Organometallic Chemistry

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Pd^{II} Complexes Possessing a Seven-Membered N-Heterocyclic Carbene Ligand**

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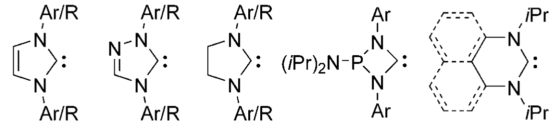
Since the discovery of stable N-heterocyclic carbenes (NHCs),[1] these complexes have found widespread use in catalysis, in which they serve both as nucleophilic catalysts[2] and as ligands in metal-mediated reactions.[3] Carbenes derived from five-membered heterocycles represent the most common class of these molecules (**1**–**3**, Scheme 1);[1–3] however, four-[4] and six-membered[5] analogues have also been reported (**4** and **5**). Most of these structures possess a



1 2 3 4 5

Scheme 1. Typical heterocyclic frameworks of NHCs.

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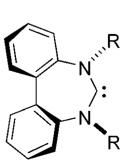
nearly planar heterocyclic framework, and this feature places constraints on the spatial arrangement of the NHC substituents. To relax this constraint, we targeted a new class of NHCs with a seven-membered heterocyclic framework **6** that would undergo a torsional twist to alleviate ring strain. Structures of this type have been analyzed previously by computational methods,[6] but synthetic examples have not been prepared. We describe herein the facile synthesis of two Pd^{II} complexes that possess the first member of this new class of carbene ligands, in which R = 2-adamantyl (2-ad).



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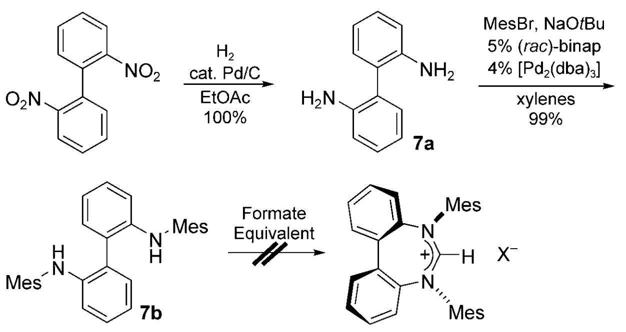
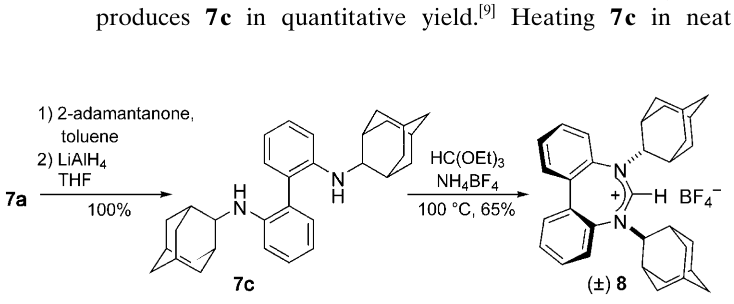
Our initial synthetic efforts targeted analogues of **6** with bulky aryl substituents (e.g., R = mesityl, 2,6-diisopropylphenyl), which are commonly found in stable NHCs. 2,2′-Diaminobiphenyl (**7a**) was obtained in quantitative yield by reduction of 2,2′-dinitrobiphenyl, and mesitylation of **7a** proceeded effectively under previously reported conditions (Scheme 2).[7] Subsequent condensation to afford the amidinium salt, however, was unsuccessful when a variety of known protocols was used. The origin of this failure is not certain, but we reasoned that it may result from the weak basicity of the diaryl amines, and therefore *N*-alkylated derivatives might be more successful.



Scheme 2. Attempted synthesis of an arylated seven-membered NHC. Mes = mesitylene, binap = 1,1′-binaphthalene-2,2′-diylbis(diphenylphosphine).

Preparation of *N*-substituted derivatives of **7a** with sterically encumbered primary and secondary alkyl groups proceeds smoothly (R = neopentyl, 2-adamantyl; Scheme 3).[8] For example, condensation of **7a** with 2-adamantanone followed by reduction of the imine with lithium aluminum hydride produces **7c** in quantitative yield.[9] Heating **7c** in neat triethylorthoformate with NH_4BF_4[10] produces the C_2-symmetric amidinium tetrafluoroborate salt **8**, which was characterized by single-crystal X-ray diffraction analysis (Figure 1).[11]



Scheme 3. Synthesis of a seven-membered biphenyl amidinium salt.

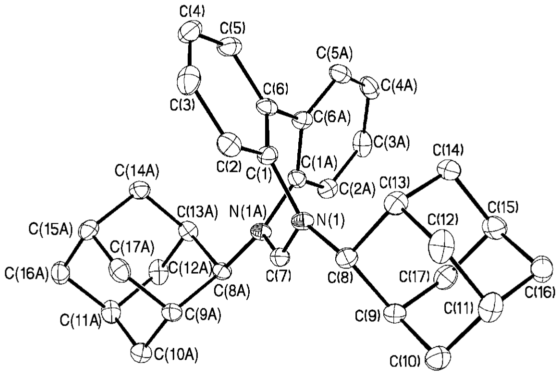
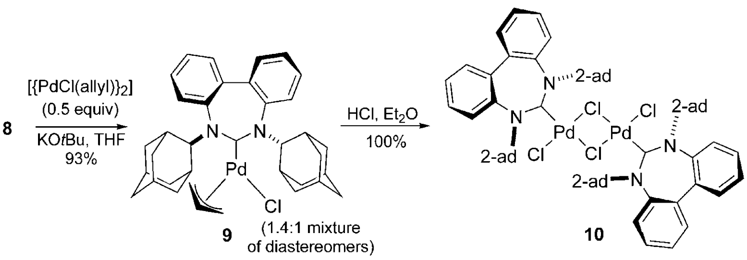


Figure 1. Molecular structure of the amidinium salt **8**. Hydrogen atoms and the BF_4^- counterion are omitted for clarity. Thermal ellipsoids are shown at 50% probability. Selected bond lengths [Å] and angles [°]: C(7)-N(1) 1.319(2), N(1)-C(1) 1.456(3), C(1)–C(6) 1.393(3), C(6)-C(6A) 1.472(4), C(1)-C(2) 1.388(3), C(2)-C(3) 1.385(3), C(3)-C(4) 1.384(3), C(4)-C(5) 1.401(3), C(55)-C(6) 1.401(3); N(1)-C(7)-N(1A) 124.2(3), C(7)-N(1)-C(8) 118.52(19), C(7)-N(1)-C(1) 117.21(18), C(1)-N(1)-C(8) 120.89(16).

The amidinium salt **8** represents an attractive NHC precursor, and our initial studies focused on the preparation of NHC-coordinated Pd^{II} complexes. Deprotonation of **8** with potassium *tert*-butoxide in a THF solution of [{PdCl(allyl)}$_2$][12–14] generated the NHC–PdCl(allyl) complex **9** in high yield (Scheme 4). This complex is air stable and can be purified by flash column chromatography on silica gel under ambient conditions. The ^{1}H NMR spectrum of **9** reveals the presence of two diastereomeric allyl rotamers in solution in a 1.4:1 ratio.[15] Single-crystal X-ray diffraction studies[11] confirmed the identity of **9** (Figure 2); a mixture of diastereomers is also present in the solid state, with the allyl group disordered over two positions in a 2.7:1 ratio.



Scheme 4. Synthesis of NHC-coordinated Pd^{II} complexes.

Protonolysis of the allyl ligand[12] of **9** with HCl produces [{PdCl$_2$(NHC)}$_2$] (**10**) in quantitative yield (Scheme 4). Only one isomer of this dimeric compound is detected in solution by ^{1}H NMR spectroscopic analysis. Single-crystal X-ray diffraction studies reveal the presence of a heterochiral dimer (Figure 3).[11]

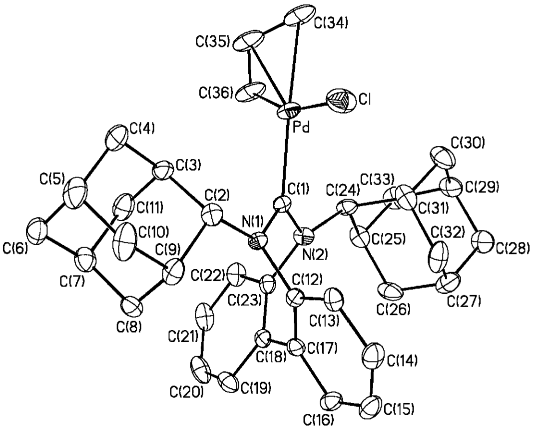


Figure 2. Solid-state molecular structure of **9**. Only the preferred orientation of the allyl group is shown. Hydrogen atoms and the solvent are omitted for clarity. Thermal ellipsoids are shown at 30% probability.

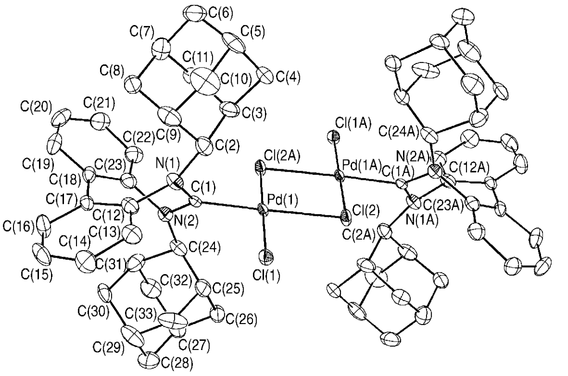
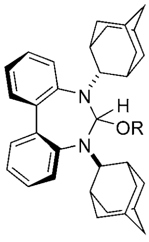


Figure 3. Molecular structure of **10**. Hydrogen atoms and solvent molecules are omitted for clarity. Thermal ellipsoids are shown at 30% probability.

The amidinium salt **8** and the NHC ligands in **9** and **10** exhibit axial symmetry arising from the torsional twist of the seven-membered ring. The torsional angle α between the two phenyl rings in **8** (C(1)-C(6)-C(6 A)-C(1 A)) is 46.1(4)°, which is similar to this angle in **9** and **10** (41.9(5) and 46.4(8)°, respectively). Another relevant metric is the torsional angle between the two N−C(2-ad) bonds, which reflects the spacial disposition of the adamantyl groups directed into the metal coordination sphere. This angle β in **8** (namely, $M = H^+$) is 56.2(5)° and expands to 72.3(8) and 79.7(1.3)° in the Pd^{II} complexes **9** and **10**, respectively. The larger size of the Pd^{II} center relative to a proton probably accounts for this increase. Overall, these torsional parameters highlight the utility of the seven-membered heterocycle to induce out-of-plane deviations in the orientation of the NHC substituents. Moreover, the C_2 symmetry of these structures supports their potential utility as templates for the preparation of non-fluxional, enantiomerically resolved analogues for use in asymmetric catalysis.

Thus far, attempts to isolate and characterize the free carbene have been unsuccessful. Numerous bases have been applied in these studies, including mesityl lithium, potassium hexamethyldisilazide, potassium *tert*-butoxide, sodium methoxide, and sodium hydride. ^1H NMR spectroscopic data reveals that alkoxide bases, which are the most effective reagents for the in situ preparation of NHC–Pd complexes form NHC–alcohol adducts **11a** and **11b**. Attempts to isolate the free carbene from such compounds by vacuum thermolysis[16] or trapping the released alcohol (in the case of the methanol adduct) in a Dean–Stark apparatus equipped with 4-Å molecular sieves and benzene at reflux were unsuccessful and only yielded slightly decomposed starting material in each case. These adducts do not react further in the presence of $[\{PdCl(allyl)\}_2]$ to form the NHC–PdCl(allyl) complex **9**. These results suggest that the preparation of **9** occurs by an in situ deprotonation of **8** by KO*t*Bu and competitive trapping of the free carbene by $[\{PdCl(allyl)\}_2]$ in solution.



11a: R = Me
11b: R = *t*Bu

Rzepa and co-workers analyzed a series of 8π-electron heterocycles, including seven-membered NHCs, by DFT computational methods.[6] These studies highlight the attenuation of antiaromatic character when such heterocyclic rings undergo a torsional twist. This conformational change enables partial Möbius aromatic stabilization[17] in addition to relief of the ring strain intrinsic to seven-membered rings. These calculations also suggest that coordination of these ligands to metal complexes results in higher inversion barriers between the two enantiomeric conformations.

In conclusion, we have prepared the first examples of metal complexes with a seven-membered N-heterocyclic carbene ligand that exhibits a tortional twist resulting in C_2 symmetry. This architecture can be readily altered with different substituents at the nitrogen atom and modifications to the biaryl backbone. Future studies will focus on the preparation of conformationally stable and enantiomerically resolved analogues, and their utility in asymmetric catalysis will be investigated.

Experimental Section

All manipulations were performed in an inert nitrogen atmosphere unless otherwise specified. Dry, oxygen-free solvents were employed. ^1H and ^{13}C NMR spectra were recorded on either a Bruker Homer-300, Bruker Athena-300, Varian Mercury-300, or Varian Inova-500 NMR spectrometer. ^1H NMR chemical shifts are reported in ppm relative to Me_4Si as the external standard, and the ^{13}C NMR chemical shifts are reported in ppm relative to $CHCl_3$. Please refer to the Supporting Information for the spectral data of all the compounds.

7a: Compound **7a** was synthesized by the adaptation of a literature procedure:[18] 2,2′-Dinitrobiphenyl (102.0 g, 417.5 mmol) and 10% Pd/C (16.4 g) were combined with EtOAc (300 mL) in a hydrogenation vessel. The vessel was pressurized to 40 psi H_2 for 3.5 h (when H_2 was no longer being consumed). The slurry was filtered through a plug of celite. Rotary evaporation followed by drying on a vacuum line gave the pure product as a light yellow–orange powder in 100% yield.

7c: 2,2′-Diaminobiphenyl (**7a**; 614 mg, 3.33 mmol) and 2-adamantanone (1 g, 6.65 mmol) were combined with *para*-toluenesulfonic acid (1% (per amine functionality)) in a Dean–Stark apparatus. The reagents were dissolved in toluene (ca. 200 mL) and refluxed for

72 h. The solvent was removed, and lithium aluminum hydride (122 mg, 3.22 mmol) was added followed by THF (ca. 200 mL). The reaction flask was heated to 50°C for 2 h followed by a careful quenching with water (ca. 100 mL) and sat. NH_4BF_4 (10 mL). The resulting slurry was filtered through a plug of celite, and the plug washed with CH_2Cl_2. The aqueous layer was washed once with CH_2Cl_2 (ca. 100 mL). The organic layers were combined, dried over $MgSO_4$, filtered, and the solvent was removed, thus yielding pure **7c** in 100% yield.

(±)-**8**: 2,2′-Bis(2-adamantylamino)biphenyl (**7c**; 5.76 g, 12.7 mmol) and NH_4BF_4 (1.3 g, 12.7 mmol) were combined under nitrogen in a 500-mL round-bottomed flask and triethyl orthoformate (c.a. 200 mL) was added. The reaction was heated to 100°C for 16 h, after which time the product precipitated as a white powder. The reaction mixture was allowed to cool to room temperature and filtered. The solid was washed with diethyl ether followed by pentane to give the amidinium salt (±)-**8** in 65% yield as a light fluffy white powder without further purification. Crystals suitable for X-ray analysis were achieved by vapor diffusion of *n*-pentane onto a solution of (±)-**8** in $CHCl_3$.

(±)-**9**: Aminidinium salt (±)-**8** (200 mg, 0.363 mmol) and [{PdCl(allyl)}$_2$] (78 mg, 0.213 mmol) were combined with KO*t*Bu (1.2 equiv) under nitrogen. The reaction mixture was stirred in THF for 12 h, filtered through celite, and purified by column chromatography under ambient conditions (SiO_2, diethyl ether/hexanes 1:1) to give the NHC–PdCl(allyl) complex (±)-**9** in 93% yield as a light yellow–tan solid. Crystals suitable for X-ray analysis were obtained by layering *n*-heptane onto a −20°C ethereal solution of (±)-**9** followed by diffusion overnight at −20°C. (±)-**9** crystallized as a mixture of diastereomers in a ratio of 73:27.

10: A 50-mL round-bottomed flask was charged with (±)-**9** (100 mg, 0.16 mmol) and ethereal HCl (2.0 mL, 2.0 M). The color of the reaction mixture instantly changed to bright yellow–orange. Diethyl ether (8.0 mL) was added, and the resultant suspension was stirred for 1 h. Volatiles were removed in vacuo, which left pure **10** as a bright yellow–orange powder in quantitative yield. Recrystallization was carried out by dissolving **10** in a small amount of toluene and adding excess *n*-pentane to cause precipitation (87% yield). Crystals suitable for X-ray analysis were achieved by vapor diffusion of *n*-pentane onto a solution of **10** in CH_2Cl_2.

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