

Self-assembly of hyperbranched spheres

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A new type of building block with two coordinatively unsaturated palladium centres has been described that self-assembles in nitromethane solution and disassembles when acetonitrile is added. The resulting hyperbranched, organopalladium spheres have a remarkably narrow size distribution as was evidenced by light-scattering, AFM and TEM measurements. Variation of the structure of the building blocks showed the possibility to vary the size of the self-assembled spheres between 100 and 400 nm.

There is an ongoing demand for the development of nanosize materials. Especially, the electronics industry is searching for nanosize architectures permitting increased processing speeds, and higher levels of integration. Current nanophysical 'engineering down' approaches can routinely fabricate structures in the range of 0.1–0.2 μm . Alternatively, chemists exploit a 'bottom up' approach to synthesize nanosize devices with molecular precision. In this respect, synthetic organic chemistry offers a powerful and versatile tool for the synthesis of large and complex molecules with a variety of functions and shapes. However, the synthesis of very large molecules using only covalent bonds is less practical. Non-covalent interactions can be exploited to connect building blocks in the construction of much larger architectures. The rational use of non-covalent interactions requires the understanding of the principles of self-assembly.¹ Our current research aims at the development of new methods of self-assembly that will lead to large structures.² Dendrimers represent a class of polymers that combine a high molecular mass with a well defined spherical shape of nanometre dimensions. Sequential synthesis, either divergent³ or convergent,⁴ can be used to grow dendrimers stepwise, generation after generation. Alternatively, instead of using this laborious method a one-pot polymerization of suitable building blocks yields less regular hyperbranched organic polymers. Recently, Fréchet *et al.* used branched monomers that contain polymerizable groups at both ends, so-called AB₂-type monomers, that yield hyperbranched polymers with a relatively narrow size distribution and high molecular masses.⁵

Recently, several groups have used transition metals to build small metallo-dendrimers.⁶ Our approach is to design AB₂-type building blocks for the self-assembly of hyperbranched coordination polymers.⁷ These building blocks should contain all information necessary to form well defined three-dimensional hyperbranched structures. In each building block **1**, two kinetically inert Pd centres and one kinetically labile CH₂CN ligand, are present. In a coordinating solvent, like MeCN, a solvent molecule is weakly coordinating to the fourth coordination site and hence the building blocks remain monomeric. Removal of this solvent and introduction of a non-coordinating solvent, such as MeNO₂, initiates intermolecular coordination of the labile ligands. This means that a new building block is added to the starting nucleus generating two new sites for further growth. Schematically the self-assembly process is shown in Fig. 1.

In a dendritic model, the centre of the self-assembled spheres will be less dense than the surface. Therefore, the size of the building blocks should be related to the size of the assemblies formed. For this reason, building blocks with different struc-

tures have been synthesized and the resulting assemblies have been studied by quasi-elastic light scattering (QELS), atomic force microscopy (AFM) and transmission electron microscopy (TEM). In this paper we present a general methodology to synthesize spherical particles in the range 100–400 nm.

Experimental

Melting points were determined with a Reichert melting point apparatus and are uncorrected. ¹H NMR and ¹³C NMR spectra were recorded in CDCl₃ (unless indicated otherwise) with Me₄Si as internal standard on a Bruker AC 250 spectrometer. Mass spectra were recorded with a Finnigan MAT 90 spectrometer using *m*-nitrobenzyl alcohol as a matrix. THF was freshly distilled from Na/benzophenone, hexane (referring to light petroleum with bp 60–80 °C) and CH₂Cl₂ from K₂CO₃. Nitromethane was washed with 1 M HCl and water and distilled from CaCl₂. NaH was a 50% dispersion in mineral oil and was used after washing with hexane. Other chemicals were of reagent grade and were used as received. Column chromatography was performed with silica gel 60H (0.005–0.040 mm) from Merck. [Pd(MeCN)₄][BF₄]₂,⁸ 5-hydroxyisophthalic acid dimethyl ester,⁹ and a,a',a''-tribromomesitylene¹⁰ were prepared according to literature procedures.

QELS was performed with a Malvern PCS 100 goniometer (Malvern Instruments, Malvern, England) at an angle of 90°, with an Adlas Model DPY 305 II, 50 mW, continuous wave

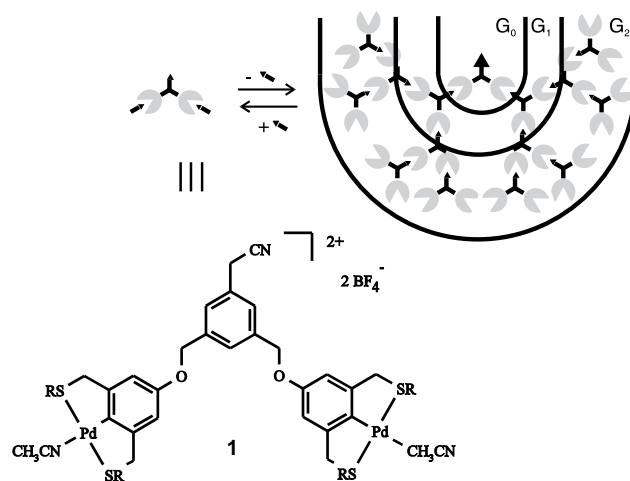


Fig. 1 Schematic representation of the self-assembly of hyperbranched polymers

diode pumped YAG laser, wavelength 532 nm (Atlas, Lübeck, Germany), and an ALV 5000 multiple tau digital correlator (ALV, Langen, Germany). The correlation function was transformed into a diameter distribution with the CONTIN program. The instrument used for atomic force microscopy (AFM) was a Nanoscope III operating in constant force (*ca.* 50 nN) mode with cantilever force constants of 0.58 N m⁻¹ and a home-made supertip. Samples for transmission electron microscopy (TEM) were prepared by slow evaporation of a nitromethane solution on a carbon-coated copper grid.

5-*tert*-Butyldimethylsilyloxyisophthalic acid dimethyl ester 3

TBDMSiCl (16.0 g, 0.106 mol) was dissolved in CH₂Cl₂ (50 ml) and was slowly added to a solution of 5-hydroxyisophthalic acid dimethyl ester **2** (11.18 g, 0.053 mol), Et₃N (6.99 g, 0.069 mol), and DMAP (catalytic amount) in CH₂Cl₂ (150 ml) at 0 °C. After stirring overnight at room temperature, the mixture was washed with 1 M HCl, a saturated aqueous solution of NaHCO₃, and brine. After drying (MgSO₄), the solvent was evaporated and **3** was obtained as a white solid upon drying under high vacuum. Yield 15.3 g (89%), mp 68–70 °C; ¹H NMR d, 8.29 (s, 1H, ArH), 7.68 (s, 2H, ArH), 3.93 (s, 6H, OCH₃), 1.00 (s, 9H, Bu^t), 0.23 (s, 6H, SiCH₃); ¹³C NMR d, 166.1, 156.0, 131.8, 125.4, 123.7, 52.6, 25.6, 18.2, -4.5; FAB MS *m/z*, 324.1 (M⁺, calc. 324.1); Anal. Calc. for C₁₆H₂₄O₅Si: C, 59.23; H, 7.46. Found: C, 59.55; H, 7.60%.

3,5-Bis(hydroxymethyl)phenol *tert*-butyldimethylsilyl ether 4

LiAlH₄ (4.8 g, 0.12 mol) was suspended in dry THF (200 ml) and a solution of diester **3** (20.0 g, 0.062 mol) in THF (100 ml) was slowly added. The mixture was stirred overnight at room temperature after which THF was evaporated. The resulting paste was dissolved in dichloromethane (200 ml) and cooled to 0 °C and 2 M HCl (100 ml) was added, after which the layers were separated. Extraction of the aqueous layer with dichloromethane (3 × 100 ml) and drying of the combined organic layers gave, after removal of the solvent, pure **4** as a white solid. Yield 15.3 g (93%), mp 99–100 °C; ¹H NMR d, 6.94 (s, 1H, ArH), 6.77 (s, 2H, ArH), 4.62 (s, 4H, CH₂O), 0.99 (s, 9H, Bu^t), 0.20 (s, 6H, SiCH₃); ¹³C NMR d, 156.0, 142.8, 118.1, 64.9, 25.7, 18.2, -4.4; FAB MS *m/z*, 268.0 (M⁺, calc. 268.1); Anal. Calc. for C₁₄H₂₄O₃Si: C, 62.64; H, 9.01. Found: C, 62.59; H, 9.19%.

3,5-Bis(chloromethyl)phenol *tert*-butyldimethylsilyl ether 5

Diol **4** (4.0 g, 0.015 mol) and Et₃N (6.2 g, 0.045 mol) were dissolved in dry CHCl₃ and cooled to 0 °C. Mesityl chloride (MsCl) (3.44 g, 0.045 mol) was slowly added at 0 °C after which the reaction mixture was slowly heated to 50 °C. Stirring overnight and subsequent washing with 1 M NaOH and 1 M HCl, drying over MgSO₄ and evaporation of the solvent gave **5** as a colourless oil. Yield 4.2 g (92%); ¹H NMR d, 6.80 (s, 1H, ArH), 6.62 (s, 2H, ArH), 4.32 (s, 4H, CH₂Cl), 0.78 (s, 9H, Bu^t), 0.00 (s, 6H, SiCH₃); ¹³C NMR d, 156.1, 139.2, 121.4, 118.9, 45.7, 26.6, 24.7, -3.5; EIMS *m/z*, 304.081 (M⁺, calc. for C₁₄H₂₂SiCl₂O: 304.081).

General procedure for the synthesis of thioethers 6a–d

3,5-Bis(phenylthiamethyl)phenol 6a. Thiophenol (5.77 g, 0.052 mol) was added to a stirred suspension of NaH (2.52 g, 0.104 mol) in THF (200 ml) and the mixture was stirred for 1 h to allow formation of the sodium thiophenolate salt. To the resulting milky solution dichloride **5** (4.0 g, 0.013 mol) was added and the reaction mixture was stirred overnight at 50 °C. After removal of the solvent the crude reaction mixture was dissolved in dichloromethane (200 ml) and washed with brine (100 ml). To remove excess of thiol the organic layer was washed with 2 M NaOH (100 ml). After drying, the organic

layer was concentrated under reduced pressure. The TBDMS groups were then removed by dissolving the thioether in THF (100 ml) and adding 1 equiv. of CsF (2.0 g, 0.013 mol). After stirring overnight at 50 °C, THF was evaporated and the residue dissolved in dichloromethane followed by washing with brine, drying over MgSO₄ and concentration *in vacuo*. Column chromatography (silica gel, eluent CH₂Cl₂) gave pincer ligand **6a** as a colourless oil. Yield 3.38 g (77%); ¹H NMR d, 7.29–7.16 (m, 10H, SPh), 6.79 (s, 1H, ArH), 6.64 (s, 2H, ArH), 4.89 (br s, 1H, OH), 4.00 (s, 4H, CH₂S); ¹³C NMR d, 155.7, 139.5, 131.2, 129.9, 128.9, 128.6, 126.4, 121.8, 114.6, 38.7; EIMS *m/z*, 338.078 (M⁺, calc. for C₂₀H₁₈OS₂: 338.080).

3,5-Bis(-1-naphthylthiamethyl)phenol 6b. White solid. Yield 76%, mp 75–77 °C; ¹H NMR d, 7.88–7.68 (m, 8H, Snaphthyl), 7.48–7.30 (m, 6H, Snaphthyl), 6.90 (s, 2H, ArH), 6.72 (s, 1H, ArH), 4.09 (s, 4H, CH₂S) ¹³C NMR d, 155.8, 139.4, 133.7, 131.9, 128.4–125.8, 122.0, 114.8, 38.5; EIMS *m/z*, 438.402 (M⁺, calc. for C₂₈H₂₂OS₂: 438.601).

3,5-Bis(*tert*-butylthiamethyl)phenol 6c. Colourless oil, solidified slowly upon standing. Yield 47%, mp 80–82 °C; ¹H NMR d, 6.89 (s, 1H, ArH), 6.70 (s, 2H, ArH), 4.68 (bs, 1H, OH), 3.67 (s, 4H, CH₂S), 1.30 (s, 18H, CH₃); ¹³C NMR d, 155.0, 140.5, 122.0, 114.5, 33.2, 30.9, 23.6; EIMS *m/z*, 298.142 (M⁺, calc. for C₁₆H₂₆OS₂: 298.143).

3,5-Bis(ethylthiamethyl)phenol 6d. Pale yellow oil. Yield 23%; ¹H NMR d, 6.83 (s, 1H, ArH), 6.69 (s, 2H, ArH), 5.21 (br s, 1H, OH), 3.62 (s, 4H, CH₂S), 2.44 (q, 4H, *J* 8.4 Hz, SCH₂CH₃), 1.23 (t, 6H, *J* 8.4 Hz, CH₃); ¹³C NMR d, 155.8, 140.5, 121.8, 114.4, 35.6, 25.6, 14.4; EIMS *m/z*, 242.080 (M⁺, calc. for C₁₂H₁₈OS₂: 242.080).

a,a'-Dibromo-a''-cyanomesitylene 7. To a solution of a,a'-tribromomesitylene (5.0 g, 0.014 mol) in MeCN (200 ml) were added powdered KCN (0.91 g, 0.014 mol), 18-crown-6 (0.25 g, 0.95 mmol), and water (0.5 ml). The mixture was refluxed for 48 h after which the solvent was evaporated and the residue was taken up in CH₂Cl₂ (100 ml). After washing with brine and drying over MgSO₄ the crude reaction mixture was concentrated *in vacuo* and purified by column chromatography (SiO₂, eluent CH₂Cl₂). This yielded pure **7** as a colourless oil which solidified upon standing. Yield 0.85 g (20%), mp 67–69 °C; ¹H NMR d, 7.40 (s, 1H, ArH), 7.32 (s, 2H, ArH), 4.47 (s, 4H, CH₂Br), 3.72 (s, 2H, CH₂CN); ¹³C NMR d, 139.6, 131.3, 129.3, 128.5, 117.3, 32.0, 23.4; EIMS *m/z*, 302.9 (M⁺, calc. 303.0); IR (KBr) 2252 cm⁻¹ (C≡N); Anal. Calc. for C₁₀H₆NBr₂: C, 39.64; H, 2.99; N, 4.62. Found: C, 39.69; H, 2.94; N, 4.50%.

General procedure for the synthesis of thioether ligands 8a–d

a,a'-Bis[3,5-bis(phenylthiamethyl)phenoxy]-a''-cyanomesitylene 8a. Compound **6a** (0.3 g, 0.75 mmol) was stirred with K₂CO₃ (0.13 g, 0.94 mmol) in MeCN (50 ml) for 1 h at room temperature (r.t.). Spacer **7** (0.13 g, 0.38 mmol) was added and the reaction mixture was stirred for 4 days at r.t. The reaction was concentrated under reduced pressure and dichloromethane (50 ml) was added to the residue. The organic layer was washed with brine, dried over MgSO₄ and concentrated. Column chromatography (silica gel, CH₂Cl₂–hexanes 80:20) gave pure **8a** as a colourless oil. Yield 0.26 g (72%); ¹H NMR d, 7.31 (s, 1H, Ar_{CN}H), 7.29–7.16 (m, 22H, SPh + Ar_{CN}H), 6.85 (s, 2H, Ar_OH), 6.79 (s, 4H, Ar_OH), 4.94 (s, 4H, CH₂O), 4.03 (s, 8H, CH₂S), 3.73 (s, 2H, CH₂CN); ¹³C NMR d, 158.6, 139.3, 138.4, 136.1, 130.7, 129.9, 128.9, 126.4, 126.0, 122.2, 117.6, 114.0, 69.2, 38.9, 23.5; EIMS *m/z*, 817.216 (M⁺, calc. for C₅₀H₄₃NO₂S₄: 817.218); IR (KBr) 2251 cm⁻¹ (C≡N).

a,a'-Bis[3,5-bis(1-naphthylthiamethyl)phenoxy]-a''-cyano-mesitylene 8b. Colourless oil. Yield 70%; ¹H NMR d, 7.80–7.59 (m, 16H, Snaphthyl), 7.47–7.32 (m, 12H, Snaphthyl), 7.30 (s, 1H, Ar_{CN}H), 7.21 (s, 2H, Ar_{CN}H), 6.95 (s, 2H, Ar_OH), 6.75 (s, 4H, Ar_OH), 4.74 (s, 4H, CH₂O), 4.12 (s, 8H, CH₂S), 3.62 (s, 2H, CH₂CN); ¹³C NMR d, 158.7, 139.2, 138.3, 133.6, 131.9, 130.5, 128.8, 128.0, 127.8, 127.7, 126.5, 126.3, 125.9, 125.8, 122.3, 114.2, 69.2, 38.8; EIMS *m/z*, 1017.280 (M⁺, calc. for C₆₆H₅₁NO₂S₄: 1017.280).

a,a'-Bis[3,5-bis(*tert*-butylthiamethyl)phenoxy]-a''-cyano-mesitylene 8c. Slightly yellow oil. Yield 25%. ¹H NMR d, 7.46 (s, 1H, Ar_{CN}H), 7.37 (s, 2H, Ar_{CN}H), 6.96 (s, 2H, Ar_OH), 6.85 (s, 4H, Ar_OH), 5.08 (s, 4H, CH₂O), 3.80 (s, 2H, CH₂CN), 3.71 (s, 4H, CH₂S), 1.33 (s, 36H, CH₃); ¹³C NMR d, 158.7, 140.4, 138.6, 130.6, 126.4, 122.5, 113.9, 69.3, 42.9, 33.4, 30.9, 23.6; EIMS *m/z*, 737.339 (M⁺, calc. for C₄₂H₅₉NO₂S₄: 737.343).

a,a'-Bis[3,5-bis(ethylthiamethyl)phenoxy]-a''-cyano-mesitylene 8d. Colourless oil. Yield 48%; ¹H NMR d, 7.47 (s, 1H, Ar_{CN}H), 7.37 (s, 2H, Ar_{CN}H), 6.88 (s, 2H, Ar_OH), 6.85 (s, 4H, Ar_OH), 5.06 (s, 4H, CH₂O), 3.77 (s, 2H, CH₂CN), 3.67 (s, 8H, CH₂S), 2.44 (q, 8H, *J* 8.4 Hz, SCH₂CH₃), 1.22 (t, 12H, *J* 8.4 Hz, CH₃); ¹³C NMR d, 158.7, 141.3, 138.5, 130.7, 127.8, 126.1, 122.2, 120.7, 117.6, 113.7, 69.2, 53.5, 37.5, 25.4, 23.5, 14.4; FAB MS *m/z*, 625.620 (M⁺, calc. for C₃₄H₄₃NO₂S₄: 625.959).

General procedure for the cyclopalladation of the pincer ligands 8a–d and conversion into the chloride complexes 9a,b and d

Bis(Pd–Cl) complex 9a. Ligand **8a** (0.50 g, 0.62 mmol) was dissolved in acetonitrile (150 ml) and placed under an Ar atmosphere. Solid [Pd(MeCN)₄][BF₄]₂ (0.54 g, 1.22 mmol) was added in one portion. The orange solution was warmed to 40 °C and stirred until the colour changed to pale yellow. After cooling to r.t. and evaporation of the solvent the yellow cyclopalladated product was obtained in quantitative yield. This product was dissolved in CH₂Cl₂–MeCN (3:1, 100 ml) and the reaction mixture was stirred vigorously for 30 min with brine (100 ml). The layers were separated and the organic layer was washed with water (100 ml) and evaporated to dryness. Purification by column chromatography (silica gel, CH₂Cl₂–MeOH, 95:5) gave **9a** as a yellow solid (1.18 g, 50%), mp 132–133 °C; ¹H NMR d, 7.81–7.74 (m, 8H, SPh), 7.39 (s, 1H, Ar_{CN}H), 7.35–7.29 (m, 14H, SPh + Ar_{CN}H), 6.64 (s, 4H, Ar_{Pd}H), 4.95 (s, 4H, CH₂O), 4.5 (bs, 8H, CH₂S), 3.76 (s, 2H, CH₂CN); ¹³C NMR d, 156.4, 152.3, 150.2, 138.4, 132.3, 131.4, 130.9, 129.8, 129.7, 126.6, 126.0, 117.7, 109.2, 69.5, 51.7, 23.6; FAB MS *m/z*, 1064.3 [(M–Cl)⁺, calc. 1064.3]; IR (KBr), 2252 cm⁻¹ (C≡N). Anal. Calc. for C₅₀H₄₁NO₂S₄Pd₂Cl₂·H₂O: C, 53.72; H, 3.88; N, 1.25. Found: C, 53.65; H, 3.73; N, 1.64%.

Bis(Pd–Cl) complex 9b. Orange solid. Yield 56%, mp 160–162 °C; ¹H NMR d, 8.30 (s, 4H, Snaphthyl), 7.94–7.76 (m, 16H, Snaphthyl), 7.52–7.49 (m, 8H, Snaphthyl), 7.40 (s, 1H, Ar_{CN}H), 7.34 (s, 2H, Ar_{CN}H), 6.67 (s, 4H, Ar_{Pd}H), 4.99 (s, 4H, CH₂O), 4.63 (br s, 8H, CH₂S), 3.76 (s, 2H, CH₂CN); ¹³C NMR d, 157.2, 150.3, 138.4, 133.4, 133.2, 131.2, 129.7, 129.3, 128.2, 127.8, 127.6, 127.1, 109.2, 69.5, 52.4, 23.1; FAB MS *m/z*, 1264.3 [(M–Cl)⁺, calc. 1264.6]. Anal. Calc. for C₆₆H₄₉NO₂S₄Pd₂Cl₂·2H₂O: C, 59.33; H, 3.99; N, 1.05; S, 9.60. Found: C, 58.93; H, 3.73; N, 1.18; S, 9.46%.

Bis(Pd–Cl) complex 9c. The cyclopalladation of ligand **8c** (0.50 g, 0.68 mmol) was performed as described for **9a**. The crude palladium complex was dissolved in CH₂Cl₂–MeCN (1:1, 50 ml) and excess NMe₄Cl (0.50 g, 4.57 mmol) was added in one portion. The reaction mixture was stirred overnight. After removal of the salts, the filtrate was evaporated to dryness. Purification by column chromatography (silica gel, CH₂Cl₂–MeOH, 95:5) gave **9c** as a brownish solid. Yield

0.14 g (20%), mp 131–132 °C; ¹H NMR d, 7.38 (s, 1H, Ar_{CN}H), 7.32 (s, 2H, Ar_{CN}H), 6.68 (s, 4H, Ar_{Pd}H), 4.97 (s, 4H, CH₂O), 4.10 (br s, 8H, CH₂S), 3.81 (s, 2H, CH₂CN), 1.69 (s, 36H, Bu^t); ¹³C NMR d, 156.2, 150.6, 138.5, 130.8, 126.5, 117.6, 108.4, 69.5, 52.0, 42.7, 30.6, 23.6; FAB MS *m/z*, 984.3 [(M–Cl)⁺, calc. 983.6]; Anal. Calc. for C₅₀H₄₁NO₂S₄Pd₂Cl₂·H₂O: C, 46.97; H, 5.36; N, 1.38. Found: C, 47.58; H, 5.36; N, 1.38%.

Bis(Pd–Cl) complex 9d. Brownish solid. Yield 16%, mp 106–107 °C; ¹H NMR d, 7.39 (s, 1H, Ar_{CN}H), 7.36 (s, 2H, Ar_{CN}H), 6.68 (s, 4H, Ar_{Pd}H), 4.98 (s, 4H, CH₂O), 4.2 (br s, 8H, CH₂S), 3.81 (s, 2H, CH₂CN), 3.19 (q, 8H, *J* 8.4 Hz, SCH₂CH₃), 1.67 (t, 12H, *J* 8.4 Hz, CH₃); FAB MS *m/z*, 871.8 [(M–Cl)⁺, calc. 871.3]. Anal. Calc. for C₃₄H₄₁NO₂S₄Pd₂Cl₂·0.5C₆H₁₄: C, 46.74; H, 5.09; N, 1.47. Found: C, 46.33; H, 4.96; N, 1.66%.

Results and Discussion

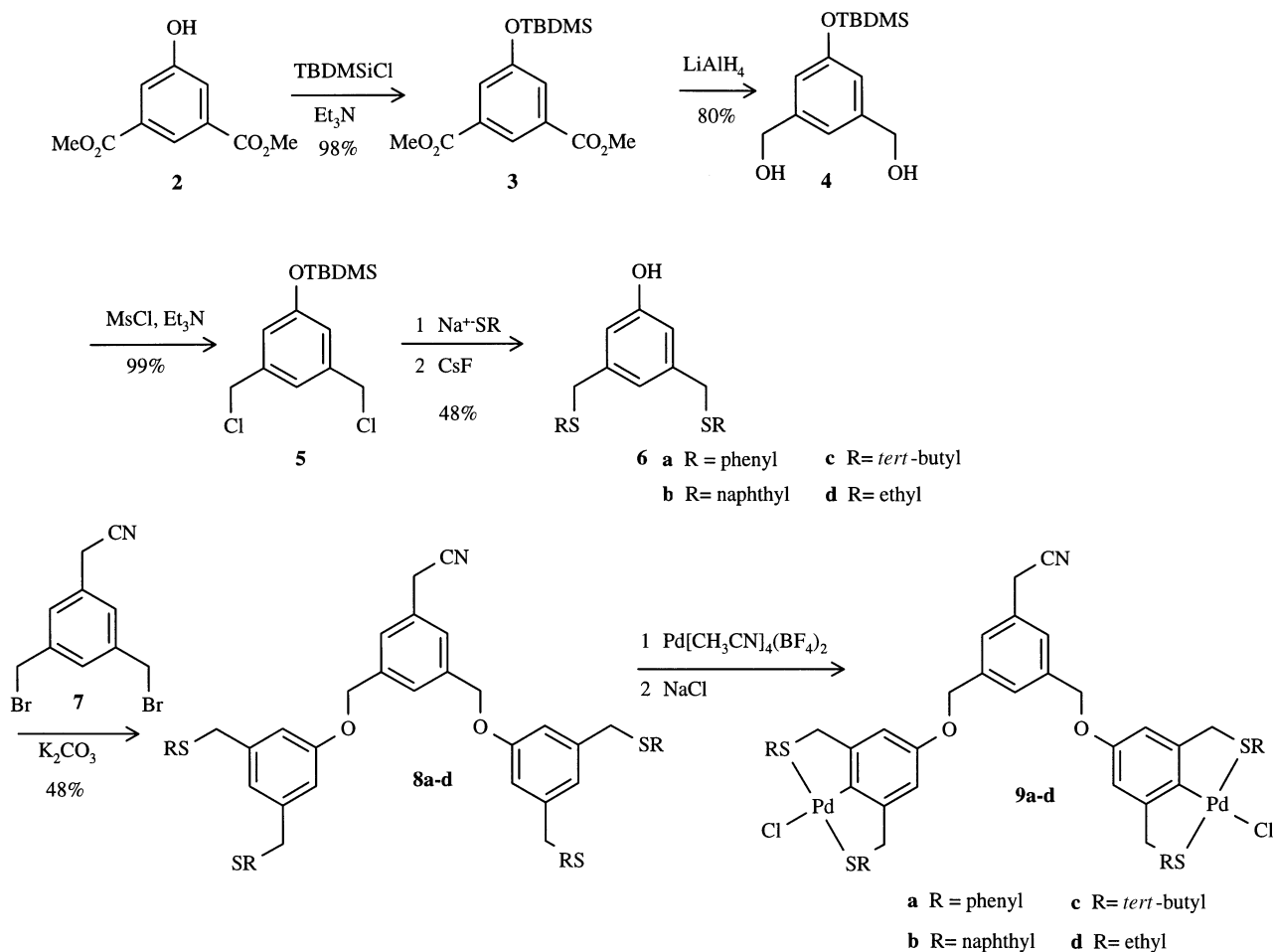
Synthesis of building blocks

A convergent synthesis route has been exploited to connect two pincer ligands to a spacer containing the kinetically labile (cyano) ligand. Key intermediates **6** were synthesized in six steps from 5-hydroxyisophthalic acid as shown in Scheme 1. The first step is the esterification of 5-hydroxyisophthalic acid according to literature procedures.⁸ The phenolic group was protected with TBDMSiCl in 95% yield and subsequently the esters were reduced with LiAlH₄ to the diol **4** in 70% yield. The diol was stirred overnight with MsCl–Et₃N at 50 °C which gave complete conversion into the dichloride **5**. The thioether functions were introduced by stirring the appropriate thiol with NaH in THF to generate the sodium thiolate, and subsequent addition of the dichloride **5**. This reaction yielded the SCS pincer ligands with the *p*-hydroxy functions protected. The TBDMSi ether was deprotected with CsF to give the SCS pincer type ligand **6** in 10% overall yield from 5-hydroxyisophthalic acid. The thioethers **6** were coupled to spacer **7** which introduces the weakly coordinating cyano group. The spacer **7** was prepared from a,a',a''-tribromomesitylene by refluxing in acetonitrile for two days with powdered KCN. From the resulting mixture **7** could be isolated in 20% yield. The formation of the benzylic ethers proceeded in rather poor yields because **7** slowly decomposed. Ligands **8a–d** were cyclopalladated with [Pd(MeCN)₄][BF₄]₂ in acetonitrile in high yields. Prior to self-assembly studies, the cationic solvento complexes were converted into chloropalladium complexes by stirring a solution in CH₂Cl₂ and MeCN with brine. This made purification easier and allowed the simple introduction of various non-coordinating anions (*vide infra*). The *tert*-butyl derivative **9c** was prepared by stirring the cationic palladium complex from **8c** with NMe₄Cl, as reaction with brine only gave intractable polymeric products.

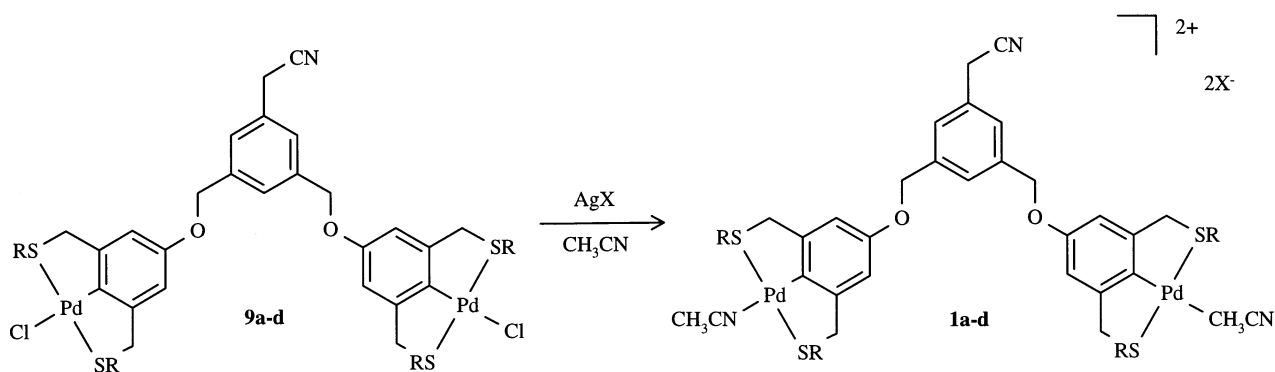
The ¹H NMR spectra of **9a–d** in CD₃CN show a broad singlet for the CH₂SR protons at δ 4.6 because of the slow conformational interconversion of the palladium(II)-containing five-membered rings.¹¹ The signal for the protons *ortho* to both donor atoms in **9a–d** at δ 6.85 is absent, indicating complete cyclopalladation. The ¹H NMR spectrum clearly showed that no cyclopalladation had occurred at other aromatic positions.

Self-assembly takes place when the CH₂CN group of one building block coordinates intermolecularly to the Pd centre of another. Therefore the Pd centres were first activated by the replacement of the chloride by different non-coordinating anions. Addition of one equivalent of the appropriate silver salt activates the Pd centre by precipitation of AgCl in a fast and quantitative reaction.† In acetonitrile solution a bis-

† This has been demonstrated using ³¹P NMR spectroscopy in an analogous PCP pincer complex; unpublished results.



Scheme 1



Scheme 2 $X^- = \text{BF}_4^-, \text{ClO}_4^-, \text{PF}_6^-, \text{triflate, tosylate, BPh}_4^-$

acetonitrile complex $\cdot 2X^-$ ($X^- = \text{BF}_4^-, \text{ClO}_4^-, \text{PF}_6^-, \text{triflate, tosylate or BPh}_4^-$) is formed (Scheme 2).

Self-assembly and characterization

The self-assembly process of **1a-d** was initiated by elimination of the acetonitrile ligands. After removal of the acetonitrile (the ^1H NMR spectrum in CD_3NO_2 showed no acetonitrile), the CH_2CN groups of the bis-palladium complexes occupy the fourth coordination site. In the IR spectrum the coordination of the cyano group was confirmed by the characteristic shift of the $\text{C}\equiv\text{N}$ stretch vibration from 2250 cm^{-1} for the monomeric building blocks to 2290 cm^{-1} upon coordination.¹² The ^1H NMR spectra of **1a-d** showed broad peaks in CD_3NO_2 ,

indicating large structures. When small amounts of acetonitrile were added to these solutions all signals became sharp. This proves that the self-assembly of **1a-d** and disassembly of the hyperbranched polymer is a reversible process. In order to obtain information on the size and shape the resulting assemblies were further characterized by QELS, TEM and AFM.[‡]

QELS measurements of nitromethane solutions of assemblies of **1a** ($X^- = \text{BF}_4^-$) showed particles with an average hydrodynamic diameter of 180 nm using the CONTIN curve-fitting

[‡] Gel permeation chromatography (GPC) was not successful. Probably the highly charged assemblies have a strong interaction with the column material and are therefore difficult to characterize using GPC.

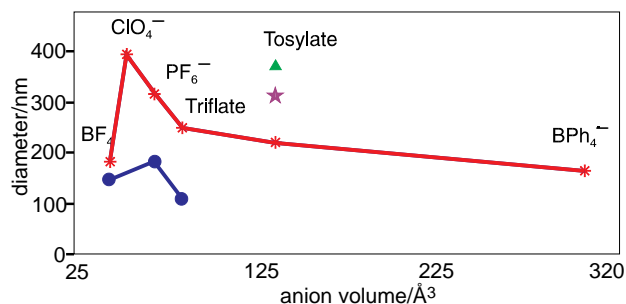


Fig. 2 Relationship between the sphere size and monomer or anion volume as measured by light-scattering (+, Et; *, Ph; |, Bu^t; \$, naphthyl)

aggregates than expected, but this might be explained by solvent or water coordination to the anion even inside the spheres, making the apparent size of this anion larger. Increasing the thioether bulk from ethyl to phenyl groups ($X^- = \text{tosylate}$) gave smaller aggregates. The naphthyl thioether building blocks showed a similar trend as the phenyl thioethers. The larger naphthyl groups gave smaller spheres in all cases. The combination of naphthyl thioethers with triflate anions formed rather small aggregates. The general conclusion from these data is that larger anions and/or thioether groups give smaller assemblies.

The size of the aggregates was also measured by contact mode AFM. Samples were prepared by evaporation of a nitromethane solution of self-assembled spheres **1a–d** on a clean gold surface. A representative part of these surfaces is shown in Fig. 3(a)–(f). In all cases, large, spherical objects

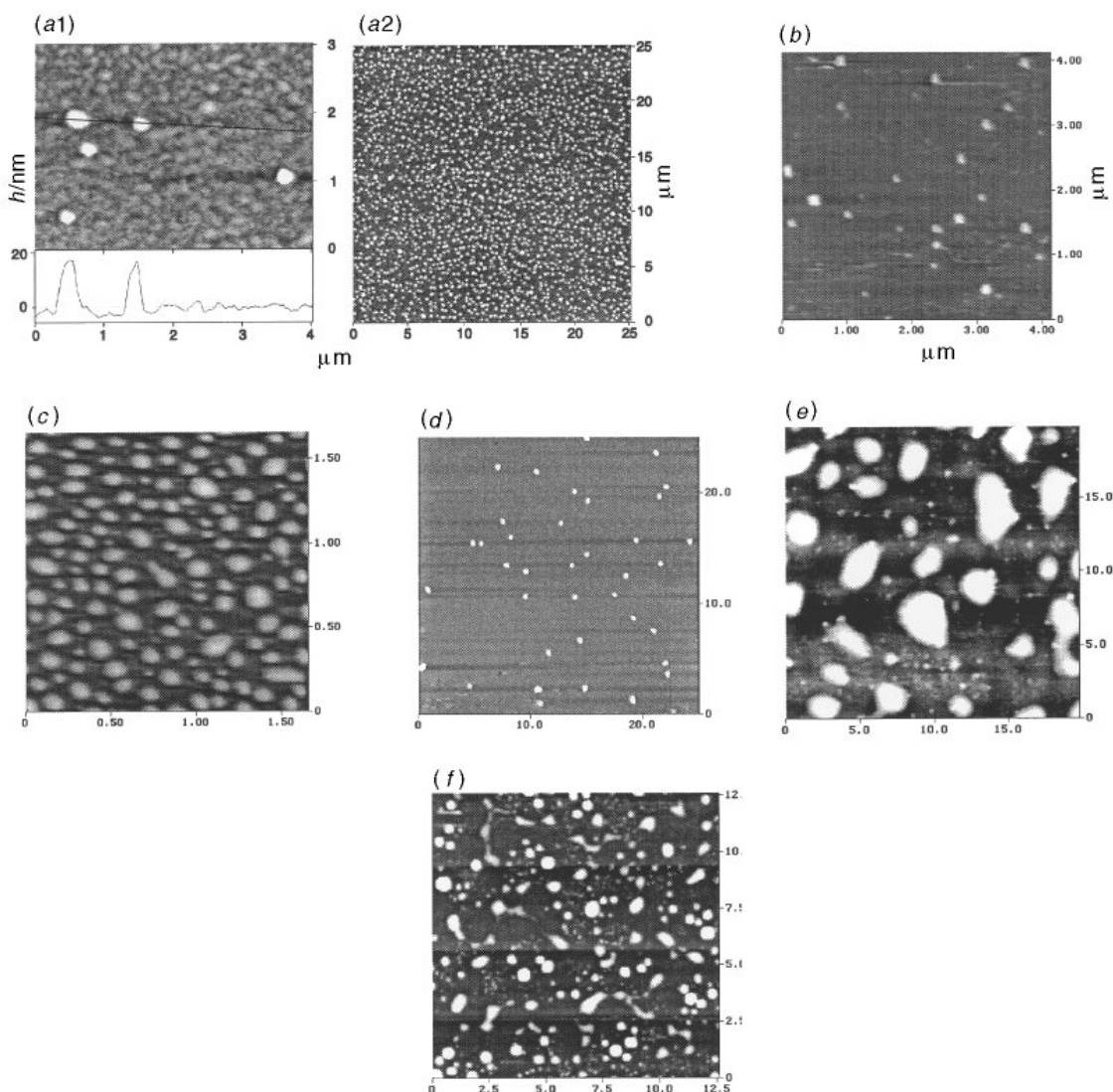


Fig. 3 AFM pictures of self-assembled spheres of (a) **9a** ($X^- = \text{BF}_4^-$); (b) **9b** ($X^- = \text{BF}_4^-$); (c) **9b** ($X^- = \text{OTf}^-$); (d) **9d** ($X^- = \text{BF}_4^-$); (e) **9a** ($X^- = \text{Tos}$); (f) **9a** ($X^- = \text{PF}_6^-$)

program. This size is independent of the sample concentration indicating that these are single particles and no clusters. From the peak width a standard deviation of approximately 30 nm was estimated. By changing the anion from ClO_4^- to BPh_4^- the size of the spheres as measured by QELS decreased from 400 to 180 nm in diameter (Fig. 2).

The sizes of the anions were calculated using the Connolly Surfaces option implemented in the Cerius2 program package.¹³ This gave arbitrary volumes which should be used only in a relative sense. The BF_4^- anion gave much smaller

were observed that correspond quite well with the dimensions determined by light-scattering. The average diameter for assemblies of **1a** ($X^- = \text{BF}_4^-$), as found by the grain size analysis routine of the instrument software of these aggregates is 205 nm, with a standard deviation of 30 nm. The aggregates seem to have a disc-like shape when studied with AFM. The flattening might be caused by spreading of the spheres on the surface or by interaction of the sample with the AFM tip. Repetitive scans of one spot 'wiped' the surface clean, which indicates that the organic material has a soft constitution.

When a glass substrate was used instead of gold, the same spheres were observed of roughly the same size. This indicates that the possible interaction of sulfur atoms in the building blocks and the gold surface did not significantly alter the morphology of the spheres. Grazing-angle FTIR spectroscopy on a gold surface covered with the spheres showed the characteristic $C\equiv N$ signal of coordinated cyano groups at 2289 cm^{-1} in agreement with the bulk spectra. From AFM data sizes of $160 (\pm 20)\text{ nm}$ for **1b** ($X^- = \text{BF}_4^-$) and $110 (\pm 20)\text{ nm}$ for **1b** ($X^- = \text{OTf}^-$) were measured respectively [Fig. 3(b) and (c)]. This is in good agreement with the QELS data (140 and 104 nm , respectively). In the case of **1a** ($X^- = \text{Tos}$) and **1a** ($X^- = \text{PF}_6^-$) extensive clustering made size determination unreliable [Fig. 3(e)–(f)].

The samples for TEM were used without additional shading or staining and the contrast results from the Pd centres that are distributed throughout the spherical assembly. In all pictures, the only structures that could be observed had spherical shapes in the expected size range. Fig. 4(a) and (b) clearly show globular aggregates in the range $150\text{--}200\text{ nm}$ for **1a** and **1c** (both with BF_4^- counter anions). This is in good agreement with the diameter measured with QELS. Fig. 4(a) shows globular structures with a light shell and a little darker nucleus. This indicates that the structures are a little thicker in the middle than at the edges, as expected for spherical assemblies. Energy dispersive X-ray spectrometry (EDX) revealed the presence of the elements Pd and S in these aggregates. The TEM image for **1a** ($X^- = \text{Tos}$) shows assemblies of ca. 225 nm [Fig. 4(c)], which is also in good agreement with QELS data (220 nm). As shown in Fig. 4(d), strong clustering is observed for **1d** ($X^- = \text{BF}_4^-$). By dividing the radius of the spheres by the size of the building blocks we estimate a number of roughly 50 'generations'. The outer layer of Pd complexes is not occupied by MeCN ligands, as these are not observed in the ^1H NMR spectrum. Probably, water present in nitromethane is coordinating to these Pd centres.¹⁴

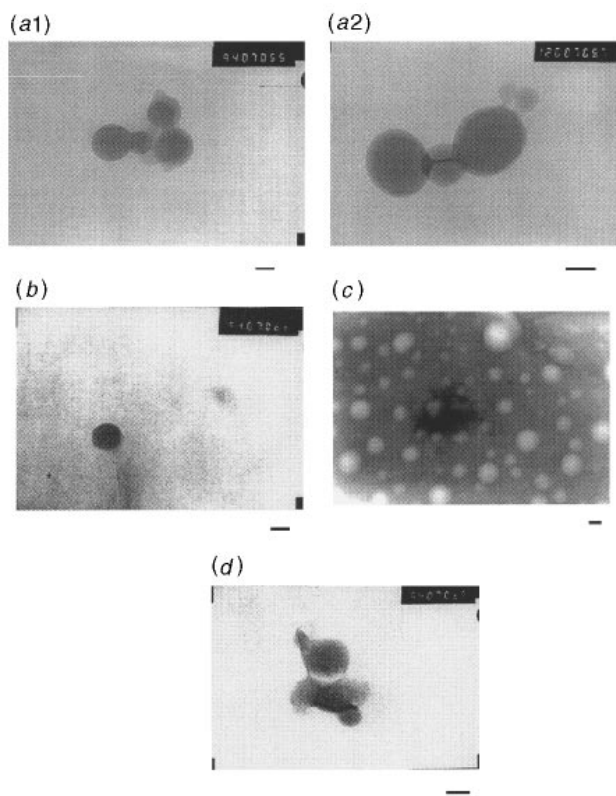


Fig. 4 TEM pictures of (a) **9a** ($X^- = \text{BF}_4^-$); (b) **9c** ($X^- = \text{BF}_4^-$); (c) **9a** ($X^- = \text{Tos}$); (d) **9d** ($X^- = \text{BF}_4^-$) (bar represents 100 nm)

A linear, non-branched palladium(II) complex containing one pincer complex and one cyanomethyl group was treated according to the same self-assembly procedures but AFM and TEM measurements did not show globular structures. This supports our concept in which branching is essential.

Indications for a dendritic structure, which results in a dense outer sphere, came from additional disassembly experiments. Light-scattering experiments show that when ca. 20 equiv. of acetonitrile per building block are added to a nitromethane solution of the spheres, they slowly disassemble in the course of $10\text{--}15\text{ min}$. The slow rate of disassembly indicates that acetonitrile cannot easily penetrate the outer shell of building blocks. When a larger nitrile like benzonitrile is used, disassembly is hardly observed, even after heating to 70°C for 15 min . Dendrimers with a similar dense shell with a solid-phase character have been reported by Meijer and co-workers.¹⁵

The explanation for the formation of rather well defined spheres and the relationship between the size of the spheres and the structure of the monomers and the non-coordinating anions, remains speculative. In our dendritic model the anions will occupy the voids created by the branching of the monomers. When these cavities become too small the anions are forced out of the sphere and will occupy the surface, thereby blocking the assembly process. The size at which this occurs, is apparently dependent on both the bulk of the bis-palladium complexes as well as the size of the anion.

Conclusions

Building blocks that contain all information necessary for self-assembly give regular assemblies with a (relatively) small polydispersity. The self-assembled structures are held together *via* coordinative bonds. Introduction of bulky groups in the building blocks and/or different sizes of non-coordinating counter anions influences the outcome of the self-assembly process. In this way spherical assemblies are obtained ranging from 100 to 400 nm in diameter.

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