Hemilabile behavior of a thioether-functionalized N-heterocyclic carbene ligand

Han Vinh Huynh,* Chun Hui Yeo and Geok Kheng Tan

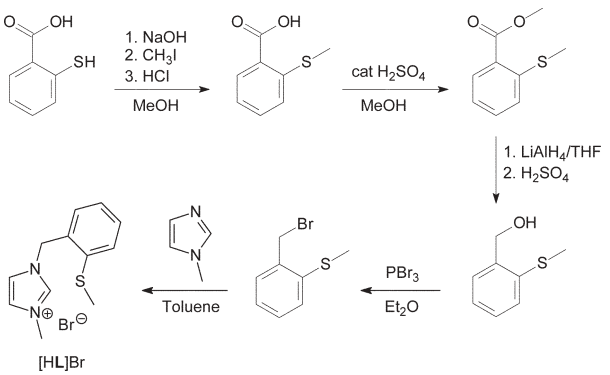
Received (in Cambridge, UK) 12th June 2006, Accepted 19th July 2006
First published as an Advance Article on the web 3rd August 2006
DOI: 10.1039/b608325k

The truely hemilabile nature of a novel thioether-functionalized N-heterocyclic carbene ligand is demonstrated in a range of Pd(II) complexes.

In recent years, N-heterocyclic carbenes (NHCs) have been the focus of intense research in organometallic chemistry and catalysis due to their unique properties.[1] Of particular interest is a donor-functionalization of NHC ligands at their nitrogen atoms, since it offers both the possibility for hemilabile coordination as well as the opportunity to immobilize[2] the resulting catalysts on polymer resins. To this point, several complexes with *N*-, *O*- and *P*-donor functionalized NHCs have been investigated.[3] Examples of NHCs functionalized with a softer sulfur atom are surprisingly rare, and to the best of our knowledge, limited to two thiolate-NHCs[4] and only one thioether-NHC.[5] Although many of the these examples are potentially hemilabile ligands, no such behavior has been reported to date.

With this contribution, we present a versatile synthetic route to the thioether-functionalized imidazolium salt [H**L**]Br and a study on the hemilabile coordination behavior of its corresponding NHC. Ligand precursor [H**L**]Br was prepared by *N*-alkylation of *N*-methylimidazole with 2-methylmercaptobenzyl bromide, which in turn was obtained in a four-step procedure from commercially available thiosalicyclic acid (Scheme 1). The straightforward synthesis affords [H**L**]Br in a very good overall yield of 64% based on thiosalicyclic acid.

The formation of [H**L**]Br was corroborated by a characteristic downfield signal in the ^{1}H NMR spectrum at 10.37 ppm for the NCHN proton and a base peak in the ESI mass spectrum at



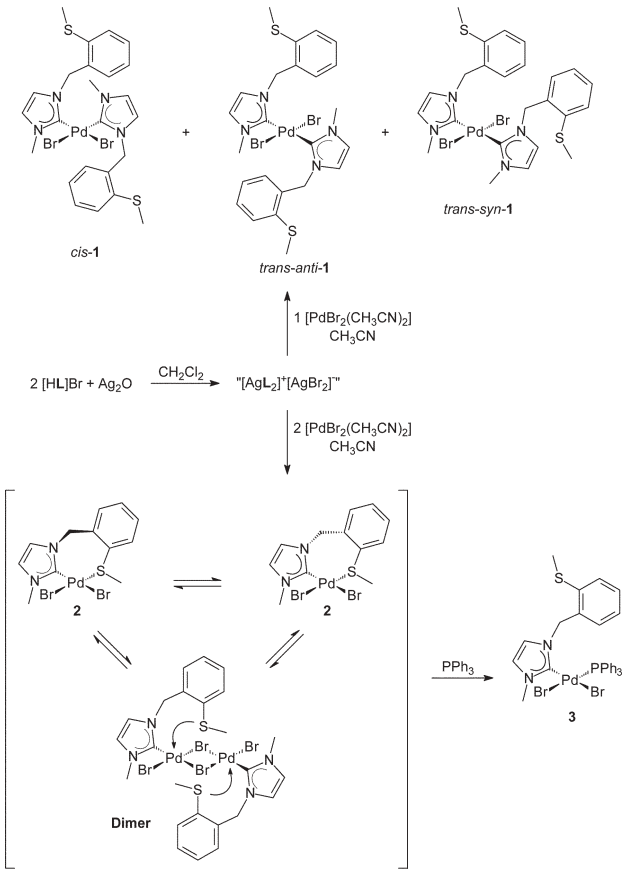
Scheme 1 Synthetic pathway for the preparation of [H**L**]Br.

Department of Chemistry, National University of Singapore, 3 Science Drive 3, 117543, Singapore, Singapore. E-mail: chmhhv@nus.edu.sg; Fax: +65 67791691; Tel: +65 65152670

m/z = 219 for the [H**L**]$^+$ fragment. In an attempt to prepare palladium(II) complexes, $Pd(OAc)_2$ was reacted with 2 equivalents of [H**L**]Br in CH_3CN or DMSO at 90 °C. However, these reactions gave rise to complex mixtures, from which only the bis(carbene) complex *cis*-**1** could be isolated in a low yield of 38%. Apparently, a deprotonation of the benzylic protons of [H**L**]Br under the relatively harsh conditions led to the formation of complex mixtures.

Consequently, the milder Ag–carbene transfer method was explored.[6] The reaction of Ag_2O with 2 equivalents of [H**L**]Br in CH_2Cl_2 afforded Ag–carbene species, which were directly filtered into a solution of $[PdBr_2(CH_3CN)_2]$. The carbene transfer onto palladium readily occurs at ambient temperature and is accompanied by precipitation of AgBr, which can be easily removed. We found that stoichiometry control is crucial for this reaction. Thus a **L** : Pd ratio of 2 : 1 affords a mixture of the isomeric bis(carbene) complexes *cis*-**1**, *trans-anti*-**1** and *trans-syn*-**1** (Scheme 2). Due to different solubilities, *cis* and *trans* isomers can be separated by washing with acetone. The remaining insoluble yellow powder (53%) contains *trans-anti*-**1** and *trans-syn*-**1**, which cannot be further separated. ^{1}H and ^{13}C{^{1}H} NMR spectra in $CDCl_3$ of the latters show two sets of signals with $C_{carbene}$ resonances at 169.9 and 169.8 ppm corresponding to the *syn* and *anti* isomers, respectively. Removal of the solvent from the acetone solution and subsequent recrystallization from $CHCl_3$ yielded an off-white powder of *cis*-**1** (~45%). Its ^{1}H NMR spectrum in CD_3CN is dominated by broad signals indicating a restricted rotation of the Pd–$C_{carbene}$ bonds in the *cis* isomer. ^{13}C{^{1}H} NMR data, on the other hand, could not be obtained due to insufficient solubility. However, an X-ray diffraction analysis on single crystals of the solvate *cis*-**1**·2DMF,† obtained by vapor diffusion of diethyl ether into a concentrated DMF solution, confirms the *cis* arrangement of the NHC ligands in the essentially square planar complex with the bulky methylmercaptobenzyl groups *anti* to each other (Fig. 1).

In order to evaluate whether the thioether function can coordinate to the Pd(II) center, the **L** : Pd ratio was changed to 1 : 1. The ^{1}H NMR spectrum of the reaction product in $CDCl_3$ shows very broad signals at ambient temperature. Upon cooling to −30 °C, some signals sharpen, and two doublets at 5.00 and 5.85 ppm are observed for the non-equivalent benzylic protons, which indirectly indicates a coordination of the sulfur function and thus the formation of the targeted complex **2**. In addition, two sets of signals are observed for the N–CH_3 and the S–CH_3 groups pointing to a rather complex mixture (*vide infra*), although elemental analysis results are found to be close to the expected values. An X-ray diffraction study on single crystals obtained from vapor diffusion of diethyl ether into a DMF solution finally



Scheme 2 Synthetic pathway for the preparation of palladium(II) NHC complexes.

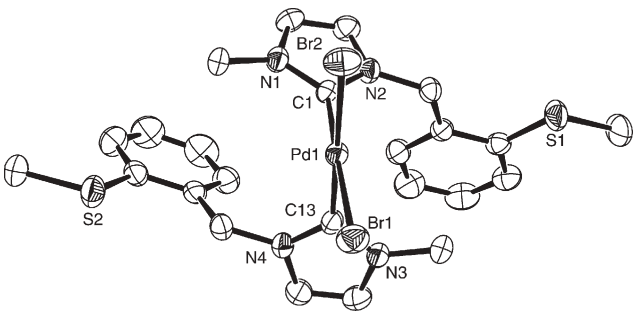


Fig. 1 Molecular structure of *cis*-**1** showing 50% probability ellipsoids. Selected bond lengths [Å] and angles [°]: Pd1–C1 1.982(3), Pd1–C13 1.992(3), Pd1–Br1 2.4856(4), Pd1–Br2 2.4785(3), C1–N1 1.350(4), C1–N2 1.348(4), C13–N3 1.347(4), C13–N4 1.357(4); C1–Pd1–C13 92.84(13), C1–Pd1–Br2 86.57(9), C13–Pd1–Br1 87.06(9), Br1–Pd1–Br2 93.539(16), N1–C1–N2 104.6(3), N3–C13–N4 104.8(3).

confirmed the identity of complex **2**,† and its solid state molecular structure is depicted in Fig. 2. The complex adopts a distorted square planar geometry with the carbene and sulfur donors in *cis* position resulting in a seven-membered chelate ring, which is in a boat-like conformation. It is worth mentioning, that the coordination of the relatively weakly donating thioether does not require abstraction of a bromo ligand (*e.g.* with Ag salts) in order to generate a more Lewis-acidic palladium center. The coordination of the sulfur atom leads to a significantly small dihedral angle

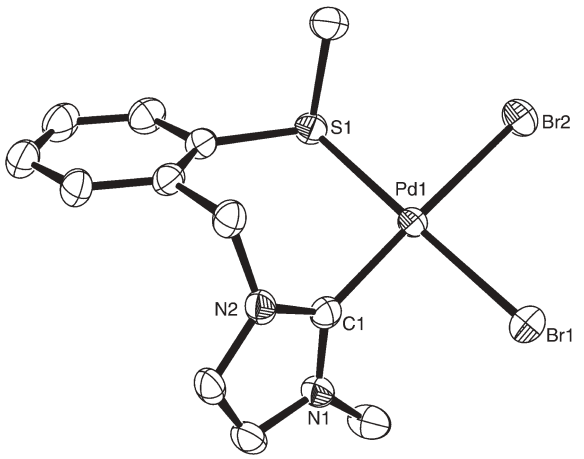


Fig. 2 Molecular structure of **2** showing 50% probability ellipsoids. Selected bond lengths [Å] and angles [°]: Pd1–C1 1.971(3), Pd1–S1 2.3079(3), Pd1–Br1 2.4508(4), Pd1–Br2 2.4792(4), C1–N1 1.343(4), C1–N2 1.335(4); C1–Pd1–S1 93.65(9), C1–Pd1–Br1 86.53(8), S1–Pd1–Br2 86.94(2), Br1–Pd1–Br2 93.070(13), N1–C1–N2 105.8(3).

of 65.155(77)° between the carbene ring plane and the $PdCSBr_2$ coordination plane. The longer Pd–Br2 bond [2.4792(4) *vs.* 2.4508(4) Å for Pd–Br1] *trans* to the carbene reflects its strong *trans* influence.

We anticipated that complex **2** undergoes two dynamic processes in solution. The first process involves flipping of the seven-membered ring, which slows down upon cooling, giving rise to the inequivalent benzylic protons observed at low temperature. The second process involves reversible de- and recoordination of the sulfur donor in a hemilabile fashion. Decoordination results in a formally unsaturated metal center, which stabilizes itself upon dimerization. The two dynamic processes are in equilibrium with at least 3 species (Scheme 2), which may explain the complex ^{1}H NMR spectrum.

To confirm the feasibilty of this proposal and thus the truely hemilabile behavior of the thioether, we added one equivalent (based on Pd) of PPh_3 to the mixture in CH_3CN. The stronger phosphine ligand is expected to cleave both the dimeric complex as well as the weaker Pd–S(Ar)R bond in **2**. Indeed, the addition of PPh_3 leads to a clean and well resolved ^{1}H NMR spectrum corroborating the formation of the mixed NHC–phosphine complex **3** as the sole product. Two doublets are observed at 5.76 and 4.71 ppm, respectively, for the two inequivalent benzylic protons with a geminal coupling constant of $^2J_{(HH)} = 14.3$ Hz. This observation is in line with a hindered rotation of the Pd–$C_{carbene}$ bond mainly due to the steric bulk of the phosphine ligand and indirectly confirms the *cis* arrangement of the NHC and PPh_3 ligands. The $^{13}C\{^1H\}$ NMR signal for the carbenoic carbon appears at 162.7 ppm and the phosphine donor resonances at 27.13 ppm in the ^{31}P NMR spectrum.

Single crystals obtained from a saturated CD_3CN solution were subjected to an X-ray diffraction analysis, and the molecular structure of **3** is shown in Fig. 3.† The metal center is coordinated by one NHC, one phosphine and two bromo ligands in a distorted square planar fashion. The former two are found in a *cis* arrangement, which is thermodynamically favored.[7] Furthermore, it can be clearly seen that the steric bulk of the phosphine ligand prevents a rotation of the Pd–$C_{carbene}$ bond.

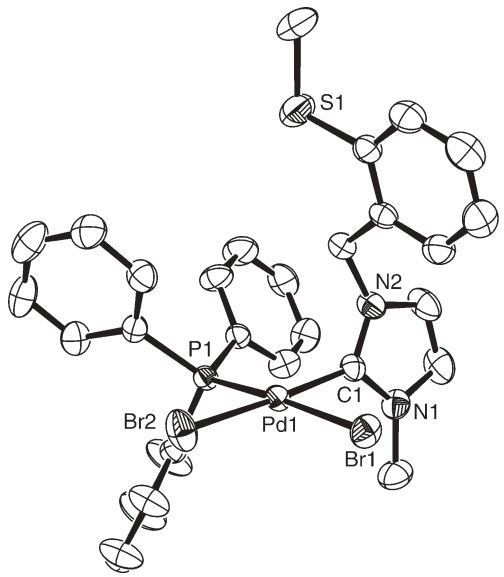


Fig. 3 Molecular structure of **3** showing 50% probability ellipsoids. Selected bond lengths [Å] and angles [°]: Pd1–C1 1.986(3), Pd1–P1 2.2642(8), Pd1–Br1 2.4775(4), Pd1–Br2 2.4785(3), C1–N1 1.349(4), C1–N2 1.350(4); C1–Pd1–P1 92.18(9), C1–Pd1–Br1 86.41(9), P1–Pd1–Br2 91.03(2), Br1–Pd1–Br2 90.763(15), N1–C1–N2 105.1(3).

In conclusion, we have presented a straightforward synthesis of the thioether-functionalized imidazolium salt [H**L**]Br. This modular synthetic route allows the introduction of a wide range of alkyl substituents at the sulfur atom, which offers the possibility to fine-tune both electronic and steric factors of the sulfur donor. We have shown that palladium(II) complexes derived from [H**L**]Br are easily accessible using the Ag–carbene transfer method. In our case, the **L** : Pd ratio determines either the formation of dicarbene (**1**) or monocarbene (**2**) complexes. Treatment of the latter with a stronger phosphine ligand cleaves the Pd–S(Ar)R bond forming complex **3**, which demonstrates a truly hemilabile behavior of the NHC ligand **L**. Studies on the catalytic activities of the complexes and extension of the methodology to other donor-functionalized NHCs are under way.‡

Notes and references

† *Crystal data*: *cis*-**1**·2DMF: $C_{30}H_{42}Br_2N_6O_2PdS_2$, M = 849.04, triclinic, a = 10.0059(6), b = 11.4835(7), c = 16.1385(10) Å, α = 76.031(1), β = 78.306(2), γ = 84.751(1)°, U = 1760.40(19) Å^3, T = 223(2) K, space group $P\bar{1}$ (no. 2), Z = 2, D_c = 1.602 g cm^{-1}, μ (Mo-Kα) = 2.951 mm^{-1}, 12426 reflections measured, 8012 unique (R_{int} = 0.0269) which were used in all calculations. The final wR^2 was 0.1006 (all data).

2: $C_{12}H_{14}Br_2N_2PdS$, M = 484.53, triclinic, a = 8.6338(5), b = 9.6410(6), c = 9.7985(10) Å, α = 107.453(1), β = 103.622(1), γ = 101.368(1)°, U = 723.96(8) Å^3, T = 223(2) K, space group $P\bar{1}$ (no. 2), Z = 2, D_c = 2.223 g cm^{-1}, μ (Mo-Kα) = 6.928 mm^{-1}, 9558 reflections measured, 3324 unique (R_{int} = 0.0232) which were used in all calculations. The final wR^2 was 0.0708 (all data).

3: $C_{30}H_{29}Br_2N_2PPdS$, M = 746.80, monoclinic, a = 9.1662(7), b = 15.3599(12), c = 20.4797(15) Å, β = 91.949(2)°, U = 2881.7(4) Å^3, T = 223(2) K, space group $P2_1/c$ (no. 14), Z = 4, D_c = 1.721 g cm^{-1}, μ (Mo-Kα) = 3.568 mm^{-1}, 20290 reflections measured, 6595 unique (R_{int} = 0.0385) which were used in all calculations. The final wR^2 was 0.0929 (all data).CCDC 610655–610657. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b608325k

‡ *Spectroscopic data*: [H**L**]Br: ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.37 (s, 1 H, NCHN), 7.65 (dd, $^3J_{(H,H)}$ = 7.5 Hz, d, $^4J_{(H,H)}$ = 1.2 Hz, 1 H, Ar–H), 7.43–7.22 (m, 5 H, Ar–H), 5.64 (s, 2 H, CH_2), 4.10 (s, 3 H, NCH_3), 2.50 (s, 3 H, SCH_3). ^{13}C{^{1}H} NMR (75.47 MHz, $CDCl_3$): δ 138.4 (s, NCN), 137.4, 131.2, 130.7, 130.5, 127.0, 126.2 (s, Ar–C), 123.4, 121.8 (s, NCH), 51.1 (s, CH_2), 36.8 (s, NCH_3), 16.1 (s, SCH_3). *cis*-**1**: ^{1}H NMR (300 MHz, CD_3CN): δ 7.36–6.82 (m, br, 12 H, Ar–H), 5.45 (s, br, 4 H, CH_2), 3.87 (s, br, 6 H, NCH_3), 2.55 (s, br, 6 H, SCH_3). **2**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50–6.54 (m, br, 6 H, Ar–H), 5.93 (s, br, 2 H, CH_2), 4.04 (s, br, 3 H, NCH_3), 2.83 (s, br, 3 H, SCH_3). **3**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.66–7.05 (m, 19 H, Ar–H), 6.56 (d, $^3J_{(H,H)}$ = 1.9 Hz, 1 H, CH), 6.40 (d, $^3J_{(H,H)}$ = 1.9 Hz, 1 H, CH), 5.76 (d, $^2J_{(H,H)}$ = 14.3 Hz, 1 H, CH_2), 4.71 (d, $^2J_{(H,H)}$ = 14.3 Hz, 1 H, CH_2), 3.61 (s, 3 H, NCH_3), 2.42 (s, 3 H, SCH_3). ^{31}P NMR (121 MHz, $CDCl_3$): δ 27.1 (s, 1 P, PPh_3). ^{13}C{^{1}H} NMR (75.47 MHz, $CDCl_3$): δ 162.7 (s, NCN), 137.5 (s, Ar–C), 134.3 (d, $^{2/3}J_{(P,C)}$ = 11.0 Hz, Ar–C), 132.3 (s, Ar–C), 131.2 (d, $^1J_{(P,C)}$ = 35.7, Ar–C), 131.0 (d, $^4J_{(P,C)}$ = 2.7 Hz, Ar–C), 130.2, 129.5 (s, Ar–C), 128.5 (d, $^{2/3}J_{(P,C)}$ = 11.0 Hz, Ar–C), 126.7, 126.3, 122.8, 121.3 (s, Ar–C), 51.4 (s, CH_2), 37.9 (s, NCH_3), 16.4 (s, SCH_3).

1 F. E. Hahn, *Angew. Chem., Int. Ed.*, 2006, **45**, 1348; V. César, S. Bellemin-Laponnaz and L. H. Gade, *Chem. Soc. Rev.*, 2004, **33**, 619; W. A. Herrmann, *Angew. Chem., Int. Ed.*, 2002, **41**, 1290.

2 J. Schwarz, V. P. W. Böhm, M. G. Gardiner, M. Grosche, W. A. Herrmann, W. Hieringer and G. Raudaschl-Sieber, *Chem.–Eur. J.*, 2000, **6**, 1773.

3 W. A. Herrmann, L. J. Gooßen and M. Spiegler, *J. Organomet. Chem.*, 1997, **546**, 357; D. S. McGuinness and K. J. Cavell, *Organometallics*, 2000, **19**, 741; S. Gründemann, A. Kovacevic, M. Albrecht, J. W. Faller and R. H. Crabtree, *J. Am. Chem. Soc.*, 2002, **124**, 10473; L. G. Bonnet and R. E. Douthwaite, *Organometallics*, 2003, **22**, 4187; H. Aihara, T. Matsuo and H. Kawaguchi, *Chem. Commun.*, 2003, 2204; B. E. Ketz, A. P. Cole and R. M. Waymouth, *Organometallics*, 2004, **23**, 2835; A. W. Waltman and R. H. Grubbs, *Organometallics*, 2004, **23**, 3105; N. Styliandes, A. A. Danopoulos and N. Tsoureas, *J. Organomet. Chem.*, 2005, **690**, 5948; F. E. Hahn, M. C. Jahnke, V. Gomez-Benitez, D. Morales-Morales and T. Pape, *Organometallics*, 2005, **24**, 6458; R. W. Wang, B. Twamley and J. M. Shreeve, *J. Org. Chem.*, 2006, **71**, 426; S. Dastgir, K. S. Coleman, A. R. Cowley and M. L. H. Green, *Organometallics*, 2006, **25**, 300; S. A. Mungur, A. J. Blake, C. Wilson, J. McMaster and P. L. Arnold, *Organometallics*, 2006, **25**, 1861.

4 D. Sellmann, W. Prechtel, F. Knoch and M. Moll, *Organometallics*, 1992, **11**, 2346; D. Sellmann, W. Prechtel, F. Knoch and M. Moll, *Inorg. Chem.*, 1993, **32**, 538; D. Sellmann, C. Allmann, F. Heinemann, F. Knoch and J. Sutter, *J. Organomet. Chem.*, 1997, **541**, 291; J. A. Cabeza, I. del Rio, M. G. Sánchez-Vega and M. Suárez, *Organometallics*, 2006, **25**, 1831.

5 H. Seo, H.-J. Park, B. Y. Kim, J. H. Lee, S. U. Son and Y. K. Chung, *Organometallics*, 2003, **22**, 618.

6 H. M. J. Wang and I. J. B. Lin, *Organometallics*, 1998, **17**, 972.

7 H. V. Huynh, Y. Han, J. H. H. Ho and G. K. Tan, *Organometallics*, 2006, **25**, 3267.