowly added AlCl₃ (0.1 g, 0.75 mmol) with stirring about 30 min at 20 °C. Then NaBH₄ (0.0475 g, 1.25 mmol) was slowly added into the mixture. After the reaction mixture was stirred at 40 °C for 55 min, the mixture was

quenched with cold water (15 ml). The aqueous layer was separated from the product and extracted with diethyl ether (3 × 15 ml). The combined organic extract was dried using anhydrous MgSO₄ and filtrated, and then the solvent was removed under reduced pressure. The residue was chromatographed on silica (eluent: hexane/diethyl ether = 9:1) to afford the pure ethylferrocene (0.1 g, 94%). On the other hand, [BMIm]BF₄ could be recovered by extraction with dichloromethane followed by evaporation and drying, which could be reused directly for the next run.

4.2. Spectroscopic data for products

¹H NMR spectra were recorded on the spectrometer operating at 400 MHz. Chemical shifts were reported in parts per million (ppm δ) and referenced to TMS. Infrared spectra were recorded as a thin film on sodium bromide and absorptions were reported in wavenumbers (cm⁻¹).

Methylferrocene: yellow crystals; m.p. 35–36 °C; IR (KBr): $\nu_{\max}/\text{cm}^{-1}$ 3090, 2922, 2894, 1458, 1102, 998, 816; ¹H NMR (400 MHz, CDCl₃): δ_{H} 1.94 (3H, s), 4.12 (4H, s), 4.17 (5H, s).

Ethylferrocene: orange oil; IR: $\nu_{\max}/\text{cm}^{-1}$ 3093, 2958, 2925, 2854, 1460, 1105, 1041, 1000, 816; ¹H NMR (400 MHz, CDCl₃): δ_{H} 1.17 (3H, t), 2.30 (2H, q), 4.17 (4H, s), 4.3 (5H, s).

Propylferrocene: orange oil; IR: $\nu_{\max}/\text{cm}^{-1}$ 3093, 2958, 2927, 2868, 1461, 1103, 1000, 814; ¹H NMR (400 MHz, CDCl₃): δ_{H} 0.91–0.94 (3H, t), 1.49–1.54 (2H, m), 2.27–2.31 (2H, 3t), 4.02–4.05 (4H, m), 4.07–4.08 (5H, s).

Phenylferrocene: yellow crystals; m.p. 74–75 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3100, 3077, 3021, 2924, 2853, 1602, 1430, 1103, 1027, 928, 820; ¹H NMR (400 MHz, CDCl₃): δ_{H} 3.58 (2H, s), 4.30–4.35 (9H, m), 7.09–7.23 (5H, m).

m-Chlorobenzylferrocene: yellow crystals; m.p. 89–90 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3073, 2920, 2851, 1627, 1569, 1470, 1103, 998, 806; ¹H NMR (400 MHz, CDCl₃): δ_{H} 3.57 (2H, s), 4.30 (9H, s), 7.01–7.17 (4H, m).

p-Chlorobenzylferrocene: yellow crystals; m.p. 78–80 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3084, 2922, 2853, 1639, 1571, 1488, 1105, 1087, 1005, 816; ¹H NMR (400 MHz, CDCl₃): δ_{H} 3.55 (2H, s), 4.30 (9H, m), 7.05–7.22 (4H, m).

n-Chlorobutylferrocene: red oil; IR: $\nu_{\max}/\text{cm}^{-1}$ 3091, 2933, 2857, 1638, 1445, 1307, 1273, 1104, 1000, 818, 727; ¹H NMR (400 MHz, CDCl₃): δ_{H} 1.62 (2H, t), 1.78–1.82

(2H, m), 2.28–2.31 (2H, m), 3.52–3.55 (2H, t), 4.15–4.20 (9H, m).

p-Methylbenzylferrocene: yellow crystals; m.p. 80–83 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3093, 3037, 3016, 2994, 2913, 2851, 1638, 1438, 1102, 1020, 997, 922, 815; ¹H NMR (400 MHz, CDCl₃): δ_{H} 2.29 (3H, s), 3.64 (2H, s), 4.07–4.08 (4H, m), 4.12 (5H, s), 7.05 (4H, s).

p-Bromobenzylferrocene: orange crystals; m.p. 99–100 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3104, 3082, 3048, 2916, 2893, 2854, 1638, 1482, 1103, 1002, 813; ¹H NMR (400 MHz, CDCl₃): δ_{H} 3.62 (2H, s), 4.06–4.08 (4H, m), 4.12 (5H, s), 7.02–7.04 (2H, m), 7.34–7.37 (2H, m).

Diferrocenylmethane: yellow crystals; m.p. 140–142 °C; IR: $\nu_{\max}/\text{cm}^{-1}$ 3090, 2923, 2853, 1464, 1406, 1103, 1000, 816; ¹H NMR (400 MHz, CDCl₃): δ_{H} 3.36 (2H, s), 4.06–4.18 (18H, m).

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