Carbocyclic Carbenes

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A Carbocyclic Carbene as an Efficient Catalyst Ligand for C–C Coupling Reactions**

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Dedicated to Professor Richard F. Heck on the occasion of his 75th birthday

Starting from the prototypes I and $II^{[1]}$ N-heterocyclic carbenes (NHCs) have proved to be efficient control ligands in organometallic homogeneous catalysis.^[2-4] It could not



mononuclear carbene complexes 4 and 5 by way of the binuclear complexes 2a,b (π -allyl) and 3a,b (σ,π -carbene) (Scheme 1). Complexes 4 and 5 were formed almost quanti-



Scheme 1. Synthesis of CHT-palladium complexes: a) CH_2CI_2 , $-10^{\circ}C$; b) 40°C (X=Cl) or 25°C (X=Br); c) in C_6H_6 , 1 equiv $L=P(C_6H_5)_3$ or $P(c-C_6H_{11})_3$; d) DMSO, ca. 150°C.

tatively when intermediates 2 and 3 were not isolated. The intermediate 2a may be isolated by interruption of the reaction at an early stage, but it rearranges into the carbene complex 3a during the further course of the reaction and during workup. The π -allyl complex 2a and the carbene complex 4 were characterized by X-ray crystallography (Figures 1 and 2).^[5,6] The constitution of the complex compounds in solution was established spectroscopically

have foreseen, but they are beginning to displace the classical organophosphanes as ligands. Metal complexes of NHCs generally have greater thermal and acid stability of their metal complexes; they frequently exhibit higher catalytic activities, are amenable to a broad range of structure variation, and are also successful as immobilized variants.^[2] Prominent examples of their application are the activation of haloarenes and olefin metathesis.^[2,4] We have now found that, as a control ligand, the simple, carbocyclic carbene **III** (cycloheptatrienylidene, CHT) is comparable with or even superior to the well-established NHCs. We describe this here with the example of the palladium complexes.

In a short reaction sequence 1,1-dichloro- and 1,1dibromocycloheptatrienes (1a and 1b, respectively) were transformed in good yield with palladium black into the

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Figure 1. ORTEP drawing of **2a** in the crystal; thermal ellipsoids set at 50% probability. Selected bond lengths [Å] and angles [°]: Pd–Cl1 2.4588(9), Pd–Cl1 *a* 2.4545(10), Pd–Cl 2.073(4), Pd–C2 2.183(5), Pd–C7 2.179(4), Pd–Cg 1.870, C1–C2 1.415(6), C1–C7 1.385(6), C2–C3 1.450(7), C3–C4 1.353(7), C4–C5 1.402(7), C5–C6 1.328(6), C6–C7 1.433(6); Cl1-Pd-Cl1 *a* 87.58(3), Pd-Cl1-Pd *a* 92.42(3), Cl1-Pd-Cg 134.10, Cl1 *a*-Pd-Cg 136.80. Symmetry operations for the equivalent atom positions *a*: –*x*, 1–*y*, 1–*z*. Cg defines the mass center of the allylic system C1, C2, and C7.

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Figure 2. ORTEP drawing of **4** in the crystal; thermal ellipsoids set at 50% probability. Selected bond lengths [Å] and angles [°]: Pd–C1 1.968(2), Pd–Cl1 2.3697(6), Pd–Cl2 2.3884(7), Pd–P 2.2483(6); Cl1-Pd-Cl2 91.83(2), Cl1-Pd-P 175.89(2), Cl1-Pd-Cl 85.14(7), Cl2-Pd-P 92.27(2), Cl2-Pd-Cl 174.55(6), P-Pd-Cl 90.76(7).

(see the Experimental Section). The bromo derivative **2b** reacts immediately to form the carbene complex **3b** and therefore cannot be isolated.

The C–C bonds of the cyclocarbene in complex 4 are almost all the same length $(1.39 \pm 0.02 \text{ Å})$, which suggests extensive 6π delocalization similar to that of the cycloheptatrienyl cation. The delocalization of the π system includes the carbene p orbital similar to that in the NHC ligands I and II so that $\pi(M \rightarrow C)$ backbonding contributes only minimally to the stabilization of the CHT complexes. Hence the cycloheptatrienylium resonance form (a in Scheme 2) is also favored in the literature for the low-valent metal complexes.^[7] This is in agreement with the Pd–C distance in 4 which at 1.968(2) Å lies in the range typical for the NHCs I and II.^[1,2] Clearly the C_7H_6 carbene is essentially a σ -

donor ligand. We used the route shown in

Scheme 1 to prepare palladium complexes of cycloheptatrienylidene for the first time. This synthesis did not require special precursors for air- and temperaturesensitive metal(0) complexes such as $[Pt{P(C_6H_5)_3}_3]$ as was previously described by Jones et al.^[8] Since our method has several steps (π -allyl intermediate!), we avoid formation of heptafulvalene, which would occur from the reductive coupling of the ligand precursor.^[7a]

The carbocyclic carbene complex **4** gave good results in numerous variants of the Heck and Suzuki coupling reactions.^[9] Thus *p*-bro-





Scheme 2. Mesomeric resonance structures of $CHT(6\pi)$ -metal complexes.

moacetophenone and *n*-butyl acrylate underwent C–C coupling at 145 °C with only 10^{-4} mol% of catalyst **4**, which corresponds to turnover numbers (TON) of the order of 10^6 at turnover frequencies (TOF) of $\geq 10^3$ h⁻¹ (Table 1, entry 1). Reaction of bromobenzene was also achieved (10^{-1} mol% cat) in 90% yield and with TON $\approx 10^4$ (Table 1, entry 2). In all examples of the Heck coupling reaction investigated the NHC reference catalyst **6**^[10] was inferior (Figure 3a). Unlike the NHC catalyst **6**, **4** did not require an induction period.

An analogous picture emerges for typical Suzuki coupling reactions (Figure 3b). With catalyst **4** ($10^{-3} \mod \%$) bromobenzene underwent quantitative coupling with phenylboronic

Table 1: Catalyzed Heck coupling.



Entry	R	Х	Cat.	PR'_3	mol% Pd	<i>t</i> [h]	Conv. [%] ^[a]	Yield [%] ^[a]	TON
1	C(O)CH₃	Br	4	_	10 ⁻⁴	14	100	100	106
2	Н	Br	4	-	0.1	14	92	90	9000
3	OCH₃	Br	4	-	0.1	14	43	42	420
4	OCH ₃	Br	4	-	1	14	59	58	58
				-		35	66	65	65
				-		104	91	89	89
5	C(O)CH₃	Cl	4	-	1 ^[b]	14	30	28	28
				-		35	63	58	58
				-		104	81	76	76
5	C(O)CH₃	Cl	3 a	PCy₃	1 ^[b]	14	76	75	75

[a] GC yield with diethylene glycol di-*n*-butyl ether as the internal standard. [b] Addition of [nBu₄N]Br (0.2 equiv.), T = 150 °C.

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Figure 3. Conversion(U)-time(t) plot for the a) Heck coupling of bromobenzene with *n*-butyl acrylate and the b) Suzuki coupling of *p*-bromoanisole with phenylboronic acid; in each case catalysts **4** (**m**, ----; **0.1** mol%) and **6** (**•**, •••••; **0.1** mol%) are compared.

acid at 130 °C and the conversion rates (TON) were of the order of 10^4 to 10^6 ; with chloroarenes TONs of up to $> 10^3$ were achieved, for example with *p*-chloroacetophenone (Table 2, entry 4). Once again catalyst **6** does not approach the carbocyclic variant **4**.

In Suzuki coupling reactions with chloroarenes catalyst **5** was more effective than the most active NHC–phosphane system previously known, which is produced in situ from **7** and PCy₃ (Table 2, entries 5–8).^[10] Better results for chloroarenes were found previously only with optimized in situ catalysts derived from Pd(OAc)₂ or [Pd₂(dba)₃] (dba = *trans*,-

Table 2: Catalyzed Suzuki coupling.

	B(OF	H)2 X + R	Xyle	[Pd] ene, Cs ₂ CO ₃ 30 °C, 14h	+ R	X—B(OH)	2
Entry	R	Х	Cat.	PR' ₃	mol % Pd	Yield [%] ^[a]	TON
1	Н	Br	4	-	10 ^{-3[b]}	100	10 ⁵
2	Н	Br	4	-	10 ^{-4[b]}	89	8.9×10 ⁵
3	OCH ₃	Br	4	-	0.01 ^[b]	43	4300
4	C(O)CH ₃	Cl	4	-	0.01	11	1100
5	Н	Cl	3 a	PCy₃	1	100	100
6	Н	Cl	7	$+ PCy_{3}^{[10]}$	1	42	42
7	OCH₃	Cl	3 a	PCy ₃	1	93	93
8	OCH ₃	Cl	7	$+ PCy_{3}^{[10]}$	1	69 ^[c]	69

[a] GC yield with diethylene glycol di-*n*-butyl ether as the internal standard. [b] K_2CO_3 as base. [c] Yield after 32 h.

trans-dibenzylideneacetone) and imidazolium salts, the structures of which were not defined.^[11]

With respect to their ready synthesis and high thermal and air stability, the catalyst complexes of cycloheptatrienylidene are at least comparable to the NHC complexes. The tremendous robustness of the CHT catalysts is demonstrated inter alia in that the complex **4** used in the catalyst experiments could be subjected to temperatures of more than 145 °C over five days without a trace of decomposition. Complex **3a** can even be purified by stirring with concentrated HCl.

We attribute the efficiency of the new class of catalysts essentially to a low metal coordination achieved with high thermal stability such that the metal–carbene unit is retained in the catalytic cycle. Whether and to what extent the carbon– metal bond determines the catalytic properties is the subject of kinetic and quantum mechanical investigations. The catalysts may be widely varied both constitutionally and structurally. It is expected above all that the substituents at positions 2 and 7 next to the carbene center exercise a far greater effect on the metal environment than is the case in the NHC five-membered-ring system. In that way we hope to solve the problem of the Heck coupling of deactivated chloroarenes which have failed with all known, molecularly defined, homogeneous catalysts.^[12]

Experimental Section

2a: Pd black (1.0 g, 9.40 mmol) and **1a** (1.47 g, 9.13 mmol) were stirred in 25 mL of dichloromethane for 6 h at -10° C. The suspension was filtered through a D4 frit, the residue was rinsed with dichloromethane (6×20 mL), and the combined rinses were concentrated under reduced pressure to a volume of 20 mL. The solution was cooled to -18° C, and the resulting red-brown crystals were filtered off and dried in vacuo. Yield: 0.21 g (9%). ¹H NMR (399.8 MHz, CD₂Cl₂): $\delta = 6.39$ (m, 2H), 5.59 (m, 2H), 5.30 ppm (m, 2H); ¹³Cl¹H} NMR (100.5 MHz, CD₂Cl₂): $\delta = 116.2$, 101.7, 89.5 ppm; elemental analysis (%) calcd for C₁₄H₁₂Cl₄Pd₂: C 31.43, H 2.26, Pd 39.78; found: C 31.76, H 2.31, Pd 39.36.

3a: Pd black (1.45 g, 13.63 mmol) and **1a** (2.15 g, 13.35 mmol) were stirred in dichloromethane (30 mL) for 24 h at -10° C. The product mixture was then extracted in two portions for 24 h in a small Soxhlet apparatus with 50 mL of boiling dichloromethane in each case. The combined extracts were concentrated under reduced pressure to 40 mL and cooled to -18° C. The precipitated orange-colored crystals were filtered off, washed with dichloromethane (10 mL), and dried in vacuo. Yield: 2.25 g (64%). M.p. 150–160 °C (decomp). ¹H NMR (399.8 MHz, [D₆]DMSO): $\delta = 5.36$ (m, 2H), 5.22 (m, 2H), 5.03 ppm (d, J = 12.0 Hz, 2H); ¹³C[¹H] NMR (100.5 MHz, [D₆]DMSO): $\delta = 185.8$ (s, carbene C), 140.2, 135.4, 133.8; IR (Nujol): $\tilde{\nu} = 346$ (terminal halogen atom), 313, 282 cm⁻¹ (bridging halogen atoms). Elemental analysis (%) calcd for C₁₄H₁₂Cl₄Pd₂: C 31.43, H 2.26, Pd 39.78; found: C 30.96, H 2.31, Pd 39.08.

4: A solution of complex **3a** (0.45 g, 0.815 mmol) and $P(C_6H_5)_3$ (0.44 g, 1.68 mmol) in C_6H_6 (20 mL) was first warmed to 80 °C with stirring and then stirred for a further 20 h at 25 °C. The resulting yellow microcrystalline needles were filtered off, washed with C_6H_6 (5 × 10 mL), purified by recrystallization from CH₃CN, and dried in vacuo. Yield: 0.80 g (93 %). MS (FAB-MS): m/z: 493 $[M-CI]^+$ (100). Elemental analysis (%) calcd for $C_{25}H_{21}Cl_2PdP$: C 56.68, H 4.00, Pd 20.09; found: C 56.42, H 3.79, Pd 19.5. Compound **4** was obtained almost quantitatively when, as described in the above method, **1a** was first allowed to react with Pd black in dichloromethane at -10 °C and

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48 h at room temperature, and then with PPh_3 in C_6H_6 at 80 °C and 24 h at room temperature.

Catalyzed reactions: a) Heck coupling: A Schlenk flask that had been evacuated and filled with argon several times was charged with sodium acetate (3.0 mmol), aryl halide (2.0 mmol), and the internal standard diethylene glycol di-*n*-butyl ether (100 mg). Then *n*-butyl acrylate (3 mmol) and degassed *N*,*N*-dimethylacetamide (DMA; 2 mL) were added, and the reaction mixture was heated to 145 °C. When the reaction temperature had been reached the catalyst solution was added against stream of argon. At the end of the reaction the reaction solution was cooled to 25 °C, treated with 1N aq. HCl (1 mL), and extracted with dichloromethane (3 × 2 mL). The organic phase was dried over MgSO₄. Conversions and yields were determined by GC analysis.

b) Suzuki coupling: A Schlenk flask that had been evacuated and filled with argon several times was charged with potassium or cesium carbonate (3.0 mmol), aryl halide (2.0 mmol), phenylboronic acid (2.4 mmol), and the internal standard diethylene glycol di-*n*-butyl ether (100 mg). Then degassed xylene (2 mL) was added, and the reaction mixture was heated to 130 °C. When the reaction temperature had been reached the catalyst solution was added against a stream of argon. At the end of the reaction the reaction solution was cooled to 25 °C, treated with water (3 mL), and extracted with diethyl ether (3 × 2 mL). The organic phase was dried over MgSO₄. Conversions and yields were determined GC analysis.

Catalyst solutions for the catalysts **4** and **6**: A solution of catalyst (0.02 mmol) in DMA (10 mL) was stored in the freezer. The concentration was selected such that 0.1 mL of the solution corresponds to a catalyst/substrate ratio of 0.01 mol% catalyst. For experiments with extremely low catalyst concentrations the catalyst solution was diluted further. Catalyst solutions for the catalysts **5** and **7**: The solutions were prepared by stirring the phosphane with **3a** or **7** (P/Pd ratio 1:1) in DMA (0.5 mL) for 10 min at 25 °C.

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- a) W. A. Herrmann, M. Elison, J. Fischer, C. Köcher, G. R. J. Artus, Angew. Chem. 1995, 107, 2602; Angew. Chem. Int. Ed. Engl. 1995, 34, 2371; b) W. A. Herrmann, C. Köcher, Angew. Chem. 1997, 109, 2256; Angew. Chem. Int. Ed. Engl. 1997, 36, 2162; c) D. Bourissou, O. Guerret, F. P. Gabbaï, G. Bertrand, Chem. Rev. 2000, 100, 39.
- [2] Review article : a) W. A. Herrmann, Angew. Chem. 2002, 114, 1342; Angew. Chem. Int. Ed. 2002, 41, 1290; b) W. A. Herrmann, T. Weskamp, V. P. W. Böhm, Adv. Organomet. Chem. 2002, 48, 1.
- [3] Since the first publication on C-C coupling reactions catalyzed by NHC complexes^[1a] in 1995 more than 200 original publications from 15 research groups have appeared.
- [4] a) W. A. Herrmann, J. Fischer, M. Elison, C. Köcher, K. Öfele (Hoechst AG), DE 4447066.5A1, 1996, EP 0721953A1, 1996 [*Chem. Abstr.* 1996, 125, 143019y]; b) W. A. Herrmann, J. Fischer, M. Elison, C. Köcher (Hoechst AG), DE 4447068.1A1, 1996, EP 0719758A1, 1996, US 5.703.269, 1997 [*Chem. Abstr.* 1996, 125, 167571y]; c) W. A. Herrmann, M. Elison, J. Fischer, C. Köcher (Celanese GmbH), DE 4447067.3A1, 1996, EP 0719753A1, 1995 [*Chem. Abstr.* 1996, 125, 167338c]; d) W. A. Herrmann (Hoechst AG), DE 4447070.3A1, 1996, EP 0721951A1, 1996 [*Chem. Abstr.* 1996, 125, 143016v]; e) W. A. Herrmann, C. Köcher, L. Goossen (Hoechst AG), DE 1961090.8A1, 1997, EP 888308, 1997, WO 9734875, 1997 [*Chem. Abstr.* 1997, 127, 318962v]; f) W. A.

Herrmann, H.-C. Militzer, U. Scholz, C. Gstöttmayr (Bayer AG), EP 1308157A1, **2003**.

- [5] X-ray crystal structure analysis of 2a: $C_{14}H_{12}Cl_4Pd_2$, $M_r = 534.88$, red fragment $(0.03 \times 0.20 \times 0.51 \text{ mm}^3)$, triclinic, $P\bar{1}$, a = 5.0196(6), b = 7.2075(8), c = 11.5141(15) Å, $a = 86.792(10), \beta = 80.650(10), \beta = 80.6$ $\gamma = 80.080(9)^{\circ}$, $V = 404.72(9) \text{ Å}^3$, Z = 1, $\rho_{\text{calcd}} = 2.195 \text{ g cm}^{-1}$ $F_{000} = 256$, $\mu = 2.886$ mm⁻¹. The preliminary investigation and data collection were carried out with a IPDS-2T diffractometer (Stoe & Cie) at the window of a rotating-anode generator (NONIUS FR591) with $Mo_{K\alpha}$ radiation (graphite monochromator, $\lambda = 0.71073$ Å) at 293 K in the range of $4.53^{\circ} < \Theta < 25.35^{\circ}$. 5867 Reflections integrated with TWIN program, data LPcorrected, and corrected for decomposition, starting from the scaling. Numerical absorptions correction ($T_{\min} = 0.544$, $T_{\max} =$ 0.812) after optimization of the crystal form. All 1168 independent reflections ($R_{\rm int} = 0.039$) [1081: $I_{\rm o} > 2 \sigma(I_{\rm o})$] used for the refinement of the 102 parameters, structure solution by direct methods and difference Fourier syntheses. All non-hydrogen atoms refined with anisotropic displacement parameters, hydrogens at calculated positions with a C-H distance of 0.93 Å and $U_{\rm iso(H)} = 1.2 \, U_{\rm eq(C)}$ refined, structure refinement (method of least squares on $\Sigma w (F_o^2 - F_o^2)^2$ converged with R1 = 0.0206 $[I_o >$ $2\sigma(I_o)$], wR2 = 0.0492 [all data], GOF = 1.041, and shift/error ratio < 0.001. The final difference Fourier map showed only small deviations ($\Delta e_{\min/\max} = +0.31/-0.30 \text{ e}\text{\AA}^{-3}$). Smaller extinction effects were corrected with SHELXL-97 (G. M. Sheldrick, SHELXL-97, Program for Refinement of Crystal Structures, Universität Göttingen, 1997) [$\varepsilon = 0.013(2)$]. The molecule lies on an inversion center. The resulting partial disorder [0.830(4):0.170(4)]of the chlorine atoms C12/C13 was observed and resolved. CCDC-683874 contains the detailed crystallographic data for this publication. The data may be obtained free of charge from the Cambridge Crystallographic Data Centre under www.ccdc.cam.ac.uk/data_request/cif.
- [6] X-ray crystal structure analysis of 4-CH₃CN: C₂₇H₂₄Cl₂NPPd, $M_r = 570.76$, yellow needles $(0.05 \times 0.10 \times 0.66 \text{ mm}^3)$, triclinic, $P\bar{1}$ (No. 2), a = 9.7796(2), b = 10.5189(2), c = 12.5658(3) Å, a = 99.2431(7), $\beta = 93.8821(6)$, $\gamma = 90.2501(6)^\circ$, V = 1272.79(5) Å³, Z = 2, $\rho_{calcd} = 1.489 \text{ g cm}^{-3}$, $F_{000} = 576$, $\mu = 1.017 \text{ mm}^{-1}$. R1 = 0.0290 [$I_o > 2 \sigma(I_o)$], wR2 = 0.0555 [all data], GOF = 1.116, shift/error ratio < 0.001. CCDC-603873 contains the detailed crystallographic data for this publication. The data may be obtained free of charge from the Cambridge Crystallographic Data Centre under www.ccdc.cam.ac.uk/data_request/cif.
- [7] a) N. T. Allison, Y. Kawada, W. M. Jones, J. Am. Chem. Soc. 1978, 100, 5224; b) P. E. Riley, R. E. Davis, N. T. Allison, W. M. Jones, Inorg. Chem. 1982, 21, 1321.
- [8] a) Z. Lu, K. A. Abboud, W. M. Jones, J. Am. Chem. Soc. 1992, 114, 10991; b) Z. Lu, W. M. Jones, W. R. Winchester, Organometallics 1993, 12, 1344.
- [9] Current literature, e.g. a) W. A. Herrmann, K. Öfele, D. von Preysing, S. K. Schneider, J. Organomet. Chem. 2003, 687, 229; b) W. A. Herrmann in Applied Homogeneous Catalysis with Organometallic Compounds, 2nd ed. (Eds.: B. Cornils, W. A. Herrmann), Wiley-VCH, Weinheim, 2002, p. 591–598; W. A. Herrmann in Applied Homogeneous Catalysis with Organometallic Compounds, 2nd ed. (Eds.: B. Cornils, W. A. Herrmann), Wiley-VCH, Weinheim, 2002, p. 775–793; W. A. Herrmann in Applied Homogeneous Catalysis with Organometallic Compounds, 2nd ed. (Eds.: B. Cornils, W. A. Herrmann), Wiley-VCH, Weinheim, 2002, p. 775–793; W. A. Herrmann in Applied Homogeneous Catalysis with Organometallic Compounds, 2nd ed. (Eds.: B. Cornils, W. A. Herrmann), Wiley-VCH, Weinheim, 2002, p. 822–828.
- [10] W. A. Herrmann, V. P. W. Böhm, C. W. K. Gstöttmayer, M. Grosche, C.-P. Reisinger, T. Weskamp, J. Organomet. Chem. 2001, 617–618, 616.
- [11] G. A. Grasa, M. S. Viciu, J. Huang, C. Zhang, M. L. Trudell, S. P. Nolan, Organometallics, 2002, 21, 2866.
- [12] A. F. Littke, G. C. Fu, J. Am. Chem. Soc. 2001, 123, 6989.

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