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Allyl Palladium Complexes of Cycloheptatrienyl-Cyclopentadienyl Phosphane Ligands in Buchwald-Hartwig Amination Reactions

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Abstract: A series of well-defined palladium allyl chloride precatalysts was synthesized using previously reported troticenyl phosphane ligands $[(\eta^7 - C_7 H_7)Ti(\eta^5 - C_5 H_4 P R_2)]$ and $[(\eta^7 - C_7 H_6 P R_2)Ti(\eta^5 - C_5 H_4 P R_2)]$ C_5H_5] (R = Cy, 'Bu) as ancillary ligands. The formation of a dimeric μ chloro-, µ-allyl-bridged Pd(I) species was observed with the ligand $[(\eta^{7}-C_{7}H_{7})Ti(\eta^{5}-C_{5}H_{4}P^{t}Bu_{2})],$ whereas L₂Pd(0) (L = [(ŋ⁷- $C_7H_6P'Bu_2$)Ti($\eta^5-C_5H_5$)]) was formed in presence of KO'Pent. In addition, the catalytic activity of the palladium allyl chloride precatalysts was investigated in Buchwald-Hartwig amination reactions with various aryl halogenides and N-methylaniline or morpholine. The cyclohexyl derivatives show almost no catalytic activity, whereas for the tert-butyl derivatives a significant difference could be observed, depending whether the seven-membered ring or the five-membered ring is functionalized.

Introduction

Palladium-catalyzed cross-coupling reactions have been thoroughly investigated in the last few decades, and the Nobel Prize in Chemistry in 2010 was awarded in this sector.^[1-6] During this time, a large variety of ligand structures became established as ancillary ligands in the formation of C-C and C-heteroatom bonds.^[7-9] One concept is the use of mono- or bidentate tertiary phosphines as additional ligands for palladium.^[10-19] The catalytically active species can either be formed in situ by use of a palladium precursor such as Pd(OAc)₂ or Pd₂(dba)₃ and the ligand, or with pre-synthesized complexes with a well-defined palladium to ligand ratio. In Figure 1, a few examples of this great variety of ligands are shown. During investigations of Buchwald-Hartwig C-N coupling reactions, much effort was spent on the ligand tuning.^[20] For example Buchwald's dialkylbiaryl phosphanes (I) are intensively studied ligands.^[21-25] They show a broad range of potential functionalization patterns, for example the commercially available S-Phos (R' = OMe) ligand.^[26] With some of these ligands, air- and moisture-stable palladium(II) phenethylamine chloride complexes were obtained, which were easily activated and proved to be highly active in amination reactions.^[27] Also, 2-phosphino-N-arylpyrrole ligands of type II and related systems show high catalytic activity in amination reactions when combined with palladium precursors.[28-31]

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Figure 1. Examples of prominent ligands for cross-coupling reactions (I-III).

Moreover, sandwich compounds such as monoor difunctionalized ferrocene phosphanes, for example of type III (e.g. R = Ph, 1,1'-bis(diphenylphosphino)ferrocene, dppf), are prominent ligands in various cross-coupling reactions in combination with transition metals.^[11,32–37] In pre-formed systems, simple alkyl phosphanes (PR₃, R = ^{*i*}Pr, Cy, ^{*t*}Bu, etc.) can be used as ligands to form Pd(0) complexes of type [L₂Pd].^[12] Another widely used group of pre-formed catalysts in C-N coupling reactions are allyl palladium chloride complexes bearing monodentate phosphanes, for example trialkylphosphanes such as NpP(^{*i*}Bu)₂ (Np = neopentyl) in $IV^{[38]}$ or the air- and moisturesandwich complex Q-Phos (Q-Phos = 1,2,3,4,5stable pentaphenyl-1'-(di-*tert*-butyl-phosphino)ferrocene) (V) (Figure 2).^[39] This concept of using allyl palladium chloride complexes, or alternatively L₂Pd(0), also works well with N-heterocyclic carbenes (NHCs, VI), another frequently used ligand class in coupling reactions.[40-50]



Figure 2. Pre-formed palladium-based catalysts including phosphanes $(\mbox{IV-V})$ and NHCs $(\mbox{VI}).$

Recently, we introduced phosphane ligands with cyclohexyl and *tert*-butyl moieties based on $[(\eta^7-C_7H_7)Ti(\eta^5-C_5H_5)]$ (**1**, troticene) and its pentamethylated derivative $[(\eta^7-C_7H_7)Ti(\eta^5-C_5Me_5)]$ (**2**, pentamethyltroticene).^[51–53] This functionalization was described

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earlier in our group for the phenyl derivatives, and these complexes were investigated as ancillary ligands in bimetallic complexes with, e.g., platinum(II), gold(I), rhodium(I) or iridium(I).^[54,55] The complete series of six ligands, four troticene phosphane derivatives 3^R and 4^R and two pentamethyltroticene phosphane derivatives 5^R bearing electron-rich phosphanes with cyclohexyl or tert-butyl moieties (Scheme 1, top), turned out to be highly active in Suzuki-Miyaura cross-coupling reactions in combination with palladium acetate, even for sterically demanding substrates. This study revealed that there is only a small difference in the catalytic activity of the derivatives 4^R, functionalized at the seven-membered ring, and 3^R, those functionalized at the five-membered ring. Also, contrary to expectations, the use of the sterically bulkier pentamethylcyclopentadienyl derivatives 5^R had no significant impact. Using these ligands, the isolation of some Pd(0) species, i.e. $[Pd(4^{fBu})_2]$ and $[Pd(5^{fBu})_2]$, by the reaction of the ligand and Pd(OAc)₂ (Scheme 1, bottom) was realized. The reductive behaviour of the seven-membered ring was further investigated by the reaction of 1 and 2 towards palladium or silver acetate, and also silver triflate. In these reactions elemental palladium or silver was formed and the formation of ditropyl or a tropylium cation was observed.^[51,53]



Scheme 1. Troticenyl phosphane ligands (top) and Pd(0) complexes with ligand 4^{rBu} and 5^{rBu} (bottom).

Considering the properties of our ligands and with regard to the ferrocene phosphane complex Q-Phos, see^[39] we wish to demonstrate with this publication the of use of troticene phosphanes as ancillary ligands for well-defined palladium catalysts based on allyl palladium chloride complexes. We present their preparation, structural characterization and application in aryl amination reactions.



Results and Discussion

The desired allyl palladium chloride complexes were synthesized by combining toluene solutions of the troticenyl phosphane ligand and the allyl palladium chloride dimer. Ligand 3^{rBu} is an exception, and in this case the reaction was carried out in tetrahydrofuran (thf). After the indicated time, the reaction mixture was filtered and dried in vacuum. The complexes 6^{R} and 7^{R} (R = Cy, 'Bu) were isolated as blue or green crystalline or amorphous solids in high yields up to 95 % (Scheme 2).



Scheme 2. Synthesis of troticenyl phosphane allyl palladium chloride complexes 6^{R} and 7^{R} (R = Cy, 'Bu) and the derivatives 7^{rBu} 1Me, 7^{rBu} 2Me and 7^{rBu} 1Ph.

As a result of the catalyst screening discussed in the next chapter, the blue or green solids $7^{rBu}1Me$, $7^{rBu}2Me$ and $7^{rBu}1Ph$ were synthesized (by the general procedure given above) in high yields with varying functionalization at the allyl moiety (Scheme 2). All compounds were characterized by ¹H, ¹³C{¹H} and ³¹P{¹H} NMR spectroscopy, X-ray crystallography (except for 6^{rBu}) and elemental analysis (see the Supporting Information for experimental data).



Figure 3. ORTEP diagram of 7^{rBu} with thermal displacement ellipsoids drawn at 50% probability. Disorder was observed at the allyl moiety and only one position of this group is shown. Two additional deuterobenzene half-molecules in the asymmetric unit and hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: Ti–C_{Cht} 2.205(3)–2.262(2), Ti–C_{Cp} 2.330(2)–2.343(2), Ti–C_{Cht} 1.4942(4), Ti–C_{Cp} 2.0040(4), Pd–P 2.3577(5), Pd–Cl 2.3929(5), Pd–C21 2.121(5), Pd–C22 2.147(4), Pd–C23 2.197(4), Ct_{Cht}–Ti–Ct_{Cp} 168.87(3), C1–P–Pd 113.35(7), P–Pd–Cl 105.88(2).

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Figure 4. ORTEP diagrams of 7^{rBu}1Me, 7^{rBu}2Me, and 7^{rBu}1Ph (solvent omitted) with thermal displacement ellipsoids drawn at 50% probability. Hydrogen atoms are omitted for clarity.

	6 ^{су}	7 ^{/Bu}	7 ^{≇u} 1Me	7 ^{/Bu} 2Me	7 ^{tBu} 1Ph	7 ^{Cy}
Ti–C _{Cht}	2.203(2)-2.218(2)	2.205(3)-2.262(2)	2.2021(11)– 2.2358(10)	2.207(2)-2.246(2)	2.206(3)-2.221(2)	2.199(2)– 2.2343(14)
Ti–C _{Cp}	2.328(2)-2.349(2)	2.330(2)-2.343(2)	2.3247(11)– 2.3445(12)	2.328(2)- 2.334(2)	2.316(3)-2.344(2)	2.322(2)-2.337(2)
Ti–Ct _{Cht}	1.4881(4)	1.4942(4)	1.5133(2)	1.4865(3)	1.4952(4)	1.4963(3)
Ti–Ct _{Cp}	2.0029(4)	2.0040(4)	2.0000(2)	1.9974(3)	1.9948(4)	1.9995(3)
Pd–P	2.3148(5)	2.3577(5)	2.3512(3)	2.3591(4)	2.3449(6)	2.3089(4)
Pd–Cl	2.3672(5)	2.3929(5)	2.3915(3)	2.3994(4)	2.3665(6)	2.3665(4)
Pd-C21/25 ^[a]	2.129(2)	2.121(5)	2.111(2)	2.218(2)	2.137(3)	2.210(2)
Pd-C22/26 ^[a]	2.158(2)	2.147(4)	2.1741(14)	2.198(2)	2.166(3)	2.155(3)
Pd-C23/27 ^[a]	2.207(2)	2.197(4)	2.2614(14)	2.106(2)	2.263(3)	2.110(2)
Ct _{Cht} -Ti-Ct _{Cp}	175.41(3)	168.87(3)	166.043(14)	172.09(2)	170.21(3)	172.67(2)
C1-P-Pd	112.84(7)	113.35(7)	114.92(4)	113.43(6)	113.49(8)	117.42(4)
P-Pd-Cl	94.03(2)	105.88(2)	104.615(11)	104.881(15)	97.39(2)	96.94(13)

Table 1. Selected bond lengths [Å] and angles [°] of complexes 6^{cy}, 7^{rBu}, 7^{rBu}1Me, 7^{rBu}2Me, 7^{rBu}1Ph and 7^{cy}.

^[a] Number of the carbon atom depends on the functionalzation at the five- or seven-membered ring.

Depending on which ring is functionalized, the signals of 6^{R} and 7^{R} for the substituted ring split into two (2:2, C₅H₄) or three multiplets (2:2:2, C₇H₆) in the ¹H NMR spectra. The corresponding unsubstituted five- or seven-membered ring gives rise to a singlet (6^{R} : 5.1–5.8 ppm, 7^{R} : 5.1–6.5 ppm). The ¹H NMR spectra of 6^{Cy} and 7^{Cy} show typical multiplets for cyclohexyl moieties between 0.7 ppm and 2.5 ppm. The protons of the *tert*-butyl moiety of 6^{rBu} gives rise to a doublet at 1.2 ppm. In the case of 7^{rBu} and its derivatives 7^{rBu} 1Me, 7^{rBu} 2Me, and 7^{rBu} 1Ph, two doublets for the *tert*-butyl moiety in the ¹H NMR spectra could be observed at around 1.2–1.4 ppm. Remarkably, for those compounds, the signals for the *α*-protons of the seven-membered ring and the two

doublets of the *tert*-butyl moieties are very broad. The signals of the protons of the unsubstituted allyl moiety in the complexes 6^{rBu} , 6^{Cy} , 7^{rBu} and 7^{Cy} split into five multiplets with a splitting pattern of 1:1:1:1:1 in the range of around 2.2–5.1 ppm. For the substituted allyl moieties in 7^{rBu} 1Me, 7^{rBu} 2Me, and 7^{rBu} 1Ph, a multiplet for each hydrogen atom can be assigned in the same region. Furthermore, a multiplet at 1.83–1.78 ppm can be found for the methyl group of 7^{rBu} 1Me and a singlet for this group at 1.62 ppm for 7^{rBu} 2Me. The protons of the phenyl ring of 7^{rBu} 1Ph can be assigned in the aromatic region. In the $^{13}C{^{1}H}$ NMR spectrum of 6^{rBu} , the doublet of the α -carbon atom is very broad, whereas this signal cannot be assigned in the $^{13}C{^{1}H}$ NMR spectra of 7^{rBu} and

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its derivatives because of peak broadening.^[53] The sevenmembered ring gives rise to a characteristic singlet for 6^{rBu} and 6^{Cy} at around 88 ppm, whereas the signal of the five-membered ring of 7^{Cy} , 7^{rBu} and its derivatives can be assigned at a characteristic chemical shift of about 100 ppm. The ³¹P{¹H} NMR spectra show one singlet in each case, shifted ca. 30 ppm to lower field compared to the free ligand. For the complexes 6^{rBu} and 6^{Cy} , the signal for the phosphorus atom can be found at 60.2 ppm and 28.9 ppm, respectively. For 7^{Cy} , the phosphorus signal occurs at 59.6 ppm, and for 7^{rBu} and its derivatives, the signal can be found in the range of 93–98 ppm.

The complexes 6^{Cy}, 7^{Cy}, and 7^{tBu} and the derivatives 7^{tBu}1Me, 7^{tBu}2Me, and 7^{tBu}1Ph were additionally characterized by singlecrystal X-ray diffraction analysis. The structure of 7^{tBu} is shown in Figure 3, the structures of 7^{tBu}1Me, 7^{tBu}2Me, and 7^{tBu}1Ph in Figure 4. The structure of 7tBu contains two half-molecules of deuterobenzene (lying on twofold axes); 7^{tBu}1Ph includes half a molecule of toluene (disordered across an inversion center). The molecular structures of 6^{Cy} and 7^{Cy} are presented in the Supporting Information (Figures S26 and S27). Selected bond lengths and angles of all complexes are reported in Table 1. The solid-state structures of these complexes show Ti-Ct_{Cht} and Ti- Ct_{CD} (Ct = centroid) distances of around 1.5 Å and 2.0 Å, respectively. These values lie in the range of other heterobimetallic complexes with troticenyl phosphane ligands.^{[51-} ^{53]} Regarding the Ct_{Cht}–Ti–Ct_{Cp} angle, complex **7^{rBu}1Me** shows the highest deviation from 180° with 166.043(14)°. This value resembles the 166.6° in the ansa-troticenyl tin complex [{(n7- C_7H_6)Ti(η^5 - C_5H_4)}Sn^tBu₂],^[56] but is larger than in the ansatroticenyl silicon or germanium complexes [{(n7-C7H6)Ti(n5- C_5H_4)EMe₂] (E = Si, Ge) with 160.5° and 161.0°.^[57,58] With 175.41(3)°, 6^{Cy} shows the least bent troticenyl moiety. The bond lengths between the palladium atom and the carbon atoms of the allyl moiety reveal an ascending sequence. Hereby, the distance between Pd-C21 is the shortest and Pd-C23 is the longest. For the complexes 7^{fBu}2Me and 7^{Cy}, this order is reversed. Comparing these bond lengths for 7tBu and its derivatives, an increasing asymmetry from the unsubstituted allyl moiety in 7^{tBu} to the phenyl derivative 7^{tBu}1Ph occurs. This was also observed by Nolan and Colacot.^[39,59] However, allyl disorder in 7^{Cy}, 7^{tBu} and 7^{tBu}1Me means that the dimensions should be interpreted with caution. The molecular structures show no interaction between the Lewisacidic titanium center and the chloride atom.[60] Indeed, the chloride atom faces away from the titanium atom, except for complex 7^{tBu}1Ph. Nevertheless, even in this case the distance is too large for any interaction (Ti...Cl 4.131(1) Å). Attempts to crystallize 6^{tBu} have failed so far, because of further reaction to the dimeric μ -chloro-, μ -allyl-bridged Pd(I) species 8 (Scheme 3). Complexes of this type can usually be formed by the a comproportionation reaction of [Pd(allyl)Cl]₂ with L₂Pd(0)^[61,62] or from the reaction of the allyl palladium chloride pre-catalyst with a base.^[39,63] These Pd(I) complexes show less catalytic activity in amination reactions and are formed after activation of the catalyst prior to the oxidative addition.[64]



Figure 5. ³¹P(¹H) NMR spectrum, recorded over 30 days, showing the conversion of 6^{reau} to the dimeric Pd(I) complex 8.

Investigations of the reactivity of 6^{tBu} showed that addition of a base is not necessary. Complex 8 can be synthesized by the reaction of 3^{rBu} with [Pd(allyl)Cl]₂ in toluene with a prolonged reaction time of up to three days. Also, ¹H and ³¹P{¹H} NMR experiments (Figure 5; see the Supporting Information, Figure S19, for ¹H NMR spectra) revealed a continuous transformation of complex 6^{rBu} over 30 days to the dimeric complex 8. The signal of 6^{rBu} can be found at 60.2 ppm; after 18 h, a new signal starts to form at 59.9 ppm. Over the following days, the signal of 6^{rBu} decreases, and after 30 days, only the new signal can be observed. This slight difference in the NMR shift was also observed by Colacot for other dimeric Pd(I) species with phosphane ligands.[39] The formation of allyl chloride was not detected during the NMR screening experiments. Performing the same experiments with the other allyl palladium chloride complexes 6^{Cy}, 7^{tBu}, and 7^{Cy} showed no formation of dimeric Pd(I) complexes. Stirring these complexes for three days in toluene revealed no decomposition products or further reactions.



Scheme 3. Formation of the μ -chloro-, μ -allyl-bridged palladium(I) species 8.

The molecular structure of compound **8** is shown in Figure 6. The Pd1–Pd2 bond length of 2.6571(2) Å is comparable to similar compounds.^[39] The molecular structure reveals that this compound is not symmetric; the troticenyl moieties are differently arranged. The Ct_{Cht1} –Ti1–Ct_{Cp1} moiety shows a greater deviation

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from 180° than the Ct_{Cht2} -Ti2- Ct_{Cp2} moiety (168.54(3)°, 173.15(3)°).



Figure 6. ORTEP diagram of 8 with thermal displacement ellipsoids drawn at 50% probability. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: Ti1–C_{cht1} 2.210(3)–2.245(3), Ti1–C_{Cp1} 2.335(3)–2.397(2), Ti1–C_{Cch1} 1.5116(4), Ti1–Ct_{Cp1} 2.0262(4), Ti2–C_{Ch2} 2.199(3)–2.2333(3), Ti2–C_{Cp2} 2.320(3)–2.353(2), Ti2–C_{Ch12} 1.4904(4), Ti2–C_{Cp2} 2.0041(4), C8–P1 1.826(2), C28–P2 1.828(2), P1–Pd1 2.3067(6), P2–Pd2 2.3262(6), Pd1–Pd2 2.6571(2), Pd1–C41 2.044(2), Pd1–C42 2.367(2), Pd2–C42 2.402(3), Pd2–C43 2.055(2), Ct_{Ch11}–Ti1–Ct_{Cp1} 168.54(3), Ct_{Ch12}–Ti2–Ct_{Cp2} 173.15(3), P1–Cl–P2 66.06(2).

Catalytic Amination of Aryl Halides. Given the known ability of the ligands **3**^R and **4**^R (R = Cy, ^{*i*}Bu) to act as ancillary ligands in Suzuki-Miyaura coupling reactions,^[51,53] we were interested in the catalytic activity of the new complexes **6**^R and **7**^R (R = ^{*i*}Bu, Cy) in Buchwald-Hartwig amination reactions. For these investigations, the coupling of 4-bromotoluene and *N*-methylaniline was chosen as a model reaction (Scheme 4).



Scheme 4. Model reaction for the amination of aryl halides.

In an initial screening with toluene as solvent, KO'Bu as base, 1 mol% catalyst loading and a temperature of 60 °C, the catalytic activity of complexes 6^{tBu}, 6^{Cy}, 7^{tBu} and 7^{Cy} was investigated (Table 2, Supporting Information Figure S29). Additionally, under these conditions [Pd(allyl)Cl]2 was tested, as was the unanalyzed reaction. The cyclohexyl derivatives 6^{Cy} and 7^{Cy} showed no significant improvement over the exclusive use of [Pd(allyl)Cl]2 and gave only 6 % GC conversion, respectively 11 %. For the tertbutyl derivative 6^{rBu} almost full conversion was observed after 4 h, whereas full conversion was obtained for 7^{tBu} after 2 h. The difference in the catalytic activity may occur through the dimerization of 6^{rBu} as previously discussed. The system Pd(OAc)₂/4^{tBu} (ratio 1:2) which is highly active in Suzuki-Miyaura coupling reactions^[53] was tested under the conditions used in the recent study for comparison, showing almost no catalytic activity in amination reactions. Since 7^{tBu} showed the highest catalytic activity, this complex was chosen for an extensive screening of the reaction conditions. This screening of various bases, solvents, temperatures and catalyst loadings for 7^{rBu} showed the optimum performance using potassium *tert*-pentoxide in toluene (see Supporting Information Table S2–S6). The temperature screening revealed shorter reaction times with rising reaction temperatures. With 60 °C, a suitable compromise between fast reaction and moderate temperature was achieved. Using these optimized conditions, 100 % GC conversion was observed after 45 min for 7^{rBu} . Screening of the catalyst loading showed that 0.5 mol% is sufficient, using 2 mL of toluene at 60 °C.

entry	catalyst	time [h]	GC yield [%]	
1	6 ^{Cy}	6	6	
2	6 ^{#Bu}	4	98	
3	7 ^{Cy}	6	11	
4	7 ^{#Bu}	2	100	
5	[Pd(allyl)Cl] ₂	6	6	
6	no catalyst	6	2.5	
7[a]	Pd(OAc) ₂ / 4 ^{<i>t</i>Bu} (1:2)	6	8	

Table 2. Evaluation of various catalysts in a model reaction study.

Reaction conditions: 4-bromotoluene (1.6 mmol), *N*-methylaniline (2.0 mmol), KO'Bu (2.4 mmol), catalyst (0.016 mmol, 1 mol%), *n*-decane (0.16 mmol, 1.0 mol%, 31 μ L), toluene (2 mL), T = 60 °C. [a] KOH as base.

Under the same conditions, the complexes 7^{rBu} **1Me**, 7^{rBu} **2Me** and 7^{rBu} **1Ph** were also investigated, revealing that 7^{rBu} still shows the highest catalytic activity, closely followed by 7^{rBu} **1Me** (Figure 7), reaching full conversion after 45 min. Even in the first minute, around 60 % conversion for 7^{rBu} and 69 % GC conversion for 7^{rBu} **1Me** were observed.



Figure 7. Comparison of the complexes **7**^{rBu} and its derivatives **7**^{rBu}**1Me**, **7**^{rBu}**2Me**, and **7**^{rBu}**1Ph** as pre-catalysts for the coupling of 4-bromotoluene with *N*-methylaniline. Reaction conditions: 4-bromotoluene (1.6 mmol), *N*-methyl aniline (2.0 mmol), KO'Pent (2.4 mmol), catalyst (0.008 mmol, 0.5 mol%), *n*-decane (0.16 mmol, 10 mol%, 31 µL), toluene (2 mL), T = 60 °C.

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The pre-catalysts **7^{rBu}2Me** and **7^{rBu}1Ph** achieved nearly full conversion after 2 h. They also exhibit an almost identical catalysis progress. With these complexes, the initiation phase

takes longer and only 7 % (7^{fBu}2Me) or 14 % (7^{fBu}1Ph) GC conversion were observed after the first minute, respectively.

Table 3. Amination of aryl bromides and chlorides with N-methylaniline or morpholine using 7 ^{/Bu} .							
entry	ArX	Х	product	t [h]	T [°C]	GC conversion/ isolated yield [%]	
1		Br		0.75	60	100 / 97	
2	×	CI	\square	7	100	100 / 94	
3 ^[a]		Br	N N N	16	60	100 / 96	
4		Br		6	60	99.7 / 91	
5 ^[a]	o X	CI		16	100	100 / 92	
6 ^[a]		Br	N N	22	60	100 / 96	
7 ^[a]		CI	0	24	100	100 / 94	
8	F ₃ C X	Br	F ₃ C	0.05	60	100 / 92	
9 ^[a]	NC	Br	NC	6	80	90 ^[b] / 80	

Aryl halide (1.6 mmol), amine (2.0 mmol), KO⁽Pent (2.4 mmol), **7^{8u}** (0.008 mmol, 0.5 mol%), *n*-decane (0.16 mmol, 10 mol%, 31 µL) as internal standard, toluene (2 mL). ^[a] catalyst loading 1.0 mol%. ^[b] After 8 h no further conversion was observed.

The most active pre-catalyst 7^{tBu} was then applied for the screening of various substrates (Table 3). Therefore, *N*-methylaniline and morpholine in combination with several aryl bromides and chlorides were investigated. In some cases, the reaction conditions had to be slightly modified. For 4-chlorotoluene, full conversion could be obtained after 7 h at 100 °C (entry 2). For the coupling of 4-bromotoluene with morpholine, full conversion was reached after 16 h at 60 °C with 1 mol% catalyst loading (entry 3). Using the deactivated 4-bromoanisole, the reaction time was increased to 6 h for *N*-methylaniline and 1 mol% catalyst loading and 22 h for morpholine (entry 4 and 6). For 4-chloroanisole and *N*-methylaniline or morpholine, the reaction temperature was

increased to 100 °C and 1 mol% catalyst loading, resulting in full conversion after 16 h and 24 h, respectively (entry 5 and 7). For the electronically activated 1-bromo-4-(trifluoromethyl)benzene only 3 minutes were necessary to achieve full conversion (entry 8). Finally, 4-bromobenzonitrile was tested; 6 h at 80 °C and 1 mol% resulted in 90 % GC conversion (entry 9). The investigations showed that no further conversion was achieved by a longer reaction time in this case, indicating deactivation of the catalyst. The isolated yields of the coupling reactions range between 80 % for 4-bromobenzonitrile and up to 97 % for 4-bromotoluene. Regarding the catalytic performance, it should be mentioned that complex **7**^{rBu} cannot compete with other preformed phosphane based catalysts, which show higher activities

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at lower temperatures.^[38,39] Since the ligands **3**^R, **4**^R and **5**^R (R = 'Bu, Cy) show high catalytic activity in combination with Pd(OAc)₂ in Suzuki-Miyaura reactions,^[51,53] the pre-formed catalysts **7**^R (R = 'Bu, Cy) were also tested in C–C coupling reactions in combination with KO'Pent (Table 4). Under these reaction conditions, only moderate conversions after 8 h at 100 °C were obtained, showing the high influence of the palladium source and the importance of a thorough screening of the reaction conditions.

Table 4. Suzuki-Miyaura Coupling	with 7 ^c	and 7 ^{tBu}	using phenyl	bromide	and
phenyl boronic acid.					

entry	cat.	ArX	product	t [h]	T [°C]	GC [%]
1	7 ^{су}	Br		0	100	89 ^[a]
2	7 ^{tBu}			8	100	77 ^[a]

Phenyl bromide (1.6 mmol), PhB(OH)₂ (2.0 mmol), KO⁽Pent (2.4 mmol), cat. (0.008 mmol, 0.5 mol%), *n*-decane (0.16 mmol, 10 mol%, 31 µL), toluene (2 mL). ^[a] not selective.

Mixing the catalytic reactions, the substrate mixture turns dark red for the first 30 to 60 s after addition of the pre-catalyst **7^{fBu}** or its derivatives. After this time the color lightens to a dark yellow. For the cyclohexyl derivatives, this color change was not observed. In addition, reactions with substrates such as aniline, which could not be successfully coupled, show no color change (see Supporting Information Table S7). To obtain more insight into the color changes, an NMR experiment was conducted. The pre-catalyst **7^{rBu}** was reacted with the base in toluene at room temperature, resulting in a dark red mixture. The ³¹P{¹H} NMR spectrum revealed four signals after two hours, which can be assigned to the complex itself at 93.1 ppm, free ligand at 67.2 ppm and two new signals at 91.7 ppm and 83.2 ppm.



Scheme 5. Reaction of 7^{tBu} with KO^tPent.

After 24 h, only the resonance at 91.7 ppm and the signal of the starting material at 93.1 ppm can be observed. The first signal seems to indicate the formation of a $[(L)_2Pd_2-(\mu-CI)(\mu-C_3H_5)]$ species similar to complex **8**, but the signals in the ¹H NMR spectrum demonstrate that the Pd(0) species $[Pd(4^{fBu})_2]$ was formed instead, showing the characteristic broad signal for the

tert-butyl moieties (Scheme 5; see the Supporting Information for the NMR spectra after 24 h).^[53]

Conclusions

A series of complexes of the type [(L)Pd(R-allyl)Cl) (L = 3^{fBu}, 3^{Cy}, 4^{Cy} R = H; 4^{rBu} R = H, 1Me, 2Me, 1Ph) have been synthesized and characterized and their catalytic potential in C-N coupling reactions investigated. The screening demonstrated that the tertbutyl derivatives, especially 7^{tBu}, are highly active, while the cyclohexyl derivatives are almost inactive pre-catalysts. Modifying the allyl moiety showed no significant improvement of the catalytic activity compared to the unsubstituted allyl group. Further studies revealed that complex 6^{rBu} forms the dimeric species [(L)₂Pd₂-(µ-CI)(μ -C₃H₅)] 8 without external influence, which reveals again the reductive potential of the cycloheptatrienyl moiety. Mechanistic investigations show the formation of the Pd(0) species [Pd(4^{tBu})₂], already observed in recent studies. In further studies, the influence of sterically more demanding cyclopentadienyl groups as Cp* or even Ph₅Cp, which would be an analog to the ferrocene phosphane Q-Phos,[33] will be investigated. This motif might lead to less air- and moisture-sensitive ligands and would be an interesting approach.

Experimental Section

Below some general synthetic protocols are shown. For full experimental details see the Supporting Information.

General Procedures for the synthesis of the allyl palladium chloride complexes 6^R and 7^R (R = Cy, 'Bu).

Method A. A solution of the ligand (2 equiv.) in 2 mL of toluene was added to a solution of $[Pd(R-allyl)Cl]_2$ (1 equiv.) in 2 mL of toluene at room temperature. After stirring for 2 h the solution was filtered and the solvent reduced to 0.5 mL, whereupon a blue crystalline solid formed. After 1 h at -40 °C, the clear supernatant solution was removed and the crystalline solid washed with *n*-pentane (2 x 3 mL). After drying in vacuum, the product was obtained as a crystalline solid.

Method B. A solution of the ligand (2 equiv.) in 2 mL of toluene was added to a solution of $[Pd(R-allyl)Cl]_2$ (1 equiv.) in 2 mL of toluene at room temperature. After stirring for 2 h the solution was filtered and the solvent reduced to 0.5 mL. The compound was precipitated with 2 mL of *n*-pentane. The supernatant solution was removed and the remaining solid washed with *n*-pentane (2 x 3 mL). After drying in vacuum, the product was obtained as a solid.

General Procedure for the Buchwald-Hartwig coupling reactions – isolated yield.

In a glove box an oven-dried Schlenk tube was charged with anhydrous base (2.4 mmol, 1.5 equiv.) and the aryl halide (1.6 mmol, 1.0 equiv.) if solid. The amine (2.0 mmol, 1.3 equiv.), *n*-decane (31 μ L, 0.16 mmol) and the aryl halide (if liquid) were mixed in 1 mL of solvent and added to the Schlenk tube. The reaction vessel was taken out of the glove box, furnished with a new Suba Seal® septum on a Schlenk line, placed in a pre-heated oil bath (except for room temperature studies) and stirred for 5 min under constant argon flow. The catalyst in 1 mL of solvent, prepared in the glove box, was added to the reaction mixture by syringe. After the

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indicated time, the reaction mixture was filtered over a small pad of silica gel, the solvent evaporated in vacuum and the crude product was purified by column chromatography over silica gel, eluted with hexane/ethyl acetate (90/10).

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Keywords: C–N coupling • palladium • sandwich complexes • phosphane ligands • titanium

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Palladium allyl chloride complexes containing troticenyl phosphane ligands [(η^{7} -C₇H₇)Ti(η^{5} -C₅H₄PR₂)] and [(η^{7} -C₇H₆PR₂)Ti(η^{5} -C₅H₅)] (R = Cy, 'Bu) as ancillary ligands were prepared and used as pre-catalysts for Buchwald-Hartwig amination reactions.

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Allyl Palladium Complexes of Cycloheptatrienyl-Cyclopentadienyl Phosphane Ligands in Buchwald-Hartwig Amination Reactions