EurJIC
European Journal of Inorganic Chemistry

A Journal of ChemPubSoc Europe

Accepted Article

Title: New Titanium Complexes and Their Use in Hydroamination and Hydroaminoalkylation Reactions

Authors: Jens Bielefeld, Ekaterina Kurochkina, Marc Schmidtmann, and Sven Doye

To be cited as: *Eur. J. Inorg. Chem.* 10.1002/ejic.201900586

Link to VoR: http://dx.doi.org/10.1002/ejic.201900586

WILEY-VCH

10.1002/ejic.201900586

WILEY-VCH

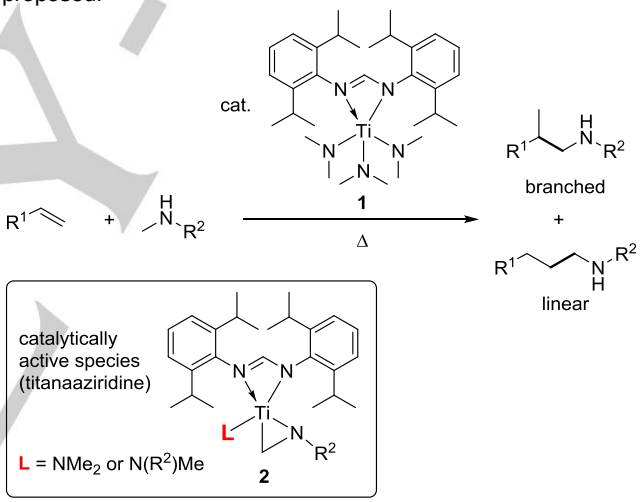
New Titanium Complexes and Their Use in Hydroamination and Hydroaminoalkylation Reactions

Jens Bielefeld,[a] Ekaterina Kurochkina,[a] Marc Schmidtmann,[a] and Sven Doye*[a]

Abstract: The synthesis of three new sterically crowded titanium complexes which all possess an identical formamidinato ligand, two dimethylamido ligands and in addition, a 2-aminopyridinato ligand that contains either an *N*-methyl, an *N*-phenyl, or an *N*-cyclohexyl substituent is presented. All new complexes are easily accessible from a common titanium mono(formamidinate) precursor and correspondingly *N*-substituted 2-aminopyridines. Furthermore, the new complexes are used as catalysts for selected hydroamination and hydroaminoalkylation reactions and finally, the catalytic performance of the new catalysts is compared with the performance of the titanium mono(formamidinate) precursor.

Introduction

Eisen´s titanium mono(formamidinate) complex **1**[1] (Scheme 1) has previously been reported as a highly active hydroaminoalkylation[2-5] catalyst that converts secondary amines and simple 1-alkenes (R^1 = alkyl) into branched hydroaminoalkylation products with high selectivity while on the other hand, corresponding reactions of styrenes (R^1 = aryl) usually give mixtures of a branched and a linear product. From a mechanistic point of view,[6] it is generally accepted that the catalytically active species of hydroaminoalkylation reactions are titanaaziridines[7] (Scheme 1) possessing two spectator ligands which do not participate in the catalytic reaction but determine the activity as well as the selectivity of the catalyst. The fact that the regioselectivity-determining step of the catalytic cycle is the insertion of the alkene substrate into the titanium carbon bond of the titanaaziridine suggests that increasing steric hindrance around the titanium center should favor the formation of branched hydroaminoalkylation products. Interestingly, in the case of mono(formamidinate) catalyst **1**, the expected catalytically active species would be titanaaziridine **2** (Scheme 1) which bears one formamidinato ligand and an additional ligand L [L = NMe_2 or $N(R^2)Me$] as the spectator ligands. Because the latter ligand L offers a promising possibility to further fine-tune the performance of the catalytic system, we recently decided to synthesize a number of derivatives of **1** in which one of the NMe_2-ligands is selectively replaced by a chelating aminopyridinato ligand.[8] In this context, it must be mentioned that our decision to focus on this type of ligands was based on the fact that aminopyridinato titanium complexes have already been used as highly active and selective catalysts for hydroaminoalkylation reactions of alkenes, styrenes and 1,3-butadienes.[9] Furthermore, it was expected that a sterically more congested titanium center would generally lead to a stronger preference for the formation of branched hydroaminoalkylation products.[6,7] However, while all these expectations are based on the assumption that the catalytically active species are monomeric it should be mentioned that hyroaminoalkylation reactions with dimeric catalytic species have also been proposed.[10]



Scheme 1. Hydroaminoalkylation of alkenes catalyzed by the titanium mono(formamidinate) complex **1**.

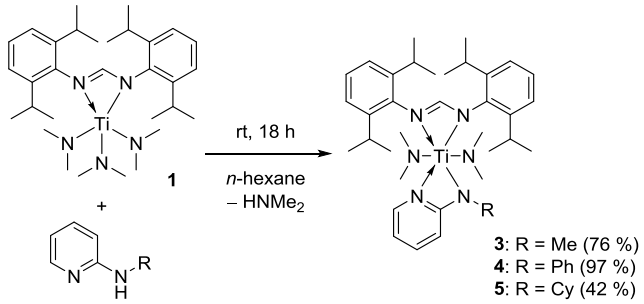
Results and Discussion

During initial attempts to replace one of the NMe_2-ligands of **1** by aminopyridinato ligands it was found that the synthesis of corresponding complexes could easily be achieved from **1** and sterically less demanding aminopyridnes such as *N*-methyl-2-aminopyridine, *N*-phenyl-2-aminopyridine, or *N*-cyclohexyl-2-aminopyridine (Scheme 2). In all these cases, the aminopyridines were simply added to a suspension of **1** in *n*-hexane and after stirring at room temperature for 18 hours, the desired new titanium complexes **3**-**5** could be isolated in yields between 42 % and 97 % by simple filtration. Subsequently, crystals of **3**-**5** suitable for X-ray single-crystal analysis could be obtained by recrystallization from toluene. On the other hand, corresponding reactions with sterically more demanding *N*-*tert*-butyl-2-aminopyridine or 2,6-di(phenylamino)pyridine failed because in these cases, the formamidinato ligand of **1** did not

[a] M. Sc. J. Bielefeld, M. Sc. E. Kurochkina, Dr. M. Schmidtmann, Prof. Dr. S. Doye
Institut für Chemie
Universität Oldenburg
Carl-von-Ossietzky-Straße 9-11, 26129 Oldenburg (Germany)
E-mail: doye@uni-oldenburg.de
Homepage: https://uol.de/oc-doye/

Supporting information for this article is given via a link at the end of the document.

stay bonded to the titanium center and as a result, *N*,*N'*-bis(2,6-diisopropylphenyl)formamidine precipitated from the reaction mixtures.



Scheme 2. Synthesis of new titanium complexes from **1** and 2-aminopyridines.

As can be seen from Figures 1-3, the solid state structures of **3**-**5** reveal similarly distorted octahedral geometries around the titanium centers. The three complexes **3**, **4** and **5** are not only very similar to each other in terms of Ti−N bond lengths and angles, but also correlate to the already known structure of their precursor **1**. In the case of **1**, the distances between the formamidine nitrogen atoms and the titanium center were reported to be 2.1847 Å and 2.2926 Å while for the three remaining dimethylamido ligands an average Ti−N distance of 1.9073 Å was found.[1] For the complexes **3** and **5**, a slight tilt of the formamidinato ligand compared to **1** is observed [Ti−N1 is shorter by 0.031 Å (**3**) / 0.011 Å (**5**); Ti−N2 is longer by 0.004 Å (**3**) / 0.010 Å (**5**)]. For complex **4**, both Ti−N bond lengths are slightly shorter compared to **1** [Δ(Ti−N1) = −0.031 Å, Δ(Ti−N2) = −0.015 Å], which hints at a significant electronic influence of the phenyl substituent of the aminopyridinato ligand. Finally, it can be mentioned that for the new complexes **3**-**5**, the Ti−N bond lengths of the dimethylamido ligands are not significantly changed compared to **1**.

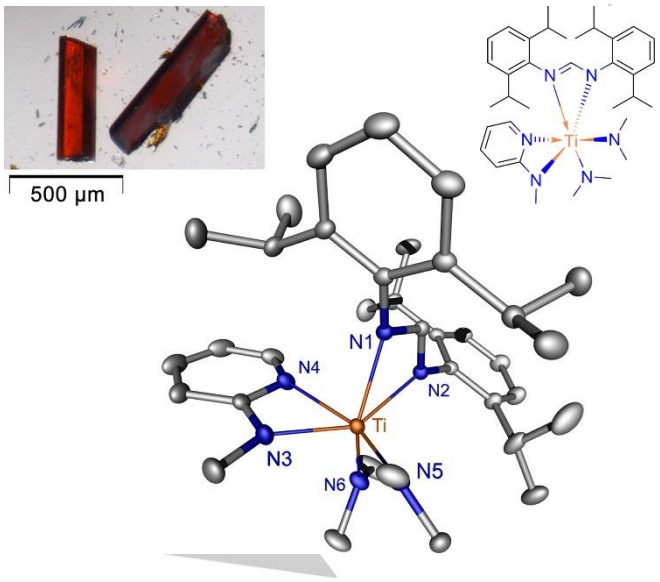


Figure 1. New complex **3**[11] bearing one *N*-methyl-2-aminopyridinato ligand. Hydrogen atoms are omitted for clarity. Selected bond lenghts (Å) and angles (°): Ti−N1 2.2530(7), Ti−N2 2.1887(6), Ti−N3 2.0420(8), Ti−N4 2.2951(10), Ti−N5 1.9135(7), Ti−N6 1.9077(9), N1−Ti−N3 98.02(3), N1−Ti−N4 89.83(3), N5−Ti−N6 96.62(4).

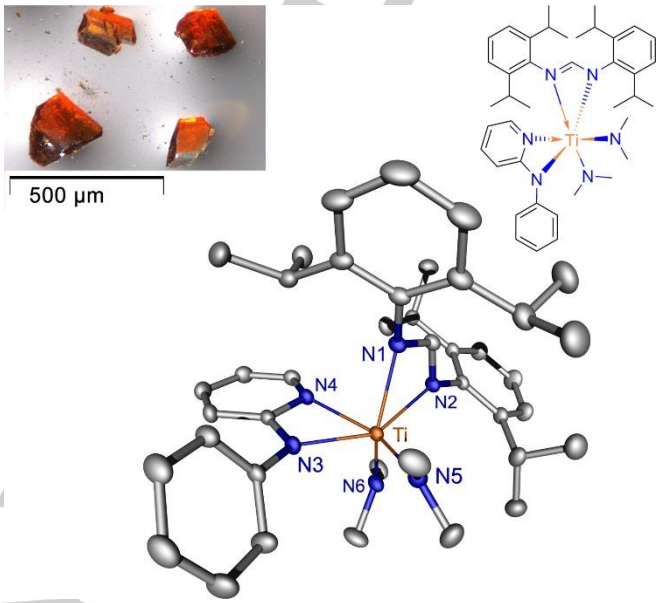


Figure 2. New complex **4**[11] bearing one *N*-phenyl-2-aminopyridinato ligand. Hydrogen atoms are omitted for clarity. Selected bond lenghts (Å) and angles (°): Ti−N1 2.2619(8), Ti−N2 2.1695(6), Ti−N3 2.0676(7), Ti−N4 2.2866(8), Ti−N5 1.9050(7), Ti−N6 1.9060(8), N1−Ti−N3 98.78(3), N1−Ti−N4 88.16(3), N5−Ti−N6 101.75(3).

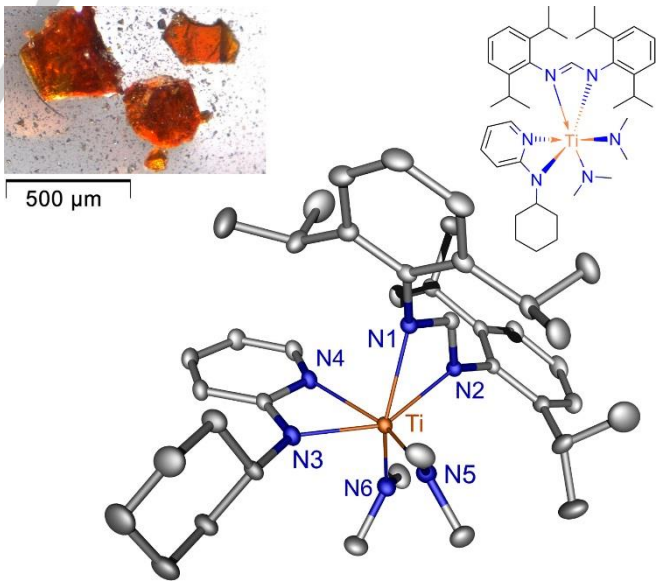
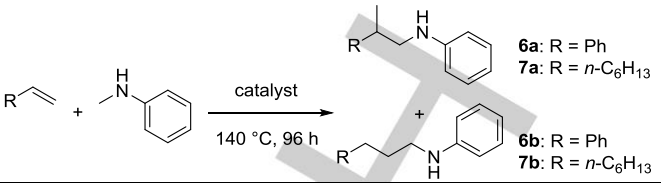


Figure 3. New complex **5**[11] bearing one *N*-cyclohexyl-2-aminopyridinato ligand. Hydrogen atoms are omitted for clarity. Selected bond lenghts (Å) and angles (°): Ti−N1 2.2812(8), Ti−N2 2.1944(7), Ti−N3 2.0374(7), Ti−N4 2.2496(9), Ti−N5 1.9211(9), Ti−N6 1.9111(9), N1−Ti−N3 100.00(3), N1−Ti−N4 87.14(3), N5−Ti−N6 99.32(4).

With sufficient quantities of **3**-**5** in hand, we then used the new complexes as catalysts for the hydroaminoalkylation of styrene with *N*-methylaniline (Table 1, entries 1-4) and compared the corresponding results with the outcome of a control experiment performed with catalyst **1**. All reactions were performed under identical conditions with a catalyst loading of 10 mol% at 140 °C in *n*-hexane in sealed Schlenk tubes. First of all, it could be confirmed that as mentioned above, complex **1** is a highly active catalyst that delivers the regioisomeric hydroaminoalkylation products **6a** and **6b** in excellent combined yield of 92 % (Table 1, entry 1). On the other hand, only a modest regioselectivity of 77:23 in favor of the branched product **6a** was achieved with this catalyst. Unfortunately, this severe drawback could not be overcome by the use of the sterically more crowded new catalysts **3**-**5** which all delivered mixtures of the regioisomeric products **6a** and **6b** in a worse ratio of only 60:40. In addition, catalysts **3**-**5** turned out to be significantly less active than **1** and as a result, only reduced combined yields between 21 % and 63 % were obtained with these catalysts. A possible explanation for the latter observation could be the sterically more demanding bidentate nature of the aminopyridinato ligands of **3**-**5** compared to the relatively small monodentate dimethylamido ligand of **1** because additional steric hindrance of the catalytically active species could slow down one or even more steps in the catalytic cycle of the overall hydroaminoalkylation reaction. In this context, it should be mentioned again that the catalytically active species is expected to be a titanaaziridine of type **2** (Scheme 1) with ligand L being a small dimethylamido or a bulky aminopyridinato ligand. The decreased regioselectivity observed with **3**-**5** suggests that the expected simple effect of an increased steric hindrance around the titanium center, which should favor the formation of branched hydroaminoalkylation products, must be overcompensated by an additional effect. In this context, it should be mentioned that titanium catalysts possessing only aminopyridinato ligands have already been reported to preferably convert styrenes into linear hydroaminoalkylation products.[9] During additional hydroaminoalkylation experiments performed with 1-octene as an example of an alkyl-substituted 1-alkene (Table 1, entries 5-8) it was then found that in this case, the performance of the catalysts **1**, **3**, **4**, and **5** does not differ significantly. In particular, the excellent regioselectivities of the reactions in favor of the branched hydroaminoalkylation product **7a** remain almost unchanged and as a result, only **7a** could be isolated in pure form from these experiments in good yields. These results are in good agreement with the well-established reactivity of alkyl-substituted 1-alkenes which are known to generally deliver branched hydroaminoalkylation products with excellent regioselectivities in the presence of early transition metal catalysts.[2] In addition, the fact that alkyl-substituted alkenes react more smoothly than styrenes[2] offered the possibility to run the hydroaminoalkylation reactions of 1-octene with a reduced catalyst loading of only 2.5 mol%.

Table 1. Hydroaminoalkylation of alkenes.

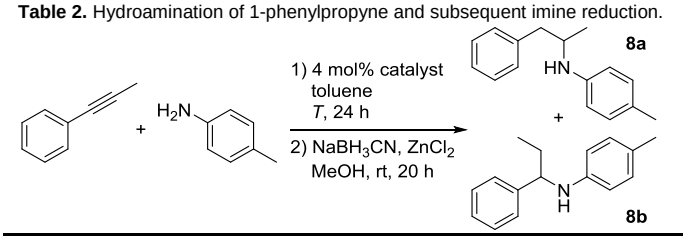


Entry	R	Catalyst (mol%)	Yield [%]	Regioselectivity [**a**/**b**][c]
1[a]	Ph	**1** (10)	92[d]	77:23
2[a]	Ph	**3** (10)	21[d]	60:40
3[a]	Ph	**4** (10)	63[d]	60:40
4[a]	Ph	**5** (10)	49[d]	60:40
5[b]	*n*-C_6H_{13}	**1** (2.5)	84[e]	98:2
6[b]	*n*-C_6H_{13}	**3** (2.5)	73[e]	98:2
7[b]	*n*-C_6H_{13}	**4** (2.5)	83[e]	97:3
8[b]	*n*-C_6H_{13}	**5** (2.5)	82[e]	97:3

[a] Reaction conditions: *N*-methylaniline (214 mg, 2.0 mmol), styrene (312 mg, 3.0 mmol), catalyst (10 mol%, 0.2 mmol), *n*-hexane (1 mL), 140 °C, 96 h. [b] Reaction conditions: *N*-methylaniline (21 mg, 0.2 mmol), 1-octene (31 mg, 0.3 mmol), catalyst (2.5 mol%, 0.005 mmol), toluene (0.1 mL), 140 °C, 96 h. [c] The regioselectivity **a**/**b** was determined by GC-analysis prior to chromatography. [d] Isolated yield of **6a** + **6b**. [e] Isolated yield of **7a**.

Because sterically more demanding titanium catalysts were often found to offer significant advantages over sterically less hindered catalysts in hydroamination reactions of alkynes,[12,13] we then turned our attention towards a corresponding reaction. In this context, it must also be mentioned that Schafer and Kempe et al. have already identified a titanium mono-aminopyridinato complex as a good hydroamination catalyst.[14] During our study, 1-phenylpropyne was reacted with *para*-toluidine (Table 2) in the presence of 4 mol% of one of the catalysts at temperatures of 60 °C or 80 °C and subsequently, in each case, the initially formed imines were directly reduced with mixtures of $NaBH_3CN$ and $ZnCl_2$ to give the regioisomeric secondary amines **8a** and **8b**. With regard to the latter reaction step, it should be mentioned that the only purpose of the reduction was to facilitate the work-up procedure and the final isolation of the products.

Table 2. Hydroamination of 1-phenylpropyne and subsequent imine reduction.



Entry	Catalyst	*T* [°C]	Yield [%][a]	Regioselectivity [**8a**/**8b**][b]
1	**1**	60	78	97:3
2		80	90	95:5
3	**3**	60	52	> 99:1
4		80	87	98:2
5	**4**	60	50	> 99:1
6		80	88	> 99:1
7	**5**	60	28	> 99:1
8		80	85	> 99:1

[a] Reaction conditions: 1) 1-phenylpropyne (279 mg, 2.4 mmol), *p*-toluidine (283 mg, 2.6 mmol), catalyst (4 mol%, 0.1 mmol), toluene (1 mL), 60 or 80 °C, 24 h; 2) sodium cyanoborohydride (302 mg, 4.8 mmol), zinc chloride (327 mg, 2.4 mmol), methanol (10 mL), room temperature, 20 h. Isolated yield of **8a** + **8b**. [b] The regioselectivity **8a**/**8b** was determined by GC-analysis prior to chromatography.

As can be seen from Table 2, mono(formamidinate) complex **1** again turned out to be the most active catalyst. However, while this advantage of **1** over the new catalysts **3**-**5** was most significant at a reaction temperature of 60 °C, the hydroamination reactions performed at 80 °C delivered the products **8a** and **8b** in comparable combined yields between 85 % and 90 % with all four catalysts. Interestingly, with regard to selectivity, the use of the new catalysts **3**-**5** offers the advantage of an improved regioselectivity. For example, at 80 °C, the regioisomeric products **8a** and **8b** were obtained in a ratio of only 95:5 with catalyst **1** (Table 2, entry 2) while the sterically mostly crowded new catalysts **4** and **5** gave almost perfect regioselectivities of more than 99:1 (Table 2, entries 6 and 7).

Conclusions

In summary, we have presented the synthesis of three new sterically crowded titanium complexes which all possess an identical formamidinato ligand, two dimethylamido ligands and in addition, a 2-aminopyridinato ligand that contains either an *N*-methyl, an *N*-phenyl, or an *N*-cyclohexyl substituent. All new complexes were easily formed at room temperature from Eisen´s titanium mono(formamidinate) complex **1** and correspondingly *N*-substituted 2-aminopyridines. Although the solid state structures of the new complexes are very similar to each other, their catalytic performance in hydroamination and hydroaminoalkylation reactions slightly differs. Most importantly, the best regioselectivities for the intermolecular hydroamination of 1-phenylpropyne with *para*-toluidine could be achieved with the sterically mostly crowded new catalysts. Overall, we have presented a very simple and cheap method for the derivatization of a catalyst which might prove useful for altering the selectivity of other highly active catalysts in the future, whenever dimethylamido spectator ligands are present in the catalyst.

Experimental Section

General information: For all syntheses of titanium complexes and their use in catalytic reactions, solvents were dried by refluxing over sodium and degassed. NMR spectra were recorded on a Bruker Fourier 300, Bruker Avance DRX 500 or Bruker Avance III 500 MHz. ^{1}H NMR spectra are referenced to the solvent (7.26 ppm for $CDCl_3$). ^{13}C NMR spectra are referenced to the solvent (77.16 ppm for $CDCl_3$ or 128.06 ppm for C_6D_6). Infrared spectra were recorded on a Bruker Vector 22 spectrometer. MS and HRMS analyses were performed on a Waters Q-TOF Premier (ESI+, TOF). GC analyses were performed on a Shimadzu GC-2010 gas chromatograph (column: FS-SE-54-CB-0.25, length = 29 m, inner diameter = 0.32 mm, film thickness = 0.25 µm, (94 %-methyl)-(5 %-phenyl)-(1 %-vinyl)polysiloxane) with a flame ionization detector. Regioselectivities were determined by the ratio of the corresponding GC areas. Catalyst **1**[1] was synthesized from cheap and readily available starting materials according to a literature procedure.[15]

Complex 3: An oven-dried Schlenk flask equipped with a stopcock and a magnetic stirring bar was transferred into a nitrogen-filled glovebox and charged with **1** (3.00 g, 5.5 mmol), *n*-hexane (60.0 mL), and 2-(methylamino)pyridine (627 mg, 5.8 mmol). After stirring the mixture at room temperature overnight, the crude product was filtered off, washed with cold *n*-hexane and was obtained as an orange solid (2.56 g, 4.2 mmol, 76 %). For x-ray analysis, the product was recrystallized from toluene (300 mg in 1 mL, +4 ºC for 48 h, sealed in a glass ampoule) and obtained as red-orange crystals (rods). ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 0.89-1.10 (m, 12 H), 1.10-1.29 (m, 12 H), 3.18 (s, 12 H), 3.20 (s, 3 H), 3.46 (br. s, 4 H), 6.09 (d, J = 8.6 Hz, 1 H), 6.31 (t, J = 6.9 Hz, 1 H), 7.08-7.14 (m, 6 H), 7.36-7.39 (m, 1 H), 7.74 (s, 1 H), 7.93 (d, J = 4.5 Hz, 1 H) ppm. ^{13}C NMR ($CDCl_3$, DEPT, 125 MHz): δ = 23.8 (CH_3), 26.2 (CH_3), 27.4 (CH), 34.8 (CH_3), 47.3 (CH_3), 100.9 (CH), 109.1 (CH), 123.4 (CH), 124.1 (CH), 138.3 (CH), 144.2 (C), 144.4 (CH), 145.5 (C), 166.0 (CH), 167.5 (C) ppm. IR (neat, KBr): 1/λ = 3062, 2965, 2856, 2803, 2763, 2665, 1601, 1544, 1473, 1449, 1325, 1283, 1261, 1236, 1188, 1149, 1107, 1047, 946 cm^{-1}. MS (ESI+): *m*/*z* (%) = 613.4 (<1) $[M+Li]^+$, 365.5 (100) $[2,6\text{-diisopropylphenyl-NH}_2\text{-CH=N-2,6-diisopropylphenyl}]^+$, 176.1 (5) $[2,6\text{-diisopropylphenyl-NH}]^+$. HRMS (ESI+): calc. ($[C_{35}H_{54}N_6TiLi]^+$) 613.4044; found 613.4046.

Complex 4: An oven-dried Schlenk flask equipped with a stopcock and a magnetic stirring bar was transferred into a nitrogen-filled glovebox and charged with **1** (1.09 g, 2.0 mmol), *N*-phenyl-2-aminopyridine (340 mg, 2.0 mmol), and *n*-hexane (9.0 mL). The solution was stirred at room temperature overnight. The product was isolated by filtration (1.30 g, 1.94 mmol, 97 %) and obtained as an orange solid. For x-ray analysis, a sample of the product was recrystallized from toluene (300 mg in 1 mL, +4 °C for 48 h, sealed in a glass ampoule) and obtained as red-orange crystals (blocks). ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 0.92-1.14 (m, 12 H), 1.14-1.34 (m, 12 H), 3.19 (s, 12 H), 3.50 (br. s, 4 H), 6.34 (d, J = 8.6 Hz, 1 H), 6.38 (t, J = 5.8 Hz, 1 H), 7.02-7.08 (m, 3 H), 7.10-7.18 (m, 6 H), 7.27-7.31 (m, 3 H), 7.79 (s, 1 H), 8.03 (d, J = 3.2 Hz, 1 H) ppm. ^{13}C NMR ($CDCl_3$, DEPT, 125 MHz): δ = 23.7 (CH_3), 26.4 (CH_3), 27.5 (CH), 47.9 (CH_3), 103.7 (CH), 110.3 (CH), 123.1 (CH), 123.4 (CH), 124.3 (CH), 124.5 (CH), 129.0 (CH), 138.4 (CH), 144.1 (C), 144.5 (CH), 145.5 (C), 148.7 (C), 165.9 (C), 166.3 (CH) ppm. IR (neat, KBr): 1/λ = 3335, 3306, 3025, 2963, 2855, 2809, 2762, 1666, 1600, 1565, 1493, 1451, 1369, 1318, 1230, 1189, 1150, 942 cm^{-1}. Elemental composition: calc. ($C_{40}H_{56}N_6Ti$) C 71.84, H 8.44, N 12.57; found C 71.83, H 9.40, N 12.61.

Complex 5: An oven-dried Schlenk flask equipped with a stopcock and a magnetic stirring bar was transferred into a nitrogen-filled glovebox and charged with **1** (1.17 g, 2.2 mmol), toluene (2.2 mL), and *N*-cyclohexyl-2-aminopyridine (380 mg, 2.2 mmol). After stirring the mixture at room temperature overnight, the product was isolated by filtration (627 mg, 0.9 mmol, 42 %) as an orange solid. For x-ray analysis, the product was recrystallized from toluene (300 mg in 1 mL, +4 °C for 48 h, sealed in a glass ampoule) and obtained as red-orange crystals (plates). ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 0.81-1.34 (m, 27 H), 1.56 (q, J = 10.2 Hz, 2 H), 1.64 (d, J = 12.8 Hz, 1 H), 1.79 (t, J = 15.0 Hz, 4 H), 3.22 (s, 12 H), 3.33-3.50 (m, 5 H), 6.18-6.24 (m, 2 H), 7.06-7.14 (m, 6 H), 7.26-7.30 (m, 1 H), 7.75 (s, 1 H), 7.92 (br. s, 1 H) ppm. ^{13}C NMR (C_6D_6, DEPT, 125 MHz): δ = 23.9 (CH_3), 26.3 (CH_2), 26.8 (CH_2), 27.7 (CH), 33.4 (CH_2), 48.6 (CH_3), 60.3 (CH), 103.7 (CH), 108.4 (CH), 123.9 (CH), 124.9 (CH), 138.2 (CH), 144.0 (C), 144.6 (CH), 146.1 (C), 167.0 (C), 167.3 (CH) ppm. IR (neat, KBr): 1/λ = 3263, 3060, 3023, 2972, 2933, 2866, 2807, 2760, 1667, 1594, 1540, 1463, 1435, 1312, 1291, 1266, 1190, 1156, 1131, 1112, 1043, 996,

945, 897, 824 cm^{-1}. Elemental composition: calc. ($C_{40}H_{62}N_6Ti$) C 71.19, H 9.26, N 12.45; found C 70.66, H 9.80, N 12.37.

Hydroaminoalkylation of styrene:[5] An oven-dried Schlenk tube equipped with a Teflon stopcock and a magnetic stirring bar was transferred into a nitrogen-filled glovebox and charged with the catalyst (10 mol%) and *n*-hexane (0.5 mL). *N*-Methylaniline (214 mg, 2.0 mmol), styrene (312 mg, 3.0 mmol), and *n*-hexane (0.5 mL) were added. The tube was sealed and the mixture was heated to 140 °C for 96 h. The mixture was cooled to room temperature and methylene chloride (40 mL) was added. The products were purified by flash chromatography (SiO_2, light petroleum ether/EtOAc = 20/1) and were isolated as yellow oils.

6a:[5] ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 1.27 (d, *J* = 7.0 Hz, 3 H), 2.99 (sext, *J* = 6.9 Hz, 1 H), 3.17 (dd, *J* = 12.4 Hz, 8.2 Hz, 1 H), 3.27 (dd, *J* = 12.4 Hz, 6.3 Hz, 1 H), 3.49 (br. s., 1 H), 6.49-6.51 (m, 2 H), 6.64 (t, *J* = 7.3 Hz, 1 H), 7.11 (t, *J* = 7.4 Hz, 1 H), 7.16-7.19 (m, 3 H), 7.25-7.28 (m, 2 H) ppm. ^{13}C NMR ($CDCl_3$, JMOD, 125 MHz): δ = 19.8 (CH_3), 39.2 (CH), 50.9 (CH_2), 113.0 (CH), 117.3 (CH), 126.7 (CH), 127.3 (CH), 128.7 (CH), 129.3 (CH), 144.6 (C), 148.2 (C) ppm.

6b:[5] ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 1.91 (pent, *J* = 7.2 Hz, 2 H), 2.70 (t, *J* = 7.4 Hz, 2 H), 3.10 (t, *J* = 7.0 Hz, 2 H), 3.54 (br. s, 1 H), 6.54 (d, *J* = 7.7 Hz, 2 H), 6.67 (t, *J* = 7.3 Hz, 1 H), 7.12-7.19 (m, 5 H), 7.25-7.28 (m, 2 H) ppm. ^{13}C NMR ($CDCl_3$, JMOD, 125 MHz): δ = 31.1 (CH_2), 33.5 (CH_2), 43.5 (CH_2), 112.8 (CH), 117.3 (CH), 126.0 (CH), 128.5 (CH), 128.5 (CH), 129.3 (CH), 141.8 (C), 148.4 (C) ppm.

Hydroaminoalkylation of 1-octene:[9b] An oven-dried 1 mL-ampoule was transferred into a nitrogen-filled glovebox and charged with the catalyst (2.5 mol%). *N*-Methylaniline (21 mg, 0.2 mmol), 1-octene (31 mg, 0.3 mmol), and toluene (0.1 mL) were added. The ampoule was sealed and the mixture was heated to 140 °C for 96 h. The mixture was cooled to room temperature and methylene chloride (5 mL) was added. The product was purified by flash chromatography (SiO_2, light petroleum ether/EtOAc = 20/1) and was isolated as colorless oil.

7a:[9b] ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 0.91 (t, *J* = 7.0 Hz, 3 H), 0.99 (d, *J* = 6.7 Hz, 3 H), 1.17-1.49 (m, 10 H), 1.76 (oct, *J* = 6.6 Hz, 1 H), 2.91 (dd, *J* = 12.2 Hz, 7.3 Hz, 1 H), 3.08 (dd, *J* = 12.2 Hz, 5.9 Hz, 1 H), 3.94 (br. s, 1 H), 6.64 (d, *J* = 7.9 Hz, 2 H), 6.71 (t, *J* = 7.3 Hz, 1 H), 7.19 (t, *J* = 8.3 Hz, 2 H) ppm. ^{13}C NMR ($CDCl_3$, JMOD, 125 MHz): δ = 14.2 (CH_3), 18.2 (CH_3), 22.8 (CH_2), 27.1 (CH_2), 29.7 (CH_2), 32.0 (CH_2), 33.0 (CH), 34.9 (CH_2), 50.7 (CH_2), 113.0 (CH), 117.3 (CH), 129.4 (CH), 148.5 (C) ppm.

Hydroamination of 1-phenylpropyne and subsequent imine reduction:[16] An oven dried Schlenk tube equipped with a Teflon stopcock and a magnetic stirring bar was transferred into a nitrogen-filled glovebox and charged with the catalyst (5 mol%), 1-phenylpropyne (279 mg, 2.4 mmol), *p*-toluidine (283 mg, 2.6 mmol), and toluene (1 mL). The tube was sealed and the mixture was heated to 60 °C or 80 °C for 24 h. The mixture was cooled to room temperature and then $NaBH_3CN$ (302 mg, 4.8 mmol), anhydrous $ZnCl_2$ (327 mg, 2.4 mmol), and methanol (10 mL) were added. After the mixture had been stirred at 25 C for 20 h, methylene chloride (40 mL) and saturated aqueous Na_2CO_3-solution (50 mL) were added. The organic layer was separated and the aqueous layer was extracted with methylene chloride (5 × 20 mL). The combined organic layers were dried with $MgSO_4$ and, after concentration under vacuum, the residue was purified by flash chromatography (SiO_2, light petroleum ether/EtOAc = 20/1) to give the products as yellow liquids.

8a:[16] ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 1.28 (d, *J* = 6.3 Hz, 3 H), 2.40 (s, 3 H), 2.82 (dd, *J* = 7.3 Hz, 13.3 Hz, 1 H), 3.07 (dd, *J* = 4.6 Hz, 13.3 Hz, 1 H), 3.49 (br. s., 1 H), 3.86-3.89 (m, 1 H), 6.71 (d, *J* = 8.2 Hz, 2 H), 7.16 (d, *J* = 8.0 Hz, 2 H), 7.32-7.37 (m, 3 H), 7.44 (t, *J* = 7.4 Hz, 2 H) ppm. ^{13}C NMR ($CDCl_3$, DEPT, 125 MHz): δ = 20.3 (CH_3), 20.5 (CH_3), 42.4 (CH_2), 49.7 (CH), 113.7 (CH), 126.3 (CH), 126.4 (C), 128.4 (CH), 129.6 (CH), 129.9 (CH), 138.7 (C), 145.0 (C) ppm.

8b:[16] ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 0.95 (t, *J* = 7.4 Hz, 3 H), 1.76-1.89 (m, 2 H), 2.18 (s, 3 H), 4.20 (t, *J* = 6.7 Hz, 1 H), 6.44 (d, *J* = 8.4 Hz, 2 H), 6.89 (d, *J* = 8.1 Hz, 2 H), 7.19-7.23 (m, 1 H), 7.25-7.27 (m, 1 H), 7.28-7.36 (m, 4 H) ppm. ^{13}C NMR ($CDCl_3$, DEPT, 125 MHz): δ = 10.9 (CH_3), 20.5 (CH_3), 31.8 (CH_2), 60.2 (CH), 113.5 (CH), 126.4 (CH), 126.7 (C), 126.9 (CH), 128.6 (CH), 129.7 (CH), 144.3 (C), 145.4 (C) ppm.

Acknowledgments

We thank the Deutsche Forschungsgemeinschaft for financial support of our research as well as Francesco Fabbretti for his help recording HRMS analyses.

Keywords: alkenes • alkynes • hydroamination • hydroaminoalkylation • titanium

[1] T. Elkin, N. V. Kulkarni, B. Tumanskii, M. Botoshansky, L. J. W. Shimon, M. S. Eisen, *Organometallics* **2013**, *32*, 6337-6352.

[2] For reviews on hydroaminoalkylation reactions of alkenes, see: a) E. Chong, P. Garcia, L. L. Schafer, *Synthesis* **2014**, *46*, 2884-2896; b) J. Hannedouche, E. Schulz, *Organometallics* **2018**, *37*, 4313-4326; c) P. M. Edwards, L. L. Schafer, *Chem. Commun.* **2018**, *54*, 12543-12560.

[3] For selected examples of late transition metal-catalyzed hydroaminoalkylation reactions of alkenes, see: a) A. T. Tran, J.-Q. Yu, *Angew. Chem.* **2017**, *129*, 10666-10670; *Angew. Chem. Int. Ed.* **2017**, *56*, 10530-10534; b) M. Spettel, R. Pollice, M. Schnürch, *Org. Lett.* **2017**, *19*, 4287-4290; c) S. M. Thullen, T. Rovis, *J. Am. Chem. Soc.* **2017**, *139*, 15504-15508; d) G. Lahm, T. Opatz, *Org. Lett.* **2014**, *16*, 4201-4203; e) M. Schinkel, L. Wang, K. Bielefeld, L. Ackermann, *Org. Lett.* **2014**, *16*, 1876-1879; f) A. A. Kulago, B. F. Van Steijvoort, E. A. Mitchell, L. Meerpoel, B. U. W. Maes, *Adv. Synth. Catal.* **2014**, *356*, 1610-1618.

[4] For examples of group 5 metal catalysts for hydroaminoalkylation reactions of alkenes, see: R. C. DiPucchio, S.-C. Rosca, G. Athavan, L. L. Schafer, *ChemCatChem* **2019**, *11*, DOI: 10.1002/cctc.201900398 and references cited therein.

[5] J. Dörfler, T. Preuß, C. Brahms, D. Scheuer, S. Doye, *Dalton Trans.* **2015**, *44*, 12149-12168.

[6] I. Prochnow, P. Zark, T. Müller, S. Doye, *Angew. Chem.* **2011**, *123*, 6525-6529; *Angew. Chem. Int. Ed.* **2011**, *50*, 6401-6405

[7] M. Manßen, N. Lauterbach, J. Dörfler, M. Schmidtmann, W. Saak, S. Doye, R. Beckhaus *Angew. Chem.* **2015**, *127*, 4458-4462; *Angew. Chem. Int. Ed.* **2015**, *54*, 4383-4387.

[8] For reviews on aminopyridinato ligands, see: a) R. Kempe, *Eur. J. Inorg. Chem.* **2003**, 791-803; b) R. Kempe, N. Hoss, T. Irrgang, *J. Organomet. Chem.* **2002**, *647*, 12-20; c) R. Kempe, *Z. Anorg. Allg. Chem.* **2010**, *636*, 2135-2147.

[9] a) J. Dörfler, S. Doye, *Angew. Chem.* **2013**, *125*, 1851-1854; *Angew. Chem. Int. Ed.* **2013**, *52*, 1806-1809; b) J. Dörfler, T. Preuß, A. Schischko, M. Schmidtmann, S. Doye, *Angew. Chem.* **2014**, *126*, 8052-8056; *Angew. Chem. Int. Ed.* **2014**, *53*, 7918-7922.

[10] J. A. Bexrud, P. Eisenberger, D. C. Leitch, P. P. Payne, L. L. Schafer, *J. Am. Chem. Soc.* **2009**, *131*, 2116-2118.

[11] CCDC 1915106 (**3**), CCDC 1915107 (**4**), and CCDC 1915109 (**5**) contain the supplementary crystallographic data for compounds **3**, **4**

and **5**. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[12] For selected reviews on hydroamination reactions, see: a) A. L. Reznichenko, K. C. Hultzsch, *Org. React.* **2015**, *88*, 1-554; b) T. E. Müller, K. C. Hultzsch, M. Yus, F. Foubelo, M. Tada, *Chem. Rev.* **2008**, *108*, 3795-3892, c) R. Severin, S. Doye, *Chem. Soc. Rev.* **2007**, *36*, 1407-1420; d) S. Doye, *Synlett* **2004**,1653-1672.

[13] For a comparison between Cp_2TiMe_2 and $Cp^*_2TiMe_2$ as catalysts for the hydroamination of alkynes, see: a) E. Haak, I. Bytschkov, S. Doye, *Angew. Chem.* **1999**, *111*, 3584-3586; *Angew. Chem. Int. Ed.* **1999**, *38*, 3389-3391; b) A. Heutling, S. Doye, *J. Org. Chem.* **2002**, *67*, 1961-1964.

[14] E. Chong, S. Qayyum, L. L. Schafer, R. Kempe, *Organometallics* **2013**, *32*, 1858-1865.

[15] J. Bielefeld, S. Doye, *Angew. Chem.* **2017**, *129*, 15352-15355; *Angew. Chem. Int. Ed.* **2017**, *56*, 15155-15158.

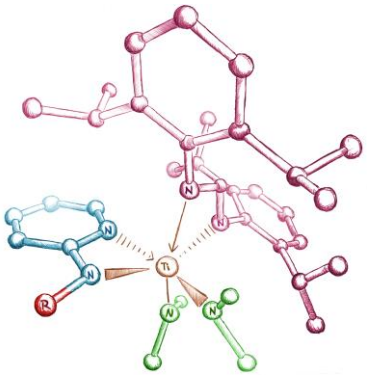
[16] C. Brahms, P. Tholen, W. Saak, S. Doye, *Eur. J. Org. Chem.* **2013**, 7583-7592.

Entry for the Table of Contents

Layout 1:

FULL PAPER

Three new sterically crowded titanium complexes which all possess an identical formamidinato ligand, two dimethylamido ligands and in addition, a 2-aminopyridinato-ligand that contains either an *N*-methyl, an *N*-phenyl, or an *N*-cyclohexyl substituent are easily accessible from a common titanium mono(formamidinate) precursor and correspondingly *N*-substituted 2-aminopyridines.



Alkene Hydroaminoalkylation

*J. Bielefeld, E. Kurochkina, M. Schmidtmann, S. Doye**

Page No. – Page No.

New Titanium Complexes and Their Use in Hydroamination and Hydroaminoalkylation Reactions