Journal of Organometallic Chemistry 695 (2010) 195–200

Contents lists available at ScienceDirect

Journal of Organometallic Chemistry

journal homepage: www.elsevier.com/locate/jorganchem

Tridentate, anionic tethered N-heterocyclic carbene of Pd(II) complexes

Satoshi Sakaguchi [a,*], Miaki Kawakami [a], Justin O'Neill [b], Kyung Soo Yoo [b], Kyung Woon Jung [b,*]

[a] Department of Chemistry and Materials Engineering and High Technology Research Center, Faculty of Chemistry, Materials and Bioengineering, Kansai University, Suita, Osaka 564-8680, Japan
[b] Loker Hydrocarbon Research Institute, Department of Chemistry, University of Southern California, Los Angeles, CA 90089, USA

ARTICLE INFO

Article history:
Received 10 July 2009
Received in revised form 30 September 2009
Accepted 13 October 2009
Available online 10 November 2009

Keywords:
N-heterocyclic carbene
Anionic tridentate ligand
NHC–Ag complex
NHC–Pd complex
Ligand-transfer reaction

ABSTRACT

The synthesis of a series of azolium salts such as azolium iodides and chlorides having both N-anionic functional group and N-alkyl group have been developed. Reaction of azolium iodides or chlorides with Ag_2O gave the corresponding NHC–Ag complexes. It was found that the resulting NHC–Ag complexes derived from azolium iodides or chlorides differ in their physical properties. The azolium chlorides as well as azolium iodides were successfully converted into the NHC–Ag complexes, which subsequently reacted with $PdCl_2(CH_3CN)_2$ to give the anionic amidate/NHC–Pd complexes. Thus, a variety of the NHC–Pd complexes could be obtained from benzimidazolium and imidazolium salts.

Published by Elsevier B.V.

1. Introduction

Control of stereoselectivity in transition–metal-catalyzed organic transformation reactions depends on development of a versatile ligand that would strongly coordinate with the metal center [1]. Polydentate ligands having stereodirecting groups could help control the stability and reactivity of metals efficiently in a variety of homogeneous catalysis reactions. Thus, a ligand that combines a strongly coordinating unit with a functional group having great influence on the electronic and steric properties of the metal center has considerable potential.

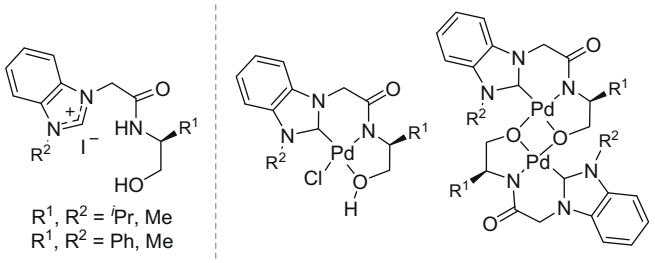
In recent years, there has been growing interest in using N-heterocyclic carbene (NHC) as a ligand for homogenous catalysis [2]. An attractive feature of NHC is not only its strong σ-donating capability to metals but also the possibility of varying the substituents on the nitrogen atom. It is possible that introduction of chiral substituents into NHC would result in enantioselective transformations in asymmetric catalysis. However, the standard chiral NHC obtained by this strategy often leads to low chiral inductions, mainly because of rapid internal rotation of the chiral substituents around the C–N axis. Therefore, to lock the N substituents in fixed conformation, a proposed strategy employs an NHC that bears both a chiral center and a hard chelating functional group on the N substituents resulting in generation of polydentate ligands [1,3].

In the last decade, heteroatom-functionalized NHC–metal complexes having stereodirecting groups have been developed. These are classified as NHC-based chelate ligands that incorporate a neutral or an anionic functional group. For the neutral-functionalized NHC, a breakthrough has been achieved by Burgess, who reports highly efficient asymmetric hydrogenation catalysis based on carbene/oxazoline iridium complexes [4]. Other important chiral bidentate NHC complexes have been developed by Gade et al. [5] and Douthwaite and coworker [6] for enantioselective hydrosilylation and alkylation, respectively. For the anionic-functionalized NHC, anionic aryloxo- or alkoxo-tethered NHC has been designed and successfully applied in catalytic asymmetric transformations. Pioneering work was done by Hoveyda and coworkers [7], where metathesis and alkylation reactions proceeded with high enantioselectivity by the use of chiral NHC–Ag complexes as ligand precursors. Arnold et al. [8] as well as Mauduit and coworkers [9] independently introduced chelating alkoxy NHC–Cu complexes for asymmetric alkylations. Thus, the anionic, tightly coordinating polydentate NHC-ligand system is expected to enhance catalyst stability and to offer a key structure for the construction of efficient stereodirecting elements.

Recently, we developed a novel chiral tridentate NHC-ligand and their Pd(II) complexes (Scheme 1) [10]. Importantly, the Pd(II) complex derived from chiral β-amino alcohol catalyzes an asymmetric oxidative Heck-type reaction with excellent enantioselectivity (up to 98% ee). However, only two kinds of ligands which are derived from (*S*)-valinol and (*S*)-2-phenylglycinol have been appeared in a previous paper. In a continuation of this study, we

* Corresponding authors. Tel.: +81 6 6368 0867; fax: +81 6 6339 4026 (S. Sakaguchi).
E-mail address: satoshi@ipcku.kansai-u.ac.jp (S. Sakaguchi).

0022-328X/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jorganchem.2009.10.011



Scheme 1. Previously reported benzimidazolium iodides and their Pd(II) complexes.

assume that easy tuning of both N-anionic functional groups and N-alkyl groups of the ligand would allow the development of a huge variety of tridentate NHC-ligands. Here, we wish to report the preparation of a series of NHC proligands such as azolium iodides and chlorides. In addition, the conversion of these azolium salts into the anionic amidate/NHC–Pd(II) complexes via NHC–Ag complexes, that has not been mentioned in detail in a previous paper, will be discussed.

2. Experimental

2.1. General procedures

All chemicals were obtained from commercial sources and were used as received. ^{1}H and ^{13}C NMR spectra were recorded on spectrometers at 270 or 400 and 67.5 or 100 MHz, respectively. Thin-layer chromatography (TLC) analysis was performed with glass-backed plates pre-coated with silica gel and examined under UV (254 nm) irradiation. Flash column chromatography was executed on silica gel 60 (Merck, mesh: 230–400; particle size: 0.040–0.063 nm). Elemental analyses were performed at Osaka University. Because most of the imidazole compounds are highly hydroscopic, collection of some analytical data was failed. X-ray diffraction measurements were made on a Rigaku RAXIS RAPID imaging plate area detector with graphite monochromated Mo Kα radiation. The structures were solved by direct methods and refined by full-matrix least-squares. The crystal data collection and refinement parameters are summarized in Supplementary material.

2.2. General procedure for preparation of **2** and **5**

To a 100 mL three-necked flask was added $ZnCl_2$ (2.9 mmol), and then the flask was dried by heating with heat-gun in vacuo. After cooling at room temperature, **1** or **4** (7.5 mmol), PhCl (10 mL), and (*S*)-valinol (7 mmol) were successively added. After stirring the reaction mixture at refluxing temperature for 15 h under N_2 atmosphere, the solvent was removed under reduced pressure. The resulting reaction mixture was dissolved in methanol (ca. 20 mL), and then silica gel (ca. 5 g) was added. The solution was stirred at refluxing temperature for 2 h. Subsequently, the silica gel was removed by filtration. The filtrate was concentrated under reduced pressure, which was purified by column chromatography on silica gel using AcOEt followed by MeOH as an eluent to afford **2** or **5** as a white solid. These compounds were reported previously [10].

2.2.1. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]imidazole (**2**)

^{1}H NMR (CD_3OD): δ 7.66 (s, 1H), 7.11 (t, J = 1.3 Hz, 1H), 6.97 (t, J = 1.3 Hz, 1H), 4.79 (d, J = 16.2 Hz, 1H), 4.73 (d, J = 16.2 Hz, 1H), 3.73–3.67 (m, 1H), 3.67–3.51 (m, 2H), 1.93–1.80 (m, 1H), 0.93 (d, J = 6.6 Hz, 3H), 0.90 (d, J = 6.6 Hz, 3H); ^{13}C NMR: δ 169.3, 139.4, 128.9, 121.7, 62.9, 58.3, 50.3, 30.0, 19.9, 18.7.

2.2.2. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]benzimidazole (**5**)

^{1}H NMR (CD_3OD): δ 8.16 (s, 1H), 7.68–7.65 (m, 1H), 7.51–7.47 (m, 1H), 7.34–7.23 (m, 2H), 5.05 (d, J = 16.3 Hz, 1H), 4.98 (d, J = 16.3 Hz, 1H), 3.75–3.67 (m, 1H), 3.67–3.52 (m, 2H), 1.94–1.80 (m, 1H), 0.93 (d, J = 4.7 Hz, 3H), 0.90 (d, J = 4.7 Hz, 3H); ^{13}C NMR: δ 169.1, 145.7, 124.4, 123.7, 120.0, 111.3, 63.0, 58.4, 48.2, 30.0, 20.0, 18.8.

2.3. General procedure for preparation of **3** and **6**

To a 300 mL round-bottom flask **2** or **5** (7.5 mmol), iodomethane (22.5 mmol), and THF (120 mL) were added. The reaction mixture was stirred under refluxing for 15 h. After cooling the solution at room temperature, a white solid, which is the desired product, was filtrated and then washed with THF. These compounds were reported previously [10].

2.3.1. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-methylimidazolium iodide (**3**)

^{1}H NMR (DMSO): δ 9.07 (s, 1H), 8.14 (br, 1H), 7.67 (d, J = 1.7 Hz, 1H), 7.66 (d, J = 1.7 Hz, 1H), 5.02 (d, J = 16.3 Hz, 1H), 4.93 (d, J = 16.3 Hz, 1H), 4.63 (br, 1H), 3.87 (s, 3H), 3.61–3.51 (m, 1H), 3.42–3.32 (m, 2H), 1.88–1.75 (m, 1H), 0.85 (d, J = 4.5 Hz, 3H), 0.83 (d, J = 4.5 Hz, 3H); ^{13}C NMR: δ 164.6, 137.6, 123.6, 122.9, 61.0, 56.4, 50.6, 35.8, 28.2, 19.5, 18.1.

2.3.2. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-methylbenzimidazolium iodide (**6**)

^{1}H NMR (CD_3OD): δ 9.55 (s, 1H), 8.01–7.95 (m, 1H), 7.93–7.86 (m, 1H), 7.75–7.67 (m, 2H), 5.43 (d, J = 16.3 Hz, 1H), 5.35 (d, J = 16.3 Hz, 1H), 4.18 (s, 3H), 3.78–3.69 (m, 1H), 3.69–3.55 (m, 2H), 1.97–1.83 (m, 1H), 0.96-0.94 (m, 6H); ^{13}C NMR: δ 167.2, 144.7, 128.3, 128.2, 114.4, 114.2, 63.0, 58.9, 49.7, 34.0, 30.0, 20.0, 18.9.

2.4. General procedure for preparation of **7**–**16**

To a flask were added N-alkylated azole (4.4 mmol), 1,4-dioxane (15 mL), and α-chloroacetoaminde (4 mmol). After stirring the reaction mixture at 110 °C for 16 h, the solvent was removed under reduced pressure. The residue was dissolved in methanol, and then activated carbon (ca. 1 g) was added. After 16 h, the activated carbon was removed by filtration. The filtrate was concentrated under reduced pressure to obtain a solid, which was purified by re-precipitation using ethyl acetate and methanol to afford the corresponding coupling product as a white solid.

2.4.1. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-methylbenzimidazolium chloride (**7**)

^{1}H NMR (CD_3OD): δ 9.55 (s, 1H), 7.97–7.89 (m, 2H), 7.73–7.68 (m, 2H), 5.42 (d, J = 16.8 Hz, 1H), 5.36 (d, J = 16.8 Hz, 1H), 4.18 (s, 3H), 3.76–3.57 (m, 3H), 1.94–1.85 (m, 1H), 0.98–0.94 (m, 6H); ^{13}C NMR: δ 166.8, 133.3, 133.1, 128.3, 128.2, 114.3, 114.2, 63.0, 58.9, 33.9, 30.2, 20.1, 18.8. Anal. Calc. for $C_{15}H_{23}ClN_3O_2 \cdot 1.5H_2O$: C, 53.17; H, 7.44; N, 12.40. Found: C, 53.73; H, 7.29; N, 12.33%. $[\alpha]_D^{25} = -9.9$ (c = 1.0 in CH_3OH). M.p. 179.4–180.0 °C.

2.4.2. 1-[2-((S)-1-hydroxy-4-methyl-2-pentanylamino)-2-oxoethyl]-3-methylbenzimidazolium chloride (**8**)

^{1}H NMR (DMSO): δ 9.80 (s, 1H), 8.60 (d, J = 8.7 Hz, 1H), 8.03–8.00 (m, 1H), 7.93–7.90 (m, 1H), 7.71–7.66 (m, 2H), 5.36 (d,

J = 16.3 Hz, 1H), 5.29 (d, J = 16.3 Hz, 1H), 4.83 (t, J = 5.7 Hz, 1H), 4.13 (s, 3H), 3.85–3.78 (m, 1H), 3.35–3.31 (m, 2H), 1.65–1.55 (m, 1H), 1.38–1.26 (m, 2H), 0.86 (d, J = 6.4 Hz, 3H), 0.79 (d, J = 6.4 Hz, 3H); ^{13}C NMR: δ 164.1, 143.6, 131.8, 126.4, 113.6, 113.5, 63.5, 49.6, 48.8, 39.8, 33.3, 24.2, 23.5, 21.8. Anal. Calc. for $C_{16}H_{24}ClN_3O_2{\cdot}2H_2O$: C, 53.11; H, 7.80; N, 11.61. Found: C, 53.09; H, 7.28; N, 11.62%. $[\alpha]_D^{25} = -10.0$ (c = 1.0 in CH_3OH). M.p. 180.0–180.4 °C.

*2.4.3. 1-[2-((S)-1-hydroxy-3,3-dimethyl-2-butanylamino)-2-oxoethyl]-3-methylbenzimidazolium chloride (**9**)*

^{1}H NMR (DMSO): δ 9.89 (s, 1H), 8.63 (d, J = 9.0 Hz, 1H), 8.03–8.00 (m, 2H), 7.67–7.65 (m, 2H), 5.53 (d, J = 16.3 Hz, 1H), 5.43 (d, J = 16.3 Hz, 1H), 4.70 (t, J = 5.7 Hz, 1H), 4.13 (s, 3H), 3.60–3.57 (m, 2H), 3.43–3.40 (m, 1H), 0.86 (s, 9H); ^{13}C NMR: δ 164.8, 143.6, 131.4, 131.3, 126.5, 126.3, 113.5, 113.4, 60.2, 59.8, 48.6, 33.5, 33.2, 26.8. Anal. Calc. for $C_{16}H_{24}ClN_3O_2{\cdot}2.5H_2O$: C, 51.82; H, 7.88; N, 11.33. Found: C, 51.50; H, 7.59; N, 11.32%. $[\alpha]_D^{25} = +15.9$ (c = 1.0 in CH_3OH). M.p. 53.4–53.8 °C.

*2.4.4. 1-[2-((S)-1-hydroxy-2-phenyl-2-ethanylamino)-2-oxoethyl]-3-methylbenzimidazolium chloride (**10**)*

^{1}H NMR (CD_3OD): δ 7.95–7.93 (m, 1H), 7.86–7.84 (m, 1H), 7.73–7.65 (m, 2H), 7.37–7.31 (m, 4H), 7.28–7.24 (m, 1H), 5.42 (d, J = 16.6 Hz, 1H), 5.38 (d, J = 16.6 Hz, 1H), 5.03–5.00 (m, 1H), 4.14 (s, 3H), 3.83–3.74 (m, 2H); ^{13}C NMR: δ 166.4, 140.5, 133.3, 133.1, 129.7, 128.7, 128.3, 128.2, 128.0, 114.3, 114.2, 66.0, 57.7, 49.6, 33.8. Anal. Calc. for $C_{18}H_{20}ClN_3O_2{\cdot}H_2O$: C, 59.42; H, 6.09; N, 11.55. Found: C, 59.39; H, 5.88; N, 11.57%. $[\alpha]_D^{25} = +105.7$ (c = 1.0 in CH_3OH). M.p. 162.5–163.0 °C.

*2.4.5. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-methylimidazolium chloride (**11**)*

^{1}H NMR (CD_3OD): δ 8.96 (s, 1H), 7.60 (d, J = 1.8 Hz, 1H), 7.59 (d, J = 1.8 Hz, 1H), 5.08 (d, J = 15.8 Hz, 1H), 5.03 (d, J = 15.8 Hz, 1H), 3.95 (s, 3H), 3.75–3.55 (m, 3H), 1.92–1.83 (m, 1H), 0.94 (m, 6H); ^{13}C NMR: δ 167.0, 139.3, 125.0, 124.4, 63.0, 58.8, 51.9, 36.6, 30.2, 19.9, 18.8. $[\alpha]_D^{25} = -10.9$ (c = 1.0 in CH_3OH).

*2.4.6. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-butylimidazolium chloride (**12**)*

^{1}H NMR (CD_3OD): δ 9.04 (s, 1H), 7.67 (t, J =3.3 Hz, 1H), 7.61 (t, J = 3.3 Hz, 1H), 5.10 (d, J= 16.5 Hz, 1H), 5.04 (d, J = 16.5 Hz, 1H), 4.25 (t, J = 14.5 Hz, 2H), 3.73–3.52 (m, 3H), 1.94–1.83 (m, 3H), 1.42–1.34 (m, 2H), 1.01–0.92 (m, 9H); ^{13}C NMR: δ 167.0, 125.0, 123.1, 63.0, 58.8, 51.9, 50.7, 33.0, 30.2, 20.4, 19.7, 18.8, 13.7. $[\alpha]_D^{25} = -11.0$ (c = 1.0 in CH_3OH).

*2.4.7. 1-[2-((S)-1-hydroxy-3-methyl-2-butanylamino)-2-oxoethyl]-3-benzylimidazolium chloride (**13**)*

^{1}H NMR (CD_3OD): δ 9.10 (s, 1H), 7.63–7.61 (m, 2H), 7.44–7.40 (m, 5H), 5.45 (s, 2H), 5.09 (d, J = 16.3 Hz, 1H), 5.04 (d, J = 16.3 Hz, 1H), 3.75–3.53 (m, 3H), 1.91–1.82 (m, 1H), 0.95 (d, J = 6.9 Hz, 3H), 0.93 (d, J = 6.9 Hz, 3H); ^{13}C NMR: δ 166.9, 138.8, 135.1, 130.4, 130.3, 129.6, 125.4, 123.2, 63.0, 58.8, 54.1, 52.1, 30.2, 19.9, 18.8. $[\alpha]_D^{25} = -13.8$ (c = 1.0 in CH_3OH). M.p. 156.1–156.5 °C.

*2.4.8. 1-[2-((S)-1-hydroxy-4-methyl-2-pentanylamino)-2-oxoethyl]-3-methylimidazolium chloride (**14**)*

^{1}H NMR (DMSO):δ 9.14 (s, 1H), 8.38 (d, J = 8.2 Hz, 1H), 7.69 (s, 1H), 7.68 (s, 1H), 4.99 (d, J = 16.5 Hz, 1H), 4.94 (d, J = 16.5 Hz, 1H), 4.81 (t, J = 11.9 Hz, 1H), 3.87 (s, 3H), 3.80–3.73 (m, 1H), 3.32–3.28 (m, 2H), 1.63–1.51 (m, 1H), 1.32–1.27 (m, 2H), 0.86 (d, J = 6.6 Hz, 3H), 0.82 (d, J = 6.3 Hz, 3H); ^{13}C NMR: δ 164.3, 137.7, 123.7, 122.9, 63.4, 50.6, 49.5, 39.9, 35.8, 24.2, 23.2, 21.9. $[\alpha]_D^{25} = -12.0$ (c = 1.0 in CH_3OH). M.p. 176.8–177.1 °C.

*2.4.9. 1-[2-((S)-1-hydroxy-4-methyl-2-pentanylamino)-2-oxoethyl]-3-butylimidazolium chloride (**15**)*

^{1}H NMR (DMSO): δ 9.29 (s, 1H), 8.50 (d, J = 8.5 Hz, 1H), 7.80 (s, 1H), 7.73 (s, 1H), 5.02 (d, J = 16.3 Hz, 1H), 4.98 (d, J = 16.3 Hz, 1H), 4.83 (t, J = 12.0 Hz, 1H), 4.21 (t, J = = 14.1 Hz, 2H), 3.80–3.72 (m, 1H), 3.33–3.29 (m, 2H), 1.79–1.72 (m, 2H), 1.61–1.55 (m, 1H), 1.32–1.21 (m, 4H), 0.90–0.80 (m, 9H); ^{13}C NMR: δ 164.3, 137.2, 123.7, 121.6, 63.3, 50.6, 49.5, 48.4, 31.3, 24.1, 23.1, 21.9, 18.6, 13.2. Anal. Calc. for $C_{15}H_{28}ClN_3O_2{\cdot}H_2O$: C, 53.64; H, 9.00; N, 12.51. Found: C, 53.95; H, 8.66; N, 12.64%. $[\alpha]_D^{25} = +5.9$ (c = 1.0 in CH_3OH). M.p. 52.8–53.1 °C.

*2.4.10. 1-[2-((S)-1-hydroxy-4-methyl-2-pentanylamino)-2-oxoethyl]-3-benzylimidazolium chloride (**16**)*

^{1}H NMR (DMSO): δ 9.34 (s, 1H), 8.37 (br, 1H), 7.81 (s, 1H), 7.72 (s, 1H), 7.42–7.38 (m, 5H), 5.50 (s, 2H), 5.04 (d, J = 16.3 Hz, 1H), 4.99 (d, J = 16.3 Hz, 1H), 4.77 (t, J = 5.9 Hz, 1H), 3.81–3.73 (m, 1H), 3.34–3.26 (m, 2H), 1.62–1.55 (m, 1H), 1.32–1.28 (m, 2H), 0.86 (d, J = 6.6 Hz, 3H), 0.82 (d, J = 6.6 Hz, 3H); ^{13}C NMR: δ 164.3, 137.4, 134.9, 129.0, 128.7, 128.2, 124.1, 121.8, 63.4, 51.8, 50.7, 49.6, 39.8, 24.1, 23.2, 21.9. Anal. Calc. for $C_{18}H_{26}ClN_3O_2$: C, 61.44; H, 7.45; N, 11.94. Found: C, 61.26; H, 7.25; N, 11.92%. $[\alpha]_D^{25} = -17.0$ (c = 1.0 in CH_3OH). M.p. 178.0–178.3 °C.

*2.5. General procedure for preparation of **3a** and **7a***

A suspension of azolium salt **3** or **7** (0.5 mmol) and silver(I) oxide (0.25 mmol) in CH_2Cl_2 (35 mL) was stirred for 1.5 h at refluxing temperature. After the reaction, a white precipitate was formed, which was filtered with suction. The resulting white solid was dissolved in DMSO-d_6, and then the NMR measurement was performed.

*2.5.1. NHC–Ag complex **3a***

^{1}H NMR (DMSO): δ 7.96 (br, 1H), 7.38 (d, J = 1.7 Hz, 1H), 7.36 (d, J = 1.7 Hz, 1H), 4.91 (d, J = 15.7 Hz, 1H), 4.80 (d, J = 15.7 Hz, 1H), 4.63 (br, 1H), 3.80 (s, 3H), 3.61–3.51 (m, 1H), 3.42–3.32 (m, 2H), 1.86–1.72 (m, 1H), 0.81 (d, J = 7.2 Hz, 3H), 0.78 (d, J = 7.2 Hz, 3H); ^{13}C NMR: δ 181.6, 166.5, 123.3, 122.4, 61.1, 55.9, 53.0, 38.0, 28.2, 19.6, 18.1.

*2.5.2. NHC–Ag complex **7a***

^{1}H NMR (DMSO): δ 8.20 (br, 1H), 7.78–7.76 (m, 1H), 7.66–7.63 (m, 1H), 7.47–7.43 (m, 2H), 5.23 (d, J = 15.9 Hz, 1H), 5.14 (d, J = 15.4 Hz, 1H), 4.67 (br, 1H), 4.05 (s, 3H), 3.60–3.56 (m, 1H), 3.44–3.43 (m, 2H), 1.87–1.82 (m, 1H), 0.86–0.84 (m, 6H); ^{13}C NMR: δ 166.0, 133.8, 133.7, 123.9, 123.7, 112.0, 111.9, 61.2, 56.1, 50.9, 35.6, 28.2, 19.7, 18.2, the carbene ^{13}C NMR resonance was not observed.

*2.6. General procedure for preparation of **8b**, **10b**, **12b** and **13b***

A suspension of azolium compound (0.12 mmol) and silver(I) oxide (0.07 mmol) in CH_2Cl_2 (5 mL) was stirred for 2 h in the dark at refluxing temperature. The reaction mixture was concentrated under reduced pressure to give a white solid. $[PdCl_2(CH_3CN)_2]$ (0.1 mmol) was added to a suspension of the resulting silver complex in CH_3CN (5 mL) in the dark at room temperature. Then, the resulting suspension was stirred for 2 h and filtered through a plug of glass fiber filter paper. The filtrate was evaporated to dryness in vacuo, and the Pd complexes were crystallized from ethyl acetate or methanol. The yield of **8b**, **10b**, **12b** and **13b** were 79%, 52%, 11% and 17%, respectively. These complexes are very stable under air and could be stored for at least 1 month at room temperature.

2.6.1. Amidate/NHC–Pd(II) complex ***8b***

^{1}H NMR ($CDCl_3$): δ 7.80 (br, 1H), 7.42–7.32 (m, 4H), 5.31 (d, J = 16.8 Hz, 1H), 5.04 (d, J = 16.8 Hz, 1H), 4.47–4.36 (m, 1H), 4.27 (s, 3H), 3.76–3.73 (m, 1H), 3.60–3.58 (m, 1H), 1.88–1.83 (m, 1H), 1.48–1.37 (m, 2H), 0.89 (d, J = 6.3 Hz, 3H), 0.86 (d, J = 6.3 Hz, 3H); ^{13}C NMR: δ 165.6, 158.4, 134.3, 133.3, 124.2, 123.7, 111.8, 110.3, 69.5, 55.7, 52.7, 42.7, 35.4, 24.8, 23.1, 22.4. Anal. Calc. for $C_{16}H_{22}ClN_3O_2Pd$: C, 44.67; H, 5.15; N, 9.77. Found: C, 44.92; H, 5.04; N, 9.62%.

2.6.2. Amidate/NHC–Pd(II) complex ***10b***

^{1}H NMR (DMSO): δ 9.11 (br, 1H), 7.87–7.85 (m, 1H), 7.73–7.71 (m, 1H), 7.47–7.39 (m, 4H), 7.29–7.18 (m, 3H), 5.26 (d, J = 3.7 Hz, 1H), 5.05 (d, J = 16.9 Hz, 1H), 4.94 (d, J = 16.8 Hz, 1H), 4.19 (s, 3H), 3.88–3.86 (m, 1H), 3.72–3.69 (m, 1H), 3.34–3.30 (m, 1H); ^{13}C NMR: δ 165.1, 141.8, 133.9, 132.8, 128.0, 126.8, 126.4, 124.0, 123.7, 111.4, 111.3, 70.6, 59.2, 52.0, 35.0. Anal. Calc. for $C_{18}H_{18}ClN_3O_2Pd$: C, 48.02.19; H, 4.03; N, 9.33. Found: C, 48.13; H, 3.74; N, 9.34%.

2.6.3. Amidate/NHC–Pd(II) complex ***12b***

^{1}H NMR (CD_3OD): δ 7.31 (d, J = 2.0 Hz, 1H), 7.22 (d, J = 2.0 Hz, 1H), 4.96–4.86 (m, 1H), 4.91 (d, J = 16.4 Hz, 1H), 4.44 (d, J = 16.4 Hz, 1H), 4.08–4.02 (m, 1H), 3.74 (d, J = 10.0 Hz, 1H), 3.61 (dd, J = 3.6 and 10.0 Hz, 1H), 3.36 (dd, J = 3.6 and 10.0 Hz, 1H), 2.19–2.09 (m, 1H), 2.01–1.86 (m, 2H), 1.42–1.32 (m, 2H), 1.01 (t, J = 7.3 Hz, 3H), 0.96 (d, J = 6.8 Hz, 3H), 0.71 (d, J = 6.8 Hz, 3H); ^{13}C NMR: δ 167.9, 146.0, 123.6, 123.4, 67.1, 65.2, 56.8, 51.1, 34.8, 31.1, 20.5, 19.8, 19.8, 14.1. Anal. Calc. for $C_{14}H_{24}ClN_3O_2Pd$: C, 41.19; H, 5.93; N, 10.29. Found: C, 41.01; H, 5.71; N, 10.24%.

2.6.4. Amidate/NHC–Pd(II)·CH_3OH complex ***13b***·CH_3OH

^{1}H NMR (DMSO): δ 8.73 (s, 1H), 7.50–7.29 (m, 7H), 6.31 (d, J = 15.1 Hz, 1H), 5.20 (d, J = 14.7 Hz, 1H), 4.84 (d, J = 16.0 Hz, 1H), 4.41 (d, J = 16.0 Hz, 1H), 4.13–4.09 (m, 1H), 3.58–3.48 (m, 2H), 3.33 (br, 1H), 3.17–3.16 (m, 3H),1.93–1.84 (m, 1H), 0.84 (d, J = 6.4 Hz, 3H), 0.53 (d, J = 6.9 Hz, 3H); ^{13}C NMR: δ 164.7, 145.8, 137.7,128.4, 128.3, 127.7, 127.3, 122.9, 122.5, 65.8, 62.6, 55.6, 52.2, 48.6, 29.5, 19.4, 19.3. Anal. Calc. for $C_{17}H_{22}ClN_3O_2Pd·H_2O$: C, 44.36; H, 5.26; N, 9.13. Found: C, 44.54; H, 4.92; N, 9.05%.

3. Results and discussion

3.1. Synthesis of azolium iodides and azolium chlorides

The NHC-ligand precursors, azolium iodides, have been successfully synthesized as shown in Scheme 2. This route slightly differs from the previous one [10]. Reaction of 1-(cyanomethyl)imidazole (**1**) with (*S*)-valinol catalyzed by $ZnCl_2$ in PhCl at refluxing temperature, followed by treatment with methanol in the presence of silica gel, afforded **2** in 44% yield. The purified **2** was allowed to react with methyl iodide in THF at refluxing temperature, giving the corresponding imidazolium salt **3** in 80% yield. Similarly, the benzimidazole **5** and the benzimidazolium salt **6** were prepared in 68% and 94% yields, respectively, from 1-(cyanomethyl)benzimidazole (**4**) and (*S*)-valinol as starting materials.

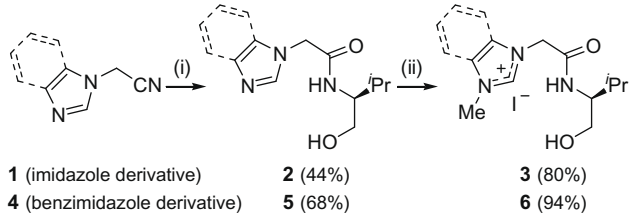
Next, we tried to introduce several N-alkyl groups instead of N-methyl group into the NHC proligand. However, it is more difficult to alkylate with ethyl iodide than CH_3I. Therefore, we proposed another synthetic route to the NHC proligand (Scheme 3). Reaction of chloroacetyl chloride with β-amino alcohol afforded α-chloroacetamide in almost quantitative yield [11], which subsequently coupled with N-alkylated azole to yield the corresponding azolium chloride. Since some N-alkylated imidazoles are commercially available, a variety of the desired azolium compounds can be synthesized using this route. According to the route shown in Scheme 3, an azolium *chloride* should be generated, whereas the previous route (Scheme 2) generates an azolium *iodide*.

Table 1 summarizes the results of the coupling reaction of α-chloroacetamides with N-methyl-, N-butyl-, or N-benzylazole derivatives. For example, 2-chloro-N-[(*S*)-1-(hydroxymethyl)-2-methylpropyl]acetamide derived from (*S*)-valinol was allowed to react with 1-methylbenzimidazole in 1,4-dioxane at refluxing temperature to give benzimidazolium chloride **7** (Run 1). NMR and IR spectra of **7** are consistent with those of **6**. The compounds **11**–**14** are obtained as hygroscopic white-colored powders; the other azolium salts are stable in air. Thus, we succeeded in preparing of a wide variety of tridentate NHC-ligand precursors bearing both N-anionic functional groups and N-alkyl groups.

3.2. Synthesis of tridentate anionic amidate/NHC–Pd complexes through NHC–Ag complexes

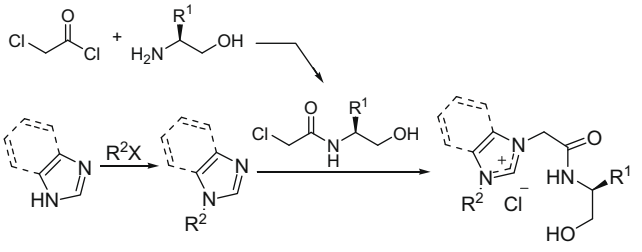
For coordination of azolium salt as NHC to palladium, a strategy based on ligand transfer with the aid of an NHC–Ag complex has been employed [12]. The reaction is driven by precipitation of silver halide salts. Compound **3** was dissolved in dichloromethane at refluxing temperature, followed by addition of 0.5 equiv. of Ag_2O to the reaction vessel. Upon continuous heating for approximately 1.5 h, a white precipitate, which is expected to be the corresponding NHC–Ag complex **3a**, was formed (Scheme 4). In a previous paper, we showed the similar reaction of benzimidazolium iodide **6** with Ag_2O [10]. Although the NHC–Ag complex **6a** obtained from **6** had poor solubility in all solvents, the complex **3a** was found to be dissolved in DMSO.

Fig. 1 shows ^{1}H NMR spectra of **3a** in DMSO-d_6. The signal at δ 9.1 ppm attributed to the imidazolium proton is observed in **3**, but not in the NHC–Ag complex **3a**. The signals at around δ 8.2 and 4.6 ppm corresponding to N–H and O–H protons, respectively, in **3** still exist in the spectrum of **3a**, indicating that no anionic amidate- and alkoxy-tethered NHC–Ag complex was formed. Arnold synthesized a chelating alkoxy NHC–Ag complex by the reaction of an imidazolium salt derived from epichlorohydrin and imidazole with Ag_2O [13]. Upon deprotonation, the signal of the carbene C



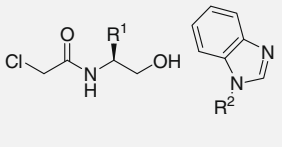
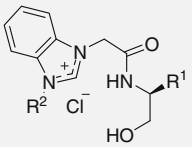
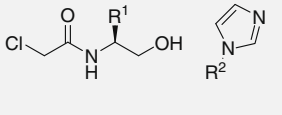
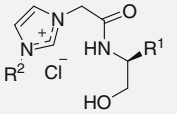
(i) (*S*)-valinol, cat.$ZnCl_2$, PhCl, rf, 15 h, followed by cat.SiO_2, MeOH, rf, 2 h. (ii) MeI, THF, rf, 15 h.

Scheme 2. Synthesis of azolium iodides **3** and **6**.

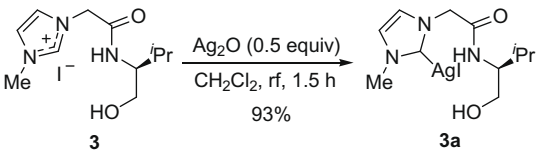


Scheme 3. Another route to azolium chloride.

Table 1
Coupling of α-chloroacetamides with N-alkylated azoles to azolium chlorides.[a]

Run	Substrate		Product (Yield%[b])	
				
1	R^1 = ^{i}Pr	R^2 = Me	**7**	(70)
2	^{i}Bu	Me	**8**	(85)
3	^{i}Bu	Me	**9**	(48)
4	Ph	Me	**10**	(82)
				
5	R^1 = ^{i}Pr	R^2 = Me	**11**	(57)
6	^{i}Pr	^{n}Bu	**12**	(66)
7	^{i}Pr	Bn	**13**	(50)
8	^{i}Bu	Me	**14**	(58)
9	^{i}Bu	^{n}Bu	**15**	(69)
10	^{i}Bu	Bn	**16**	(92)

[a] Experimental procedure: N-Alkylated azole (4.4 mmol) was allowed to react with α-chloroacetamide (4 mmol) in 1,4-dioxane (15 mL) at 110 °C for 16 h.
[b] Isolated yield.



Scheme 4. Reaction of **3** with Ag_2O.

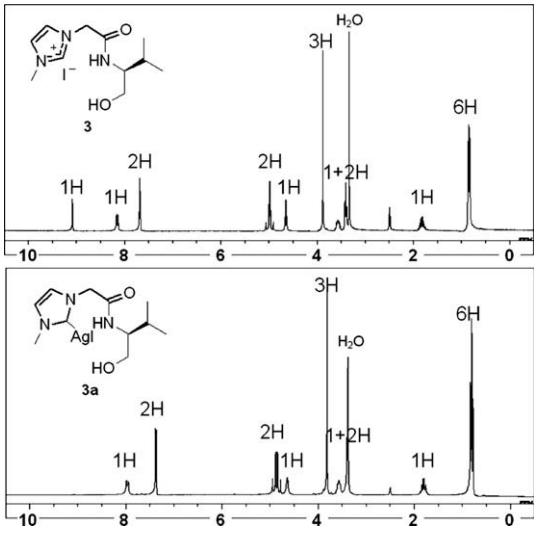
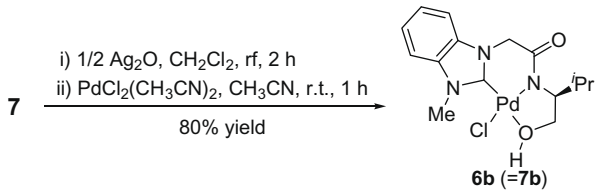


Fig. 1. ^{1}H NMR of **3** and **3a** in DMSO-d_6.

shifts to higher frequency by about 40 ppm [14]. The characteristic carbene C value of 182 ppm is consequently observed.

Next, we examined the reaction of the benzimidazolim chloride **7** with Ag_2O to form the corresponding NHC–Ag complex **7a**. Although **7a** has the same skeleton as the NHC–AgI complex **6a**, it was found that they differ in their physical properties. The silver



Scheme 5. Synthesis of Amidate/NHC–Pd(II) Complex **6b** (= **7b**) from **7** via NHC–Ag complex **7a**.

chloride complex **7a** is light sensitive, unlike the silver *iodide* complex **6a**. In fact, the color of the compound **7a** immediately changes from white to brown during the isolation procedure. It is well-known that NHC–AgCl complexes are light sensitive and that preparation of these complexes should be carried out under exclusion of light [15]. In addition, the *chloride* **7a** is easily dissolved in DMSO, while the corresponding *iodide* **6a** has poor solubility, as described above. Other azolium compounds **8**–**16** can also be transformed into the corresponding NHC–Ag complexes by allowing them to react with Ag_2O in CH_2Cl_2.

Based on these results, synthesis of the NHC–Pd(II) complexes was examined. In a previous communication, we showed a one-pot procedure for preparation of the NHC–Pd complex **6b** without isolation of the NHC–Ag complex **6a** that was generated by the reaction of benzimdazolium *iodide* **6** with Ag_2O [10]. Now, we are interested in the synthesis of **6b** from the corresponding azolium *chloride* **7**. Treatment of **7** with 0.5 equiv. of Ag_2O gave a white precipitate. After removal of the solvent under reduced pressure, $PdCl_2(CH_3CN)_2$ in CH_3CN solution was added to the reaction vessel. Stirring the reaction mixture at room temperature for 1 h gave the desired anionic amidate/NHC–Pd complex **6b** (= **7b**) in 80% yield (Scheme 5).

In the same manner, the conversion of various benzimidazolium and imidazolium chlorides **8**–**16** into the corresponding NHC–Pd complexes has been examined, and several amidate/NHC–Pd complexes **8b**, **10b**, **12b**, and **13b** from **8**, **10**, **12**, and **13**, respectively, were successfully obtained as single crystals. X-ray diffraction studies were performed (Fig. 2).

Table 2 shows the bond lengths around Pd metal in these complexes. Attention should be given to the Pd–N bond length.

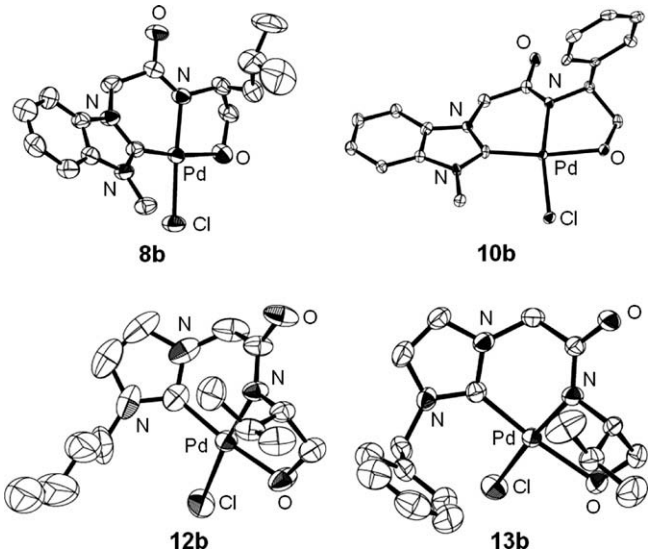


Fig. 2. X-ray structures of several amidate/NHC–Pd(II) complexes.

Table 2
Bond lengths around Pd in several amidate/NHC–Pd complexes.

Product	Pd–C	Pd–N	Pd–O	Pd–Cl
6b (= **7b**)	1.937(2)	1.980(2)	2.110(18)	2.313(15)
8b	1.948 (5)	2.010(5)	2.116(4)	2.303(18)
10b	1.968(4)	2.012(3)	2.089(3)	2.320(10)
12b	1.938(4)	1.992(3)	2.103(3)	2.308(11)
13b	1.946(3)	1.988(2)	2.102(2)	2.330(10)

Douthwaite reports that the Pd–N bond length in a neutral amine/NHC–Pd complex is 2.058(12) Å [16]. On the other hand, Luo prepared an anionic amide/NHC–Pd complex, in which the Pd–N bond length is shortened to 2.006(4) Å [14]. Similarly, the length of the Pd–N bond in our complex **12b** is 1.992(3) Å (Table 2). These facts indicate that anionic coordination exists between N and Pd in **12b**. This may suggest that formation of the NHC–Pd complex by reaction of the NHC–Ag complex with $PdCl_2(CH_3CN)_2$ proceeds with immediate loss of HCl. In general, a strong base is needed to deprotonate the NH after Pd coordination, affording an anionic complex. However, it is notable that no base was needed for preparation of the anionic amidate complex **12b** by ligand-transfer reaction between the NHC–Ag complex and Pd species. A similar observation is reported by Luo and coworkers [14].

4. Conclusions

We have developed efficient synthetic routes to two kinds of azolium salts, azolium iodide and chloride, having both N-anionic functional group and N-alkyl group. These azolium compounds were successfully converted into NHC–Ag complexes, which subsequently reacted with $PdCl_2(CH_3CN)_2$ to give anionic amidate/NHC–Pd complexes. Further studies on transition metal-catalyzed asymmetric syntheses by the use of the tridentate anionic tethered NHC-ligands are now in progress.

Acknowledgments

This work was supported by Grant-in-Aid for Scientific Research (C) (20550103) from Japan Society for the Promotion of Science (JSPS).

Appendix A. Supplementary material

CCDC 739454, 739456, 739457, and 739458 contain the supplementary crystallographic data for **8b**, **10b**, **12b** and **13b**. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via http://www.ccdc.cam.ac.uk/data_request/cif. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2009.10.011.

References

[1] (a) L.H. Gade, S. Bellemin-Laponnaz, in: F. Glorius (Ed.), Topics in Organometallic Chemistry, vol. 21, Springer, Berlin, 2007, pp. 117–157;
(b) L.H. Gade, S. Bellemin-Laponnaz, Coord. Chem. Rev. 251 (2007) 718–725;
(c) M.C. Perry, K. Burgess, Tetrahedron: Asymmetry 14 (2003) 951–961.
[2] (a) F.E. Hahn, M.C. Jahnke, Angew. Chem., Int. Ed. 47 (2008) 3122–3172;
(b) M.S. Sigman, A.D. Jensen, Acc. Chem. Res. 39 (2006) 221–229;
(c) W.A. Herrmann, Angew. Chem., Int. Ed. 41 (2002) 1290–1309;
(d) D. Bourissou, O. Guerret, F. Gabba, G. Bertrand, Chem. Rev. 100 (2000) 39–92.
[3] (a) S.T. Liddle, I.S. Edworthy, P.L. Arnold, Chem. Soc. Rev. 36 (2007) 1732–1744;
(b) D. Pugh, A.A. Danopoulos, Coord. Chem. Rev. 251 (2007) 610–641.
[4] (a) X.H. Cui, Y.B. Fan, M.B. Hall, K. Burgess, Chem. Eur. J. 11 (2005) 6859–6868;
(b) M.C. Perry, X.H. Cui, M.T. Powell, D.R. Hou, J.H. Reibenspies, K. Burgess, J. Am. Chem. Soc. 125 (2003) 113–123;
(c) S. Nanchen, A. Pfaltz, Chem. Eur. J. 12 (2006) 4550–4558.
[5] L.H. Gade, V. César, S. Bellemin-Laponnaz, Angew. Chem., Int. Ed. 43 (2004) 1014–1017.
[6] (a) R.E. Douthwaite, Coord. Chem. Rev. 251 (2007) 702–717;
(b) R. Hodgson, R.E. Douthwaite, J. Organomet. Chem. 690 (2005) 5822–5831.
[7] (a) T.L. May, M.K. Brown, A.H. Hoveyda, Angew. Chem., Int. Ed. 47 (2008) 7358–7362;
(b) M.K. Brown, T.L. May, C.A. Baxter, A.H. Hoveyda, Angew. Chem., Int. Ed. 46 (2007) 1097–1100. and references cited therein.
[8] P.L. Arnold, M. Rodden, K.M. Davis, A.C. Scarisbrick, A.J. Blake, C. Wilson, Chem. Commun. (2004) 1612–1613.
[9] (a) H. Hénon, M. Mauduit, A. Alexakis, Angew. Chem., Int. Ed. 47 (2008) 9122–9124;
(b) D. Martin, S. Kehrli, M. d'Augustin, H. Clavier, M. Mauduit, A. Alexakis, J. Am. Chem. Soc. 128 (2006) 8416–8417;
(c) H. Clavier, L. Coutable, L. Toupet, J.C. Guillemin, M. Mauduit, J. Organomet. Chem. 690 (2005) 5237–5254.
[10] S. Sakaguchi, K.S. Yoo, J. O'Neill, J.H. Lee, T. Stewart, K.W. Jung, Angew. Chem., Int. Ed. 47 (2008) 9326–9329.
[11] G. Guillemot, M. Neuburger, A. Pfaltz, Chem. Eur. J. 13 (2007) 8960–8970.
[12] I.J.B. Lin, C.S. Vasam, Coord. Chem. Rev. 251 (2007) 642–670.
[13] P.L. Arnold, A.C. Scarisbrick, A.J. Blake, C. Wilson, Chem. Commun. (2001) 2340–2341.
[14] W. Wei, Y. Qin, M. Luo, P. Xia, M.S. Wong, Organometallics 27 (2008) 2268–2272.
[15] M. Poyatos, A. Maisse-François, S. Bellemin-Lanponnaz, L.H. Gade, Organomtallics 25 (2006) 2634–2641.
[16] R.E. Douthwaite, J. Houghton, B.M. Kariuki, Chem. Commun. (2004) 698–699.