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Monomeric and dendritic second generation Grubbs- and Hoveyda–Grubbs-type catalysts for olefin metathesis

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ABSTRACT

The synthesis and characterization of monomeric and dendritic Grubbs II and Hoveyda–Grubbs II-based complexes are reported. These complexes were synthesized via a route based on the connection of monomeric or dendritic *N*-alkyl-*N*′-mesitylimidazol-2-ylidene pre-ligands to Grubbs I or Hoveyda–Grubbs I complexes. The immobilization of a modified Grubbs II type catalyst on a G_0 carbosilane dendrimer was successfully carried out. Together with monomeric Grubbs II and Hoveyda–Grubbs-analogs and several commercially available olefin metathesis catalysts, the soluble, homogeneous G_0-dendritic Grubbs II complex was tested as catalyst in the ring closing metathesis of diethyl diallylmalonate. The immobilized complex proved to outperform its monomeric analog in this reaction at room temperature, whereas it was found to be slightly slower at reflux temperature.

1. Introduction

Olefin metathesis is nowadays widely used for the synthesis of complex cyclic and acyclic molecules with potential pharmaceutical, biomedical and food applications [1–4]. Further industrial applications for olefin metathesis lie in polymer chemistry [5], for example, in the synthesis of polymers like polynorbornene or polydicyclopentadiene [6]. Four of the most successful olefin metathesis catalysts are the ruthenium-based first and second generation Grubbs and Hoveyda–Grubbs catalysts **A**–**D** (Fig. 1) [7–10].

Immobilization of these metathesis catalysts to polymeric supports in order to enable catalyst separation and catalyst reuse has been accomplished via a number of different approaches, as was nicely reviewed by Buchmeiser [11] For the immobilization of the ruthenium-based catalysts **A**–**D** insoluble supports like polystyrene (PS) [12,13], and poly(vinylpyridine) (PVPy) [14] based resins, monolithic silica rods [15–17], as well as inorganic supports like silica and alumina [18,19] are frequently used as supporting materials. In many of these examples the heterogenized metathesis catalysts have been reused successfully in ring closing metathesis (RCM), ring opening metathesis polymerization (ROMP), and other metathesis reactions.

Examples of the immobilization of metathesis catalysts on soluble supports have also been described [10,20–24]. In most cases the immobilization of a Hoveyda–Grubbs II catalyst was accomplished via the alkylidene ligand. Separation and reuse of these soluble, immobilized metathesis catalysts was accomplished by means of nanofiltration, fluorous extraction, or solvent-induced precipitation.

In an ongoing research program on immobilized homogeneous catalysis, we are interested in developing the concept of compartmentalized catalysis through the use of molecular weight enlarged homogeneous catalysts. These enlarged catalysts can be separated based on their size using nanofiltration reactors [25,26] or through a so-called tea bag approach [27–29]. In the latter approach the enlarged homogeneous catalyst is placed inside a semi-permeable compartment and is introduced into a reaction mixture. In this set-up, catalysis can take place inside the membrane compartment while the formed product can diffuse out from the membrane compartment into the outer solution. After reaction completion, the compartment containing the immobilized catalyst can be easily removed from the reaction mixture and in principle be reused.

Earlier, we presented the first example of compartmentalized auto-tandem catalysis through the use of carbosilane dendrimer-immobilized pincer Pd complexes [30]. These dendritic pincer Pd complexes were successfully reused in several consecutive runs in a stannylation/electrophilic addition sequence leading to homo-allylic alcohols. We are currently interested in extending the scope of compartmentalized homogeneous catalysis towards

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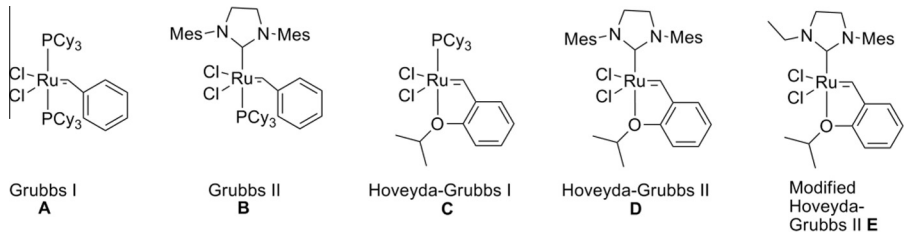


Fig. 1. Various first and second generation Grubbs and Hoveyda–Grubbs catalysts.

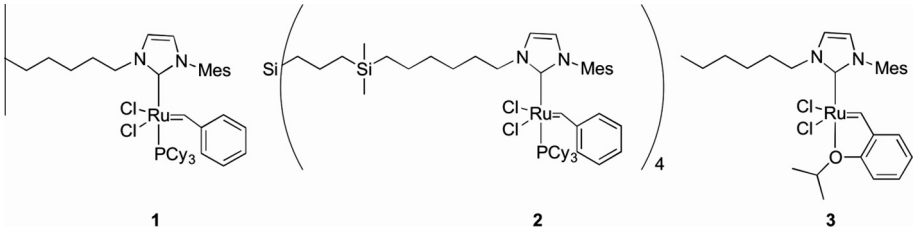


Fig. 2. Monomeric and dendritic second generation Grubbs and Hoveyda–Grubbs-type catalysts **1**–**3**.

olefin metathesis, being one of the most useful methods for carbon–carbon coupling. The combination of dendrimer-immobilized olefin metathesis catalysts with other molecular weight enlarged catalysts in multiple semi-permeable compartments is envisioned to lead to compartmentalized orthogonal tandem catalysis, in which several reaction steps are catalyzed by different compartmentalized catalysts [31].

The immobilization of Hoveyda–Grubbs type catalysts on carbosilane dendrimers was earlier reported by Hoveyda and co-workers [10]. In this case, immobilization of the ruthenium catalysts was accomplished via the alkylidene ligand leading to recyclable olefin metathesis catalysts. These complexes have also been used to reveal the "boomerang" (release/return) mechanism of this class of complexes [32]. It was postulated that the catalyst is first released from its (dendritic) support before it enters the catalytic cycle. When substrate conversion reaches completion, the complex returns to the support by coordination of the immobilized 2-isopropoxybenzylidene to the ruthenium center. Interestingly, Plenio and co-workers recently showed that catalyst return might not take place at all for the small fraction of catalysts that is actually involved in RCM [33,34].

Regardless of the existence of the 'return' part in the boomerang mechanism, these dendritic catalysts would not have been suitable for our compartmentalized catalysis purpose. After release from the dendritic support, the molecular catalytic species would be able to diffuse through the membrane along with the reaction substrate and product. The return of the permeated ruthenium center to its dendritic alkylidene ligand would then be very improbable, which would lead to ruthenium leaching and ultimately to a lower recyclability of the immobilized catalyst. Accordingly, this would violate the compartmentalized nature of the enlarged catalysts. For these reasons, we have opted to immobilize metathesis catalysts via the NHC ligand to dendritic supports.

Here, we present the synthesis of new dendritic NHC ligand-immobilized second generation Grubbs-type catalysts **2** and of its monomeric first and second generation Hoveyda–Grubbs analogs **1** and **3** (Fig. 2). These homogeneous metathesis catalysts were investigated in the RCM of diethyl diallylmalonate and compared to well-known metathesis catalysts **A**, **B** and **D**. Finally, the use of dendritic homogeneous catalyst **2** was attempted in a compartmentalized metathesis set-up.

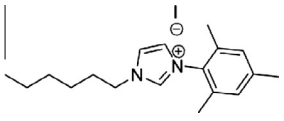
2. Experimental

2.1. General

All reactions were carried out using standard Schlenk techniques under an inert dinitrogen atmosphere unless stated otherwise. All solvents were carefully dried and distilled prior to use. All standard reagents were purchased commercially and used without further purification. 1-Mesitylimidazole was synthesized according to a procedure described by Liu et al. [35]. Carbosilane dendrimers **7** and **8** were synthesized according to Van der Made's procedure [36]. All other reagents were purchased from Acros Organics and Sigma–Aldrich Chemical Co. Inc. and used as received. ^{1}H (400 MHz), ^{13}C (100 MHz), and ^{31}P (121 MHz) NMR spectra were recorded on a Varian 400 MHz spectrometer at 25 °C, chemical shifts are given in ppm referenced to residual solvent resonances. High resolution mass spectroscopy (HRMS) has been performed on a Waters LCT Premier XE Micromass instrument using the electrospray ionization (ESI) technique. MALDI-TOF MS spectra were acquired using a Voyager-DE Bio-Spectrometry Workstation mass spectrometer equipped with a nitrogen laser emitting at 337 nm. GC analysis was carried out using a Perkin Elmer Clarus 500 GC equipped with an Alltech Econo-Cap EC-5 column.

2.2. Synthesis

2.2.1. 3-Hexyl-1-mesitylimidazolium iodide *4*

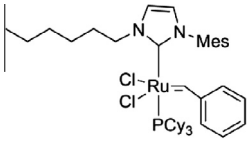


1-Mesitylimidazole (50 mg, 0.270 mmol), 1-chlorohexane (37 μL, 0.270 mmol) and sodium iodide (0.081 g, 0.540 mmol) were dissolved in toluene (2 mL) and the mixture was stirred at 110 °C for 16 h. A syrup precipitated and was separated from the

liquid phase by decantation. The syrup was washed with hexanes (3 × 5 mL), redissolved in CH_2Cl_2 (5 mL) and filtered through a glass filter. The solvent was evaporated *in vacuo* to afford a white solid in 64% yield (64 mg).

^{1}H NMR ($CDCl_3$): δ 10.23 (s, 1H, NC*H*N), 7.63 (s, 1H, C$H_{imid.}$), 7.19 (s, 1H, C$H_{imid.}$), 7.02 (s, 2H, C$H_{mesitylene}$), 4.68 (t, 2H, CH_2N, ^3J = 7.2 Hz), 2.35 (s, 3H, *p*-CH_3), 2.09 (s, 6H, *o*-CH_3), 2.05–1.98 (m, 2H, NCH$_2$CH_2), 1.43–1.28 (m, 6H, CH_2), 0.88 (t, 3H, CH_3, ^3J = 6.8 Hz); ^{13}C NMR ($CDCl_3$): δ 141.6, 138.1, 134.4, 130.8, 130.1, 123.6, 123.2, 50.9, 31.3, 30.7, 26.0, 22.6, 21.4, 18.0, 14.1; IR (cm^{-1}): 3057 (m), 2955 (s), 2928 (s), 2858 (m), 1608 (w), 1561 (s), 1544 (s), 1201 (s). ESI-HRMS (*m*/*z*): Calc. for $C_{18}H_{27}N_2$ $[M-I]^{++}$: 271.2174. Found 271.2168. The bromide analog of **5** has been described by Strassner [37].

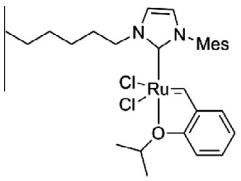
2.2.2. (3-Hexyl-1-mesitylimidazolium)$Cl_2Ru(=CHC_6H_5)(PCy_3)$ **1**



3-Hexyl-1-mesitylimidazolium iodide **4** (100 mg, 0.25 mmol) was dissolved 10 mL toluene (10 mL). Potassium *tert*-butoxide (189 μl of a 20 wt.% solution in dry THF, 0.30 mmol, 1.2 equiv.) was added and the reaction mixture was stirred for one hour at room temperature. Via a cannula a solution of Grubbs I catalyst **A** (234.4 mg, 0.30 mmol, 1.2 equiv.) in toluene (70 mL) was added, whereupon the reaction mixture was stirred for 16 h. at room temperature. Next, the mixture was filtered and the filtrate was concentrated *in vacuo* at room temperature. Purification was performed by column chromatography with neutral alumina under nitrogen pressure using hexanes/diethyl ether (9/1) as eluents. This yielded a brown solid in 80% yield (163 mg).

^{1}H NMR (C_6D_6): δ 19.77 (s, 1H, Ru = C*H*Ar), 8.17 (m, 2H, Ru = CHArH_{ortho}), 7.12 (s, 1H, C$H_{imid.}$), 6.94 (m, 3H, Ru = CHAr$H_{meta+para}$), 6.55 (s, 1H, C$H_{imid.}$), 6.15 (m, 2H, C$H_{arom,mesityl}$), 4.64 (t, 2H, ^3J = 7.6 Hz, NCH_2,), 2.55 (m, 2H, NCH$_2$CH_2), 2.12 (s, 3H, Ar–*para*-CH_3), 2.07–1.04 (m, 45H, aliphatic C*H* and CH_2), 0.86 (t, 3H, ^3J = 6.8 Hz, CH$_2$CH_3). ^{13}C NMR (C_6D_6): δ 292.4, 188.8, 148.4, 138.2, 136.5, 130.2, 129.7, 129.2, 128.4, 125.5, 122.8, 121.6, 50.9, 36.0, 31.9, 30.6, 30.0, 28.1, 27.1, 26.9, 22.8, 20.9, 18.5, 14.1. ^{31}P NMR (C_6D_6): δ 34.7. ESI-HRMS (*m*/*z*): Calc. for $C_{43}H_{65}Cl_2N_2PRu$ $[M-H]^+$: 811.3234. Found 811.3194.

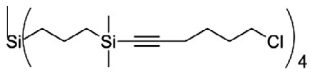
2.2.3. (3-Hexyl-1-mesitylimidazolium)$Cl_2Ru(=CHC_6H_4$-ortho-OiPr) **3**



3-Hexyl-1-mesitylimidazolium iodide **4** (69 mg, 0.170 mmol) and KO*t*Bu (23 mg, 0.170 mmol) were suspended in toluene (5 mL) and the mixture was stirred for 5 min. In a different flask, Hoveyda–Grubbs I catalyst **C** (69 mg, 0.114 mmol) was dissolved in toluene (5 mL) and added to the first mixture. Finally, silver(I) chloride (49 g, 0.340 mmol) was added and the mixture was stirred at reflux temperature for 1 h. The suspension turned from brown to brown-green. Then, the mixture was filtered through a glass filter and the filtrate was concentrated to dryness *in vacuo*. The resulting brown solid was purified by column chromatography over silica (eluent gradient used: CH_2Cl_2/hexanes (9:1, *v*/*v*) to pure CH_2Cl_2). Crystals for X-ray diffraction were obtained by diffusion of hexanes into a CH_2Cl_2 solution of the pure solid. Green–brown crystals appeared in 34% yield (34 mg).

^{1}H NMR ($CDCl_3$): δ 16.44 (s, 1H, Ru = C*H*Ar), 7.50 (m, 1H, C$H_{arom., styrene}$), 7.24 (m, 1H, C$H_{imid.}$), 7.10 (s, 2H, C$H_{arom., mesityl}$), 7.00–6.90 (m, 3H, C$H_{arom., styrene}$), 6.89 (s, 1H, C$H_{imid.}$), 5.19 (septet, 1H, ^3J = 5.0 Hz, OC*H*), 4.90 (t, 2H, ^3J = 7.6 Hz, NCH_2), 2.50 (s, 3H, Ar–*para*-CH_3), 2.23–2.18 (m, 2H, NCH$_2$CH_2), 2.02 (s, 6H, Ar–*ortho*-CH_3), 1.81 (d, 6H, ^3J = 5.0 Hz, CHCH_3), 1.60 (m, 2H, NCH$_2$CH$_2$CH_2), 1.50–1.35 (m, 4H, aliphatic CH$_2$), 0.95 (t, 3H, ^3J = 7.6 Hz, CH$_2$CH_3); ^{13}C NMR ($CDCl_3$): δ 288.8, 172.4, 152.8, 144.6, 139.8, 137.6, 129.3, 129.2, 124.6, 122.8, 122.4, 121.4, 113.1, 75.3, 52.4, 31.6, 31.0, 29.9, 27.0, 22.9, 22.2, 21.5, 18.3, 14.3. ESI-HRMS (*m*/*z*): Calc. for $C_{28}H_{38}Cl_2N_2ORu$ $[M]^+$: 590.1407. Found 590.1403.

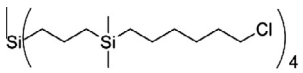
2.2.4. Tetrakis-(3-((6-chlorohex-1-ynyl)dimethylsilyl)propyl)silane **9**



6-Chloro-1-hexyne (0.47 mL, 3.85 mmol) was dissolved in THF (20 mL) and cooled to −78 °C. Upon the dropwise addition of a 2 M solution of LDA in THF/hexanes (1.97 mL, 3.94 mmol, 1.03 equiv.) the solution turned dark yellow. After 30 min at −78 °C, a solution of Si(CH$_2$CH$_2$CH$_2$SiMe$_2$Cl)$_4$ (**7**, 0.50 g, 0.87 mmol) in THF (5 mL) was added dropwise. The mixture was allowed to reach room temperature and was stirred for a further 16 h. After this period all volatiles were removed *in vacuo*. The residue was dissolved in CH_2Cl_2 (50 mL) and washed with an aqueous saturated NH_4Cl solution (3 × 50 mL). The organic phase was dried over anhydrous $MgSO_4$, filtered and concentrated to afford an orange syrup. This moisture-sensitive product has been used without further purification in the next synthesis step.

^{1}H NMR ($CDCl_3$): δ 3.57 (t, 8H, ^3J = 6.8 Hz, CH_2Cl), 2.27 (t, 8H, ^3J = 6.8 Hz, C≡C–CH_2), 1.90 (m, 8H, CH_2CH$_2$Cl), 1.68 (m, 8H, C≡C–CH$_2$CH_2), 1.39 (m, 8H, SiCH$_2$CH_2), 0.69–0.57 (m, 16H, SiCH_2), −0.11 (s, 24H, SiCH_3); ^{13}C NMR ($CDCl_3$): δ 107.0, 84.7, 44.7, 31.7, 26.0, 21.4, 19.4, 18.7, 17.2, −1.2.

2.2.5. Tetrakis-(3-((6-chlorohexyl)dimethylsilyl)propyl)silane **11**

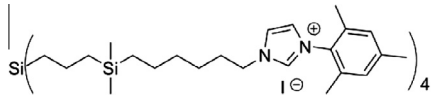


Tetrakis-(3-((6-chlorohex-1-ynyl)dimethylsilyl)propyl)silane **9** (1.20 g, 1.35 mmol) and Pd on charcoal (10 wt.% Pd, 28 mg, 0.270 mmol, 20 mol%) were suspended 20 mL of absolute EtOH (20 mL) and placed in a 50 mL autoclave (Parr-4590 micro-reactor). After evacuation and purging the autoclave with hydrogen, the mixture was stirred at room temperature under a pressure of 25 bar of H_2 for 5 h. Then, the solution was filtered over Celite and the solvent was removed *in vacuo*. The resulting orange syrup

was purified by flash chromatography over silica gel using CH_2Cl_2 as eluent. A colorless syrup was obtained in 41% yield (0.50 g) over two steps.

^{1}H NMR ($CDCl_3$): δ 3.53 (t, 8H, ^3J = 6.8 Hz, CH_2Cl), 1.75 (m, 8H, CH_2CH$_2$Cl), 1.42 (m, 8H, CH_2CH$_2$CH$_2$Cl), 1.37–1.22 (m, 24H), 0.59–0.50 (m, 16H, SiCH_2), 0.46 (m, 8H, SiCH_2), −0.05 (s, 24H, SiCH_3); ^{13}C NMR ($CDCl_3$): δ 45.4, 33.1, 32.8, 26.8, 24.0, 20.5, 18.8, 17.8, 15.6, −3.0.

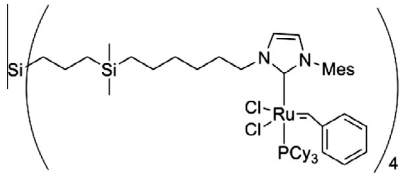
2.2.6. Tetrakis-(3-((6-(3-mesitylimidazolium)hexyl)dimethylsilyl) propyl)silane iodide **5**



Tetrakis-(3-((6-chlorohexyl)dimethylsilyl)propyl)silane **11** (0.50 g, 0.55 mmol) and 1-mesitylimidazole (0.45 g, 2.42 mmol, 4.4 equiv.) were dissolved in toluene (6 mL). Sodium iodide (0.66 g, 4.40 mmol, 8 equiv.) was added and the suspension was stirred at 110 °C for 18 h. During this period, a biphasic mixture was obtained. The upper solution was removed and the remaining syrup was washed several times with hexanes. The syrup was dissolved in CH_2Cl_2 whereupon a white solid precipitated. These inorganic salts were removed by filtration and the filtrate was concentrated *in vacuo* yielding a pale yellow solid in 61% yield (0.68 g).

^{1}H NMR ($CDCl_3$): δ 10.10 (s, 4H, NC*H*N), 7.99 (s, 4H, C$H_{imid.}$), 7.25 (s, 4H, C$H_{imid.}$), 6.98 (s, 8H, CH_{arom}), 4.66 (t, 8H, ^3J = 6.8 Hz, NCH_2), 2.33 (s, 12H, Ar–*para*-CH_3), 2.06 (s, 24H, Ar–*ortho*-CH_3), 2.05–1.93 (m, 8H, NCH$_2$CH_2), 1.40–1.20 (m, 32H, aliphatic CH_2), 0.60–0.50 (m, 16H, SiMe$_2$CH_2), 0.45 (m, 8H, Si$_{core}$CH_2), 0.06 (s, 24H, SiCH_3); ^{13}C NMR ($CDCl_3$): δ 141.4, 137.8, 134.4, 130.9, 130.2, 130.1, 123.8, 50.8, 33.4, 30.9, 26.2, 24.1, 21.4, 20.5, 18.8, 18.0, 17.8, 15.6, -2.9. IR (cm^{-1}): 3054 (w), 2915 (s), 2854 (m), 1608 (w), 1563 (w), 1545 (w), 1246 (s), 1201 (s), 1067 (s). ESI-HRMS (*m*/*z*): Calc. for $C_{92}H_{152}I_3N_8Si_5$ $[M-I]^+$: 1890.8146. Found: 1890.8818, Calc. for $C_{92}H_{152}I_2N_8Si_5$ $[M-2I]^{2+}$: 881.9551. Found: 881.9565, Calc. for $C_{92}H_{152}IN_8Si_5$ $[M-3I]^{3+}$: 545.6686. Found: 545.6622.

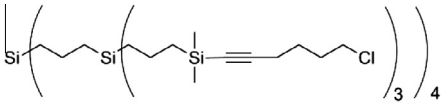
2.2.7. Dendrimer **2**



Imidazolium salt **5** (100 mg, 50 μmol) was dissolved in toluene (8 mL) using an ultrasonic agitation bath. A solution of potassium *tert*-butoxide in THF (20 wt.%, 107 μL, 200 μmol, 4.0 equiv.) was added dropwise to the solution. The reaction mixture was stirred for 1 h at room temperature, whereupon a solution of Grubbs I catalyst **A** (153 mg, 200 μmol, 4.0 equiv.) in toluene (40 mL) was added slowly. The reaction mixture was stirred for 16 h. at room temperature, upon which its color changed from purple to purple-brown. After filtration, all volatiles were removed *in vacuo* at room temperature. The resulting brown residue was washed with Et_2O several times and purified by column chromatography under an inert nitrogen atmosphere (neutral alumina, hexanes/ethyl acetate 2:1, *v*/*v*) to yield a dark brown solid in 70% yield (124 mg).

^{1}H NMR (C_6D_6): δ 19.80 (s, 4H, Ru = C*H*Ar), 8.19 (m, 8H, Ru = CHArH_{ortho}), 7.15 (s, 4H, C$H_{imid.}$), 6.98 (m, 12H, Ru = CHAr$H_{meta+para}$), 6.59 (s, 4H, C$H_{imid.}$), 6.21 (m, 8H, C$H_{arom, mesityl}$), 4.75 (m, 8H, NCH_2,), 2.62 (m, 8H, NCH$_2$CH_2), 2.16 (s, 12H, Ar–*para*-CH_3), 2.10–1.08 (m, 188H, aliphatic C*H* and CH_2), 0.90–0.60 (m, 24H, SiCH$_2$), 0.67–0.60 (m), 0.18 (bs, 24H, SiCH_3). ^{13}C NMR (C_6D_6): δ 291.2, 188.0, 151.9, 138.2, 136.8, 136.5, 130.5, 129.5, 129.2, 125.5, 123.0, 120.7, 50.6, 36.0, 35.4, 31.9, 29.9, 28.1, 27.1, 27.0, 26.7, 26.4, 22.9, 19.2, 18.6, 18.1, 14.2, −3.1. ^{31}P NMR (C_6D_6): δ 34.7. MALDI-TOF MS: (*m*/*z*) Calc. for $C_{192}H_{304}Cl_8N_8P_4Ru_4Si_5Na$ $[M+Na]^+$: 3703.8. Found: 3703.0.

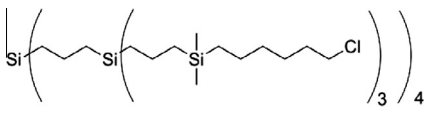
2.2.8. Tetrakis-(tris-(3-((6-chlorohex-1-ynyl)dimethylsilyl)propyl)silane **10**



6-Chloro-1-hexyne (1.1 mL, 9.2 mmol, 14 equiv.) was dissolved in THF (40 mL) and cooled to −78 °C. A 2 M solution of LDA in THF/hexanes (4.60 mL, 9.2 mmol, 14 equiv.) was added dropwise to the first solution and stirred for 30 min at −78 °C. Then a solution of dendrimer **8** (1.91 g, 0.66 mmol) in THF (10 mL) was added dropwise at the same temperature. After addition, the mixture was allowed to reach room temperature and was stirred for another 16 h. The solvent was evaporated *in vacuo* and the resulting residue was dissolved in CH_2Cl_2 (50 mL) and washed with an aqueous saturated NH_4Cl solution (3 × 50 mL). The organic phase was dried over anhydrous $MgSO_4$, filtered and concentrated to afford an orange syrup. This air-sensitive product has been used without further purification in the next synthesis step.

^{1}H NMR ($CDCl_3$): δ 3.61 (t, ^3J = 6.6 Hz, 24H, CH_2Cl), 2.30 (m, 24H, C≡CCH_2), 1.93 (m, 24H, CH_2CH$_2$Cl), 1.73 (m, 24H, C≡CCH$_2$CH_2), 1.43–1.25 (m, 32H, SiCH$_2$CH_2), 0.73–0.63 (m, 64H, SiCH_2), 0.16 (s, 72H, Si–CH$_3$). ^{13}C NMR ($CDCl_3$): δ 105.8, 83.9, 43.7, 31.1, 25.6, 21.5, 20.9, 19.6, 19.3, 19.0, 18.4, 17.0, −1.3.

2.2.9. Tetrakis-(tris-(3-((6-chlorohexyl)dimethylsilyl)propyl)silane **12**

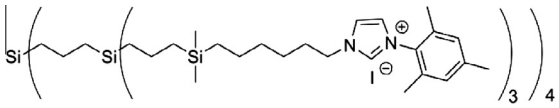


Dendrimer **10** (1.65 g, 0.57 mmol) and Pd on charcoal (10 wt.% Pd, 118 mg, 0.11 mmol, 20 mol%) was suspended in ethyl acetate (20 mL) and placed in a 50 mL autoclave (Parr-4590 micro-reactor). After evacuation and purging the autoclave with hydrogen, the mixture was stirred at room temperature under a pressure of 25 bar of H_2 for 16 h. Then the solution was filtered through Celite and the solvent was evaporated. The residue was redissolved in CH_2Cl_2 (5 mL) and placed into a dialysis bag. This bag was placed into a beaker containing a mixture of CH_2Cl_2/MeOH (500 mL; 9:1,

v/*v*) and dialyzed for 2 h. This procedure was repeated twice. Finally, the contents of the dialysis bag were evaporated, yielding **12** as a pale yellow syrup (60% over two steps, 1.02 g).

^{1}H NMR ($CDCl_3$): δ 3.51 (t, ^3J = 6.6 Hz, 24H, CH_2Cl), 1.79 (m, 24H, CH_2CH_2Cl), 1.42–1.18 (m, 104H, CH_2), 0.58–0.34 (m, 88H, $SiCH_2$), −0.05 (s, 72H, $SiCH_3$). ^{13}C NMR ($CDCl_3$): δ 45.4, 33.2, 32.9, 26.9, 24.0, 20.6, 18.8, 18.4, 18.1, 17.9, 17.6, 15.6, −3.0.

2.2.10. Tetrakis-(tris-(3-((6-(3-mesitylimidazolium)hexyl)dimethylsilyl)propyl)silane iodide ***6***



Dendrimer **12** (500 mg, 0.170 mmol), 1-mesitylimidazole (442 mg, 2.38 mmol, 14 equiv.) and sodium iodide (612 mg, 4.08 mmol, 24 equiv.) were dissolved in toluene (6 mL). This mixture was refluxed for 72 h. In this period, the product precipitated from the solution as a syrup. The supernatant was removed by careful decantation and the syrup was washed with hexanes (3 × 10 mL). Then the syrup was dissolved in CH_2Cl_2 whereupon inorganic sodium salts precipitated from the solvent. The solution was filtered and the filtrate was concentrated *in vacuo*. The product was further purified via passive dialysis in CH_2Cl_2/MeOH (500 mL; 9:1, *v*/*v*; 3 cycles of 2 h.) yielding a pale yellow solid in 69% (740 mg).

^{1}H NMR ($CDCl_3$): δ 9.98 (s, 12H, NC*H*N), 8.18 (s, 12H, $CH_{imid.}$), 7.28 (s, 12H, $CH_{imid.}$), 6.97 (s, 24H, $CH_{arom.}$), 4.67 (m, 24H, NCH_2), 2.32 (s, 72H, Ar–*para*-CH_3), 2.07 (s, 36H, Ar–*ortho*-CH_3), 1.42–1.18 (m, 128H, aliphatic CH_2), 0.65–0.38 (m, 88H, $SiCH_2$), −0.05 (s, 72H, $SiCH_3$). ^{13}C NMR ($CDCl_3$): δ 141.3, 137.0, 134.3, 130.8, 130.0, 124.3, 123.7, 50.5, 33.3, 30.9, 26.1, 24.0, 21.3, 20.4, 18.7, 18.0, 17.9, 17.8, 17.7, 17.4, 15.6, −3.3. ESI-HRMS (*m*/*z*): Calc. for $C_{288}H_{480}I_9N_{24}Si_{17}$ $[M-3I]^{3+}$: 1964.5259. Found: 1964.6520. Calc. for $C_{288}H_{480}I_8N_{24}Si_{17}$ $[M-4I]^{4+}$: 1441.6683. Found: 1441.6671. Calc. for $C_{288}H_{480}I_7N_{24}Si_{17}$ $[M-5]^{5+}$: 1127.9538. Found 1127.7056. Also peaks for $[M-6I]^{6+}$, $[M-7I]^{7+}$ and $[M-8I]^{8+}$ have been successfully identified.

2.3. Crystallographic data for complex ***3***

$C_{28}H_{38}Cl_2N_2ORu$ + disordered solvent, Fw = 590.57,[1] brown plate, 0.36 × 0.33 × 0.06 mm^3, monoclinic, $P2_1/c$ (No. 14), a = 15.06929(4), b = 12.7795(2), c = 16.1807(2) Å, β = 104.002(1)°, V = 3023.46(6) Å^3, Z = 4, D_x = 1.297 g/cm^3 ,[1] μ = 0.72 mm^{-1} .[1] 66 907 Reflections were measured on a Nonius KappaCCD diffractometer with rotating anode (graphite monochromator, λ = 0.71073 Å) up to a resolution of $(\sin\theta/\lambda)_{max}$ = 0.65 Å^{-1} at a temperature of 150(2) K. Intensity integration was performed with Eval15 [38]. The SADABS program [39] was used for scaling and analytical absorption correction (0.67–1.00 correction range). 6917 Reflections were unique (R_{int} = 0.040), of which 5684 were observed [$I > 2\sigma(I)$]. The structure was solved with Direct Methods using the program SHELXS-97 [40]. The structure was refined with SHELXL-97 [40] against F^2 of all reflections. Non hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were introduced in calculated positions and refined with a riding model. The crystal structure contains solvent accessible voids (289.1 Å^3/unit cell) filled with disordered solvent molecules. Their contribution to the structure factors was secured by back-Fourier transformation using the SQUEEZE routine of PLATON [41] resulting in 79 electrons/unit cell). 313 Parameters were refined with no restraints. R_1/wR_2 [$I > 2\sigma(I)$]: 0.0333/0.0919. R_1/wR_2 [all refl.]: 0.0441/0.0976. S = 1.105. Residual electron density between −0.45 and 1.03 e/Å^3. Geometry calculations and checking for higher symmetry was performed with the PLATON program [41].

[1] Derived values do not contain the contribution of the disordered solvent molecules.

2.4. Protocol for the RCM of diethyl diallylmalonate with the catalyst present in solution

In a representative experiment, the appropriate catalyst (5 mol% [Ru], 8 μmol), was added to a solution of diethyl diallylmalonate (0.16 mmol, 38.4 mg, 39 μL) and hexamethylbenzene (internal standard, 0.032 mmol, 5.2 mg) in dry CH_2Cl_2 (6 mL). The reaction stirred at room temperature or at 40 °C in an inert nitrogen atmosphere. Aliquots of 50 μL for GC analysis were regularly taken with an airtight syringe.

2.5. Protocol for the RCM of diethyl diallylmalonate with dendritic catalyst ***2*** *present in a dialysis bag*

In a tailor-made reaction vessel, which is equipped with a stirring bar, a NS50 joint and a nitrogen inlet, dry CH_2Cl_2 (90 mL) was added. To the solvent were subsequently added diethyl diallylmalonate (2.4 mmol, 580 mg, 580 μL) and hexamethylbenzene (internal standard, 0.48 mmol, 78 mg). A closed dialysis bag (Aldrich, benzoylated cellulose membranes, MWCO = 2000 Da) filled with a solution of **2** (30 μmol, 1.25 mol%, 5 mol% Ru) in CH_2Cl_2 (5 mL) was placed in this solution. At regular intervals, samples of the outer solution were taken and analyzed by GC. After the reaction had finished, the dialysis bag containing the catalyst was directly placed in a fresh batch of substrates to start a new catalytic run. Again, at regular intervals, samples of the outer solution were taken and analyzed by GC.

2.6. Protocol for the RCM of diethyl diallylmalonate with dendritic catalyst ***2*** *present in a dialysis bag, recycling of* ***2*** *by means of precipitation*

In a tailor-made reaction vessel, which is equipped with a stirring bar, a NS50 joint and a nitrogen inlet, dry CH_2Cl_2 (60 mL) was added. To the solvent were subsequently added diethyl diallylmalonate (2.4 mmol, 580 mg, 580 μL), hexamethylbenzene (internal standard, 0.48 mmol, 78 mg) and **2** (30 μmol, 1.25 mol%, 5 mol% Ru). At regular intervals, samples of the outer solution were taken and analyzed by GC. After the reaction had finished, the solution was concentrated *in vacuo* to 10% of its original volume. Dry hexanes (60 mL) were added, whereupon a brown precipitate formed. This precipitate was isolated via filtration under a nitrogen environment and redissolved in CH_2Cl_2 (60 mL) whereupon a new batch of substrate and internal standard was added. At regular intervals, samples of the solution were taken and analyzed by GC.

3. Results

3.1. Synthesis

The series of modified monomeric and dendritic (Hoveyda-)Grubbs II-type catalysts **1**–**3** were synthesized via a synthetic route based on Blechert's method for the synthesis of 3-methyl-1-mesitylimidazol-2-ylidene and 3-ethyl-1-mesitylimidazol-2-ylidene derived catalysts (Fig. 3) [42]. The NHC

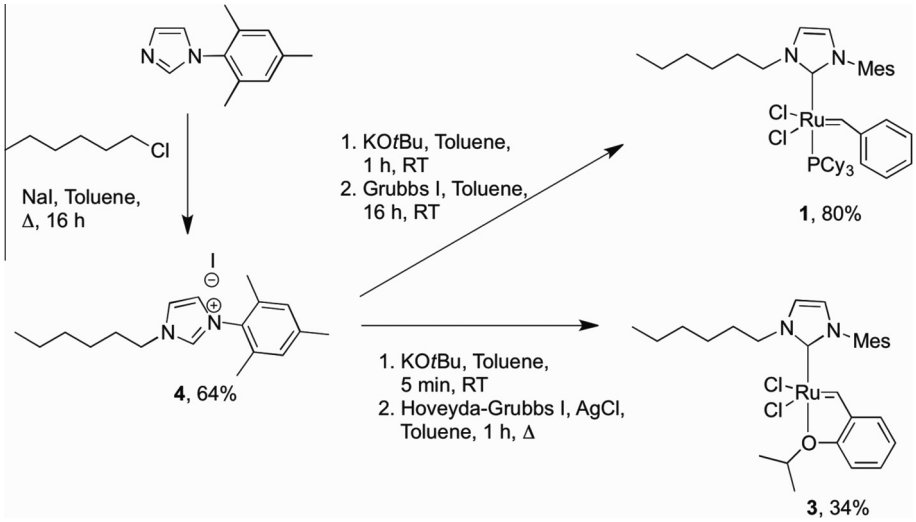


Fig. 3. Synthesis of modified monomeric Grubbs II and Hoveyda–Grubbs II complexes **1** and **3**.

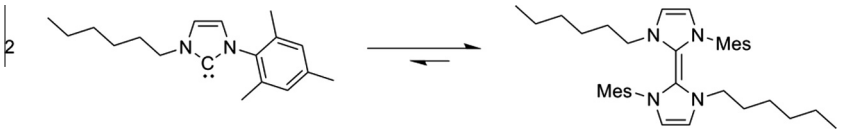


Fig. 4. Wanzlick equilibrium between two carbenes and an enetetramine.

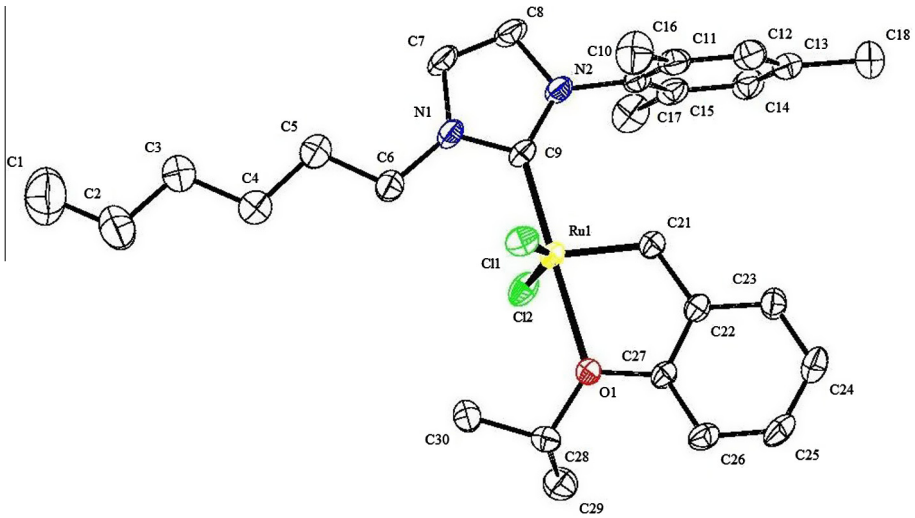


Fig. 5. ORTEP representation of the molecular structure of **3**. Displacement ellipsoids are drawn at the 50% probability level. Hydrogen atoms and disordered solvent molecules are omitted for clarity.

ligands used for **1**–**3** contain either an *n*-hexyl group or are connected to a dendritic carbosilane core via an *n*-hexyl linker.

The monomeric preligand **4** was synthesized in a one-step procedure starting from 1-mesitylimidazole (Fig. 3) [35]. Upon treatment of 1-mesitylimidazole with 1-chlorohexane and sodium iodide in refluxing toluene, 3-hexyl-1-mesitylimidazolium iodide **4** was formed in 64% isolated yield. Sodium iodide was added to the reaction mixture to generate 1-iodohexane *in situ* via a Finkelstein reaction in order to assist the nucleophilic substitution by the weak 1-mesitylimidazole nucleophile [43]. In the first step of the synthesis of mononuclear complexes **1** and **3**, preligand **4** was treated with potassium *tert*-butoxide to create the corresponding free NHC ligand *in situ*. Next, a solution of either Grubbs I catalyst **A** or Hoveyda–Grubbs I catalyst **C** was added to the toluene solution containing the NHC ligand to form complex **1** or **3**, respectively. Similar to related complexes [44,45], the synthesis of complex **1** was found to take place at room temperature and the complex could be purified by means of column chromatography using neutral alumina under inert conditions in 80% yield. The resulting brown complex was found to be more air and moisture sensitive

Table 1
Selected bond lengths (Å) and angles (°) for complex **3**, Hoveyda–Grubbs II complex **D** [10], and Blechert's modified Hoveyda–Grubbs catalyst **E** that contains a 3-ethyl-1-mesitylimidazol-2-ylidene ligand [42].

	3	D	E
Ru(1)–C(9)	1.983(2)	1.981(5)	1.966(4)
Ru(1)–C(21)	1.834(2)	1.828(5)	1.817(4)
Ru(1)–O(1)	2.2764(16)	2.261(3)	2.269(3)
N(1)–C(9)	1.369(3)	1.351(6)	1.341(6)
N(2)–C(9)	1.363(3)	1.350(6)	1.344(5)
Ru(1)–C(9)–N(1)	121.73(18)	120.8(15)	118.4(3)
Ru(1)–C(9)–N(2)	134.49(18)	131.6(16)	134.4(3)
C(9)–Ru(1)–C(21)	100.27(10)	101.5(14)	102.46(18)
O(1)–Ru(1)–C(9)	179.36(8)	176.2(14)	177.46(15)
Cl(1)–Ru(1)–Cl(2)	151.62(3)	156.5(5)	154.11(5)

than commercially available Grubbs II catalyst **B** and was therefore stored under inert conditions.

In the case of complex **3** the metalation step did not take place at room temperature and therefore harsher conditions (*i.e.* higher temperatures) were necessary. When using these elevated temperatures a side reaction occurred, which seriously decreased the overall yield of the metalation. Under these reaction conditions, the 3-hexyl-1-mesityl NHC ligand showed a strong tendency to dimerize to form enetetramines (Fig. 4). The absence of a second mesitylene group on the NHC scaffold influences this Wanzlick equilibrium [46–48] in a negative way [49]. In this respect, the often used 1,3-dimesitylimidazol-3-ylidene ligands are known to be thermodynamically stable at room temperature and can be stored in solution [50]. Higher temperatures in synthetic protocols and/or the use of other ligands can lead to undesired dimerization though. In the use of NHC's as ligands in transition metal–carbene complexes, this side reaction has been reported frequently [51,52].

Complex **3** was purified by column chromatography and was isolated in 34% yield. Crystals of **3** suitable for X-ray diffraction were obtained by hexane diffusion into a CH_2Cl_2 solution of the complex. The molecular geometry of the ruthenium center in **3** is close to square pyramidal (Fig. 5), as previously observed for the 'parent' Hoveyda–Grubbs II complex **D** [10] and Blechert's modified Hoveyda–Grubbs catalyst **E** (Fig. 1), that contains a related 3-ethyl-1-mesitylimidazol-2-ylidene ligand [42]. The C(9)–Ru(1)–O(1) bond angle of **3** (179.36(8)°) is slightly larger than the corresponding angle in complexes **D** (176.2(14)°) and **E** (177.46(15)°). Another interesting observation is that the Ru(1)–C(9)–N(1) bond angle for **3** (121.73(18)°) is closer to the same angle in **D** (120.8(15)°) than in **E** (118.4(3)°). Related to this observation, the Ru(1)–C(9)–N(2) bond angle in **3** (134.49(18)°) is closer to the angle in **E** (134.4(3)°) than in **D** (131.6(16)°). Other bond lengths and angles are very similar for the three complexes and a selection of bond lengths and angles is shown in Table 1. The orientation of the methyl groups of the isopropoxy-moiety in **3** was found to be in accordance with the orientation in **D** and **E**. The hexyl chain of complex **3** is fully stretched in the solid state, *i.e.* the distance C(1)–C(6) is 6.309(6) Å, which corresponds to the most common distance of 6.3 Å for hexyl groups [53].

Dendritic ligands **5** and **6** were obtained via a synthetic route starting from chlorodimethylsilyl-terminated carbosilane dendrimers **7** (G_0) and **8** (G_1)[36] and 6-chlorohex-1-yne (Fig. 6). In the first two steps of this route, an elongated chloroalkyl-terminated carbosilane dendrimer was synthesized. In the first step, 6-chlorohex-1-yne was deprotonated with LDA in THF at −78 °C. The chlorodimethylsilyl-terminated carbosilane dendrimers **7** or **8** were then added to these cold solutions to afford oligosilylalkynyl compounds **9** and **10**, respectively. Because of their instability towards oxygen and moisture, these silylalkynyl dendrimers were reduced immediately using Pd/C-mediated hydrogenation to afford the stable silylalkyl dendrimers **11** (G_0) and **12** (G_1). Treatment of these dendrimers with 1-mesitylimidazole in the presence of sodium iodide furnished the dendritic preligands **5** and **6**. These tetra- and dodecacationic dendritic compounds were characterized via ^1H, ^{13}C NMR and ESI-HRMS analysis.

The dendritic oligo-imidazolium ligands **5** and **6** exhibited a very poor solubility in toluene, benzene, and hexanes, which are the typical solvents used for the deprotonation of imidazolium ligands and the *in situ* metalation with first generation (Hoveyda)–Grubbs complexes to afford second generation (Hoveyda)–Grubbs complexes. Clear solutions of the G_0 preligand could be obtained by placing a toluene solution of **5** into an ultrasonic bath for a period of 1 h. The metalation of **5** via deprotonation with potassium *tert*-butoxide and treatment with Grubbs I complex **A** at room temperature successfully gave tetranuclear complex **2** (Fig. 7). This novel dendritic modified Grubbs II type complex was characterized by means of ^1H, ^{13}C, and ^{31}P NMR. Monitoring of the benzylidene proton during the metalation reaction by means of ^1H NMR showed that Grubbs complex **A** fully converted into the dendritic complex **2**.

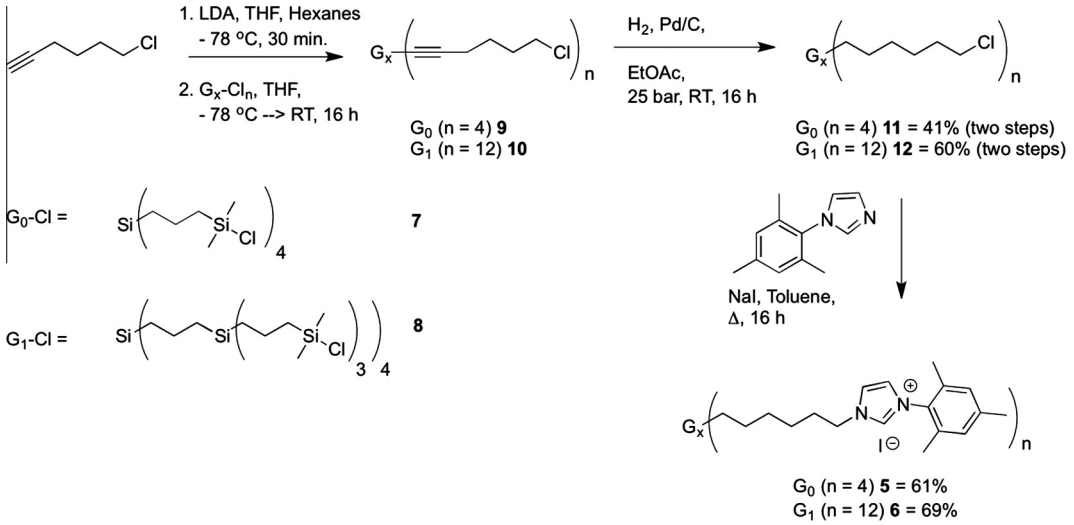


Fig. 6. Synthesis of G_0 and G_1 dendritic mesitylimidazolium ligands.

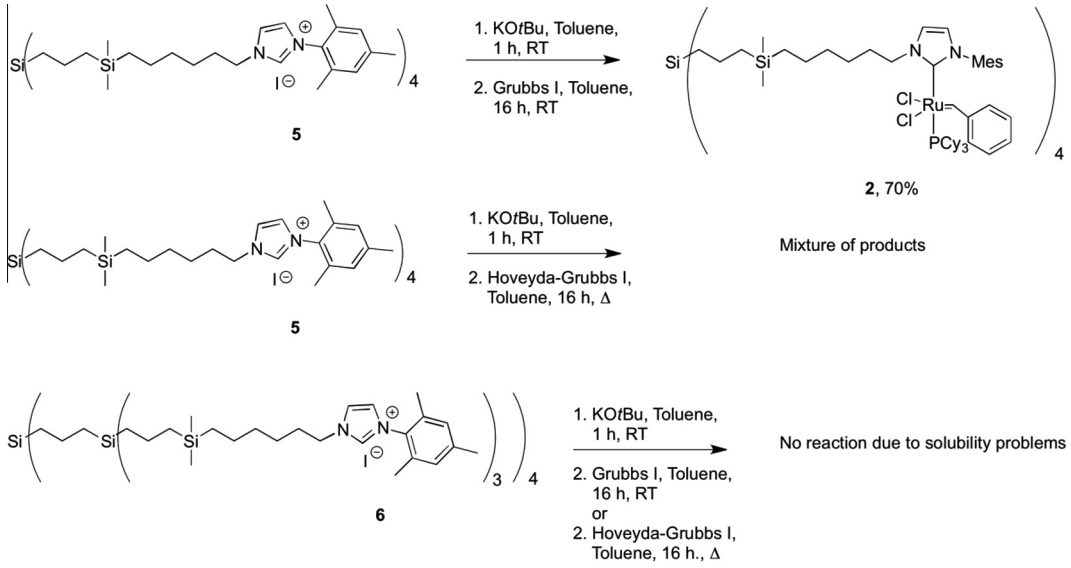


Fig. 7. Synthesis of dendritic G_0 modified Grubbs II catalysts and attempted synthesis of dendritic G_0 modified Hoveyda–Grubbs II catalysts and dendritic G_1 modified (Hoveyda-) Grubbs catalysts.

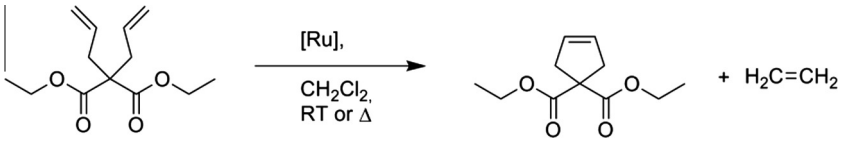


Fig. 8. RCM of diethyl diallylmalonate to diethyl cyclopent-3-ene-1,1-dicarboxylate.

Table 2
Comparison of the initial rate (conversion in % after 15 min) and the 50% and 90% substrate conversion times in the ruthenium-catalyzed RCM reaction of diethyl diallylmalonate.[a]

Catalyst	Conversion after 15 min (%)		50% Conversion (min)		90% Conversion (min)	
	RT	Reflux	RT	Reflux	RT	Reflux
Grubbs I **A**	82	88	10	8	24	21
Grubbs II **B**	40	95	24	8	91	17
Hoveyda–Grubbs II **D**	46	85	20	9	146	25
1	17	80	122	10	401	35
2	35	74	75	10	294	64
3	16	38	90	26	n.d.[b]	193

[a] Reaction conditions: 0.16 mmol diethyl diallylmalonate in 6 mL CH_2Cl_2 using 5 mol% Ru.
[b] After 24 h 87% conversion was found.

The benzylidene proton signal displayed a clear shift from 20.02 to 19.80 ppm. ^{31}P NMR analysis showed a single phosphorus resonance at 34.6 ppm for **2**, while for Grubbs complex **A** this signal is found at 36.6 ppm. Furthermore, compound **2** was successfully analyzed by MALDI-TOF MS. A parent peak at $m/z = 3703.0$ was observed (calculated value for $[M+Na]^+$ is $m/z = 3703.8$). No signals corresponding to species of lower ruthenium content or to the free ligand were observed.

The formation of a dendritic G_0 modified Hoveyda–Grubbs II complex proved troublesome for several other reasons besides solubility. Because of the dendritic nature of the preligand, the peripheral groups are in close proximity. Therefore, enetetramine formation in case of dendritic NHC ligands is an even bigger issue than in the case of a monomeric NHC ligand (*vide supra*), which can be considered as a negative dendritic effect. Upon treatment of dendritic preligand **5** with potassium *tert*-butoxide and subsequent addition of a toluene solution of Hoveyda–Grubbs I complex **C**, a mixture of products was observed after 16 h at reflux temperature. According to integral analysis in ^{1}H NMR approximately 25% of the dendritic arms was successfully loaded with a ruthenium center in this procedure. Probably the other 75% of the dendritic carbene moieties underwent dimerization to enetetramines. A signal attributed to the imidazolium protons of the enetetramine was indeed observed as a pseudo-singlet at 5.51 ppm, which is close to the reported values for similar enetetramine compounds [54,55]. The ruthenium loading was not improved by a longer reaction time or by dilution of the reaction mixture. Performing the reaction at lower temperatures rather than at reflux temperatures also did not lead to higher conversions. In addition, the use of KHMDS as base did not lead to an improved ruthenation. Due to the low ruthenium loading of the dendritic Hoveyda–Grubbs materials obtained from this procedure and their likely dispersity, these were not included in the catalytic testings.

The ruthenation of G_1 dendritic ligand **6** was attempted in a similar manner as for dendritic ligand **5**. As mentioned earlier, the solubility of **6** in toluene, benzene, and hexanes was found to be poor. For the G_0 ligands an ultrasonic treatment led to a clear solution after 1 h, but unfortunately this method did not lead to any solubility of G_1 ligand **6**. Addition of potassium *tert*-butoxide in an attempt to induce solubility upon deprotonation also did not lead to a clear solution. Therefore, disappointingly, our attempts to synthesize dendritic G_1 complexes were unsuccessful.

3.2. Catalysis

The mononuclear complexes **1** and **3** and tetranuclear dendritic complex **2** were tested as catalysts in the ring closing metathesis (RCM) reaction of diethyl diallylmalonate to form diethyl cyclo-

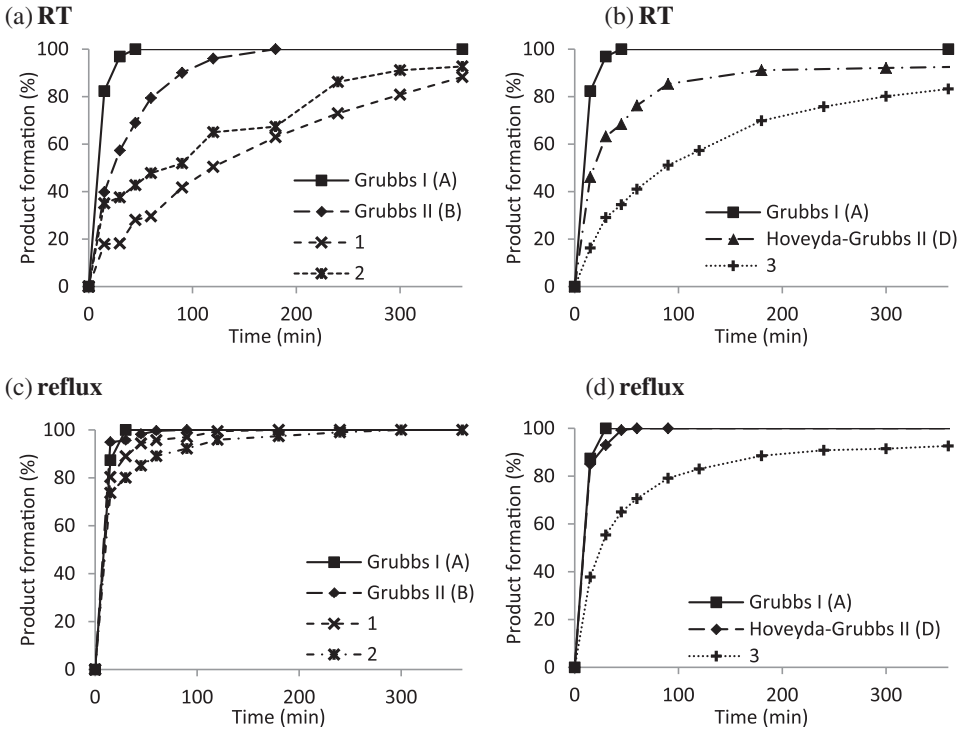


Fig. 9. Kinetic profiles of the RCM reaction of diethyl diallylmalonate: (a) Grubbs I catalyst **A** and Grubbs II-type catalysts **B**, **1** and **2** at ambient temperature; (b) Grubbs I catalyst **A** and Hoveyda–Grubbs II-type catalysts **D** and **3** at ambient temperature; (c) **A**, **B**, **1** and **2** at 40 °C; (d) **A**, **D** and **3** at 40 °C (for reaction conditions: see Table 1).

pent-3-ene-1,1-dicarboxylate (Fig. 8). The activity of these complexes in the reaction was compared experimentally to the activity of commercially available Grubbs catalysts **A** and **B** and Hoveyda–Grubbs catalysts **D**. The reactions were performed in dichloromethane at room temperature and at reflux temperature using 5 mol% ruthenium (i.e. 5 mol% catalyst for all monomeric complexes and 1.25 mol% catalyst for dendritic complex **2**).

Comparison of the various Grubbs-type catalysts showed that all catalysts gave complete substrate conversion at room temperature and at reflux temperature, except for catalyst **3** at room temperature (Table 2; Fig. 9a and b). At room temperature the commercially available Grubbs and Hoveyda–Grubbs catalysts gave very fast initial conversions, as was reported earlier [8,56]. In our setup, Grubbs I (**A**) showed 90% conversion only after 24 min, while Grubbs II (**B**) and Hoveyda–Grubbs II (**D**) showed 90% conversion after 91 and 146 min, respectively. Complexes **1** and **2** gave full conversions, but in somewhat lower reaction rates. Dendritic catalyst **2** showed a faster conversion than its monomeric analog **1** (294 and 401 min for 90% conversion, respectively), and especially the difference in initial rate was found to be striking (35% and 17% conversion after 15 min, respectively). In fact, the initial rate of dendritic catalyst **2** is closer to the initial rate of catalysts **B** and **D** than to those of **1** and **3**. Hoveyda–Grubbs-based catalyst **3** was found to be the least active catalyst among those tested. In fact, this was the only catalyst that did not show a complete reaction after 24 h. At this time, a conversion of 87% was reached.

At reflux temperatures, the reaction rates for all tested catalysts increase substantially (Fig. 9c and d). For the three commercial catalysts and catalysts **1** and **2** very high conversions (74–95%) were observed after only 15 min. All tested commercial catalysts showed 90% conversion within 17–25 min. Compound **1** was able to compete with these catalysts by showing 90% conversion after 35 min. At these slightly elevated temperatures, its dendritic analog **2** was found to be slower than **1**, whereas it was faster at ambient temperatures. Also the initial rate of dendritic catalyst **2** was somewhat lower than its monomeric analog, although still 74% conversion was achieved within 15 min. The time for **2** to reach 50% of substrate conversion was 10 min, whereas it took slightly more than 1 h to reach 90% conversion. Again, catalyst **3** was found to be much slower than all other tested catalysts: after 15 min 38% of diethyl diallylmalonate conversion was observed, while it took more than 3 h before 90% of ring-closure was achieved.

3.3. Recycling experiments

Next, dendritic catalyst **2** was used in the RCM of diethyl diallylmalonate in a compartmentalized reaction setup. In this experiment, a CH_2Cl_2 solution (5 mL) of the dendritic catalyst was placed in a closed dialysis bag. This dialysis bag was placed into a vessel containing a CH_2Cl_2 solution (90 mL) of diethyl diallylmalonate. The dialysis membrane had a mass weight cut off (MWCO) of 2000 Da, thereby allowing the substrates to permeate through the membrane, but keeping dendritic compound **2** (3703 Da) inside the dialysis bag. Agitation of the reaction mixture was brought about by means of a magnetic stirring bar at the bottom of the vessel.

Unfortunately, in this compartmentalized setup hardly any substrate conversion was observed. After 6 h, only 2% of the starting material had reacted, whereas after a full week only 16% of the diallylmalonate was converted into the cyclopent-3-ene product. The most probable reason for this inactivity is that the presence of minute amounts of water at the surface of the dialysis bag could not be totally excluded in this reaction set-up. The dialysis bags were purchased in an aqueous solution to prevent the membrane from drying. For our RCM purposes, the presence of water should be carefully avoided, as it is known that this might lead to catalyst deterioration [57,58]. Therefore these bags were pretreated by washing them consecutively in dry, degassed solutions of methanol and CH_2Cl_2 for 1 h each before use in the RCM experiment.

Apparently, these pretreatments could not fully preclude the presence of small amounts of water.

Next, recycling of the dendritic catalyst was tested in a non-compartmentalized manner, i.e. by means of catalyst precipitation after reaction completion. Using dendritic catalyst **2** under catalytic conditions at room temperature, full conversion was observed after 12 h. At that time, the reaction solution was concentrated to approximately 10% of its original volume (9 mL) and hexanes (90 mL) were added. The formed precipitate was filtered under nitrogen from the colorless solution and redissolved in CH_2Cl_2 (90 mL). Then, a new batch of diethyl diallylmalonate was added and the reaction was followed in time. Disappointingly, in this second run no product formation was observed at all. Apparently, either at the end of the first run or during workup catalyst deterioration had taken place.

4. Discussion

4.1. Synthetic considerations

The immobilization of a (Hoveyda)–Grubbs catalyst to a dendritic support can in principle take place at either of the multiple ligands that coordinate to the ruthenium center of modified first and second generation (Hoveyda)–Grubbs catalysts. These ligands include: (1) the phosphine ligand (for catalysts **A**–**C**), (2) the halogen ligands (for catalysts **A**–**D**), (3) the alkylidene ligand (for catalysts **A**–**D**), and (4) the *N*-heterocyclic carbene (NHC) ligand (for catalysts **B** and **D**). Synthetic difficulties, loss in catalytic activity and halogen scrambling are three reasons why the first two sites of immobilization have only occasionally been reported [12,59,60]. Immobilization via the alkylidene ligand to (mainly) Hoveyda–Grubbs II catalyst **D** has been reported more often [10,20,21,24,32,61–66], but is not applicable for our purpose (*vide supra*). Therefore, immobilization of the Ru centers via the NHC ligands to the dendritic support was the method of choice in our study.

We have opted for a facile immobilization manner via the NHC ligands, i.e. by the use of *N*-alkyl-*N*′-mesitylimidazol-2-ylidene ligands through the replacement of one of the mesitylene groups by an alkyl group. This method has been investigated before by other research groups [17,42,67–70], and has the advantage of a straightforward synthetic route towards the NHC–Ru compounds from commercially available starting materials. Limitations in this method are the consequences on catalyst stability and activity that result from the presence of a single mesitylene moiety on the NHC ligand of the resulting Ru-compounds, which *e.g.* enhances the chance for (inter- or intramolecular) ligand dimerization during carbene ruthenation. In particular in the case of dendritic NHC ligands, enetetramine byproduct formation was observed, and as a result significantly hampered, *i.e.* low yielding, metalation reactions that lead to mixtures of products were yielded. Especially because of the use of high temperatures that were required for the ruthenation step of the NHC ligand with Hoveyda–Grubbs catalyst **C**, byproduct formation was found to be troublesome. When Grubbs catalyst **A** was used for this metalation, no signs of enetetramine formation were observed, probably because this synthetic step was successfully performed at ambient temperatures. Dendritic ligands showed higher amounts of enetetramine formation (a negative dendritic effect), since for these ligands the carbene ligands are in close proximity by definition. The more frequently used 1,3-dimesitylimidazol-2-ylidene ligands are known to be thermodynamically stable, and therefore rather inert toward this dimerization [50].

Among others, the groups of Blechert [13], Buchmeiser [15,71], Hoveyda [62], Grubbs [22,23,72] and Weck [73] have also reported on NHC-immobilized ruthenium-based metathesis catalysts. In these cases, a hydroxymethyl-functionalized 1,3-dimesitylimidazol-2-ylidene ligand was used to accomplish a covalent linkage to the support. Initially, we also made attempts to synthesize dendritic Hoveyda–Grubbs type catalysts using this hydroxyl-modified NHC ligand, through the formation of a siloxane bond with the carbosilane dendrimer. However, the formed siloxane bonds turned out to be very susceptible towards hydrolysis and partially deteriorated during aqueous workup. Modifications in the synthesis and purification routes did not lead to NHC-modified dendrimers of sufficient purity.

Immobilization of NHC ligands via one of the two mesitylene groups was reported by Grubbs [72] and by Gilbertson [74]. The Hoveyda–Grubbs II catalyst was successfully immobilized onto silica gel and peptide chains, respectively in this way. The rather elaborate synthetic route towards mesitylene-functionalized imidazolium preligands may be considered as a drawback in this approach, but in retrospection the increased thermodynamic stability and catalytic advantages of these 1,3-dimethylimidazol-2-ylidene based systems might have outweighed the synthetic disadvantages.

4.2. Catalytic considerations

Comparison of the novel Grubbs and Hoveyda–Grubbs-type catalysts **1**–**3** in the RCM of diethyl diallylmalonate has led to a number of interesting observations. When dendritic catalyst **2** is compared to its monomeric analog **1**, the dendritic catalyst appears to be slightly more active at room temperature (93% versus 89% conversion after 6 h). This effect is even more clear upon comparison of the initial rates of **2** and **1** (35% versus 17% conversion after 15 min). An explanation for this observation could be that the dendritic scaffold in **2** causes a certain degree of steric crowding, which might compensate for the decreased steric bulk around the NHC–Ru moiety due to the lack of one mesitylene group; accordingly, a higher initial catalytic rate was observed for **2** compared to **1**. At reflux temperature monomeric catalyst **1** slightly outperforms dendritic catalyst **2**, possibly due to the faster deactivation of the dendritic catalyst, which cancels out advantageous steric effects. For the modified Hoveyda–Grubbs catalyst **3** a lower activity was observed as compared to catalyst **1** (Fig. 9). Still, this novel catalyst showed reasonable to good catalytic activity towards diethyl diallylmalonate with 80% conversion after 5 h at ambient temperatures and a complete conversion after 5 h at 40 °C.

Besides these observations, a lower overall reactivity in the RCM of diethyl diallylmalonate was observed for the novel complexes **1**–**3** compared to commercially available Grubbs catalysts **A**, **B** and **D**. The replacement of one of the mesitylene moieties by an alkyl group and the use of a saturated imidazolium-based NHC ligand instead of an unsaturated imidazolinium-based ligand, like in Grubbs II catalysts, makes the ruthenium center less sterically crowded and more electron rich [75–77], resulting in a somewhat lower activity. Similar effects have recently also been reported by other research groups. Verpoort and co-workers reported on a comparison of catalyst **B** to, among others, a modified Grubbs II complex bearing a 3-octyl-1-mesityl-NHC ligand in the ROMP of 1,5-cyclooctadiene [68]. Also Blechert and co-workers observed somewhat lower reaction yields of modified Grubbs II or Hoveyda–Grubbs II complexes that contain 3-methyl-1-mesityl-NHC or 3-ethyl-1-mesityl-NHC ligands in the cross metathesis of different olefin substrates compared to catalysts **B** and **D** [42]. These complexes, however, sometimes show entirely different product selectivities than the more active complexes **B** and **D**. Finally, Fürstner showed that the RCM of diethyl diallylmalonate was significantly slower than when performed with catalyst **B**, but could be successfully performed in three successive runs by

using second generation ruthenium benzylidene metathesis catalysts bearing hydroxyalkyl chains on their NHC ligands.[17].

5. Conclusions

Summarizing, we have presented the synthesis and application of new monomeric and dendritic (Hoveyda–)Grubbs-type ruthenium catalysts that contain a 3-alkyl-1-mesityl-NHC ligand. In the RCM reaction of diethyl diallylmalonate these catalysts showed good conversions, but the catalytic rate was found to be considerably lower than for commercially available olefin metathesis catalysts. The dendritic catalyst **2** showed a higher activity compared to its monomeric analog at room temperature and a somewhat lower activity at reflux temperatures. Complex **2** was found to be too moisture-sensitive to be successfully applied in compartmentalized catalysis. By changing to the more stable Hoveyda–Grubbs-type catalysts and by using a different type of NHC ligand, *e.g.* a 1,3-dimesitylimidazol-2-ylidene ligand for these complexes, a catalytic system would be created that is more active and would be less affected by the presence of minute amounts of water in the reaction mixture. The immobilization of the catalyst to the dendritic support could then either take place via the imidazolium ring or via one of the two mesitylene groups of the NHC ligand. With such improved dendritic Hoveyda–Grubbs catalysts the way would be paved for the first example of successful compartmentalized olefin metathesis. This will be the subject of further investigations.

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Appendix A. Supplementary material

CCDC 932412 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ica.2013.06.018.

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