Pergamon

TETRAHEDRON

Tetrahedron 57 (2001) 8875–8882

Unsymmetrical dendrimers with tridentate pyridylthioether coordination sites as repeating units: useful precursor for the synthesis of palladium-containing metallodendrimers

Gavino Chessa,[a,*] Luciano Canovese,[a] Lucia Gemelli,[a] Fabiano Visentin[a] and Roberta Seraglia[b]

[a]*Dipartimento di Chimica, Università di Venezia, Calle Larga S. Marta 2137, I-31123, Venezia, Italy*
[b]*CNR, Centro di Studio sulla Stabilità e Reattività dei Composti di Coordinazione, Via Marzolo 1, I-35100, Padova, Italy*

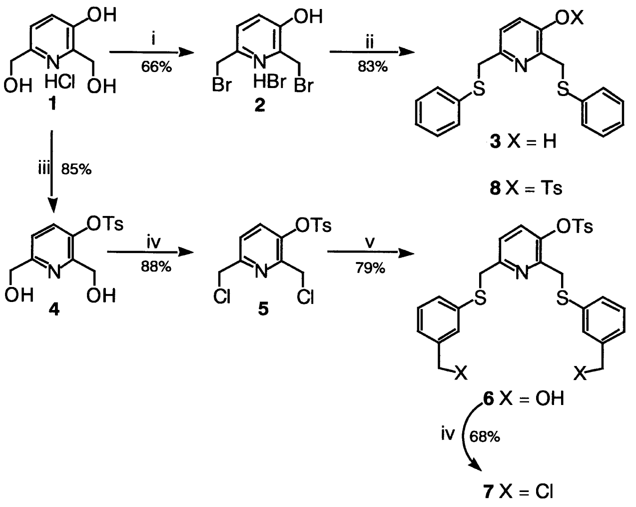
Received 15 May 2001; accepted 30 August 2001

Abstract—Unsymmetrical pyridylthioether monomers derived from 2,6-bis(hydroxymethyl)-3-hydroxypyridine hydrochloride have been used to synthesize dendritic structures by a convergent route. The coupling of the monomers has been achieved by the Mitsunobu reaction. The presence of repeating SNS pincer units makes these molecules precursors of metallodendrimers. The complexation of each binding site with palladium has been achieved upon reaction either with $Pd_2(DBA)_3CHCl_3$ in the presence of fumaronitrile or $PdCl_2(CH_3CN)_2$. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The synthesis of metallodendrimers is one of the main areas of interest in the chemistry of dendrimers because the resulting materials lead to investigations aimed at developing applications in catalysis, electrochemistry and photophysics.[1–4] The synthetic research on dendrimers has allowed access to dendritic macromolecules incorporating metal centres in specific zones as well as throughout all layers.[5,6] Usually, the synthesis of dendrimers with metals in each repeat unit is based on the use of appropriate transition metal coordination complexes as building blocks. In principle, metallodendrimers of this type could be assembled by complexation of a preformed dendritic superstructure with transition metals. For example by this synthetic procedure small organophosphine dendrimers containing up to five palladium nuclei have been prepared.[7] However, due to the complexity of the task, this approach has few additional examples.[8,9]

In our research project aimed at the assembly of palladium-containing dendrimers we became interested in the development of dendritic structures containing binding sites with high affinity for palladium. To this end it is desirable to have building blocks that, after incorporation in the dendritic structure, can easily form stable complexes with palladium. Previous studies[10,11] in this area suggest that tridentate SNS pyridylthioether ligands have the pre-requisite to achieve this target. We have consequently chosen building blocks 3 and 6 (Scheme 1). An additional feature of these monomers is the unsymmetrical arrangement of the coupling functionalities, which is rather unusual, because the dendrimers described in the literature are generally prepared using symmetrical building blocks. Since Denkewalter and coworkers[12] disclosed the synthesis of a chiral dendritic polylysine in 1983, relatively few examples have been reported of dendritic structures dealing with unsymmetrical monomers. Most of these reports are concerned with L-lisynyl[13] or L-glutamyl[14] dendrimers.[15,16]



Scheme 1. *Reagents and conditions*: i, 48% HBr, reflux, 6 h; ii, DMSO, KOH, PhSH, 1 h, 25°C; iii, CH_2Cl_2, TsCl, Et_3N, 24 h, 25°C; iv, CH_2Cl_2, MsCl, Et_3N, reflux; v, DMF, K_2CO_3, 3-mercaptobenzyl alcohol, 18-crown-6, 24 h, 45°C.

Keywords: dendrimers; metallodendrimers; pyridylthioethers; palladium complexes.

[*] Corresponding author; e-mail: chessa@unive.it

PII: S0040-4020(01)00871-7

With a view to enhance the knowledge of the applicability of pyridine-based unsymmetrical building blocks like **3** and **6** in the synthesis of molecular scaffolds to encapsulate transition metals and to achieve novel metal-containing materials with interesting properties, this study explores the synthesis of pyridylthioether-based dendrimers using a convergent strategy and their complexation with palladium derivatives.

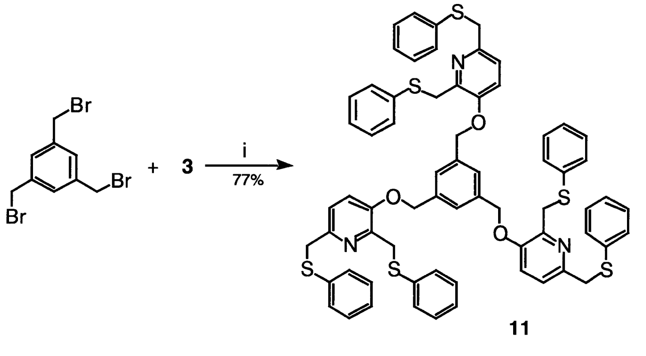
2. Results and discussion

The synthesis of the monomers **3** and **6** is depicted in Scheme 1.

Both molecules were derived from 2,6-bis(hydroxymethyl)-3-hydroxypyridine hydrochloride **1**,[17] which has been smoothly prepared from commercially available 3-hydroxypyridine. Treatment of 1 with 48% aqueous HBr, according to the literature procedure,[18] afforded the dibromide **2**, which, upon reaction with benzenethiol in dry DMSO in the presence of powdered KOH, yielded the bis(phenylthiomethyl)pyridinol **3** in 83% yield. To facilitate the experimental conditions in the synthesis of the second building block we employed the *p*-toluenesulfonate group to protect the phenol-type functionality of 2,6-bis(hydroxymethyl)-3-hydroxypyridine hydrochloride **1**. Protection of **1** to obtain the corresponding *p*-toluenesulfonate ester **4** was achieved regioselectively in 85% yield using *p*-toluenesulfonyl chloride and Et_3N in dry dichloromethane.[19] The two hydroxymethyl functionalities were then converted to the corresponding choromethyl groups by reaction with methanesulfonyl chloride and Et_3N in dry dichloromethane[20] to afford the dichloride **5** in 88% yield. Finally, regioselective S-alkylation of 3-mercaptobenzyl alcohol[21] with the *p*-toluenesulfonate ester protected monomer **5** using K_2CO_3/18-crown-6 in dry DMF gave the hydroxymethyl-terminated building block **6** in 79% yield after purification by column chromatography.

Following a convergent strategy,[22] monomer **3** was first attached to the core molecule 1,3,5-tris(bromomethyl)benzene,[23] under typical conditions for ether synthesis (K_2CO_3/DMF), to give the first generation dendrimer **11** in 77% yield (Scheme 2).

Then, pyridylthioether **3** was coupled to monomer **6** using the Mitsunobu reaction (PPh_3, DEAD, THF)[24] to afford the protected second-generation (G-2) dendron **9** as shown in Scheme 3. The crude product, a yellowish oil, proved difficult to purify by silica gel column chromatography due to the poor separation of the desired product from contaminants. Nevertheless, use of dichloromethane with increasing amounts (up to 3%) of diethyl ether allowed separation of a product of acceptable purity in 66% yield.



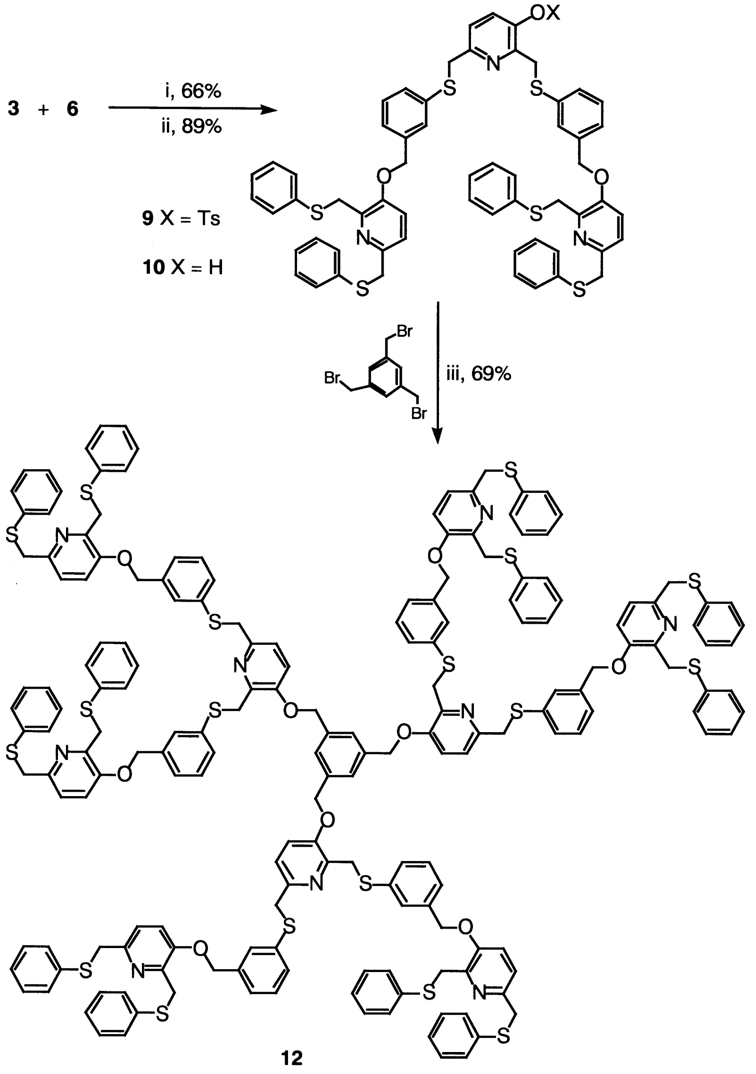
Scheme 2. *Reagents and conditions*: i, DMF, K_2CO_3, 24 h, 65°C.

The need to increase the yield of the coupling step prompted us to examine an alternative approach for the assembly of the G-2 dendron **9**. Conversion to the corresponding benzylic chloride of the two benzyl alcohol groups of monomer **6** was thus undertaken by reaction with methanesulfonyl chloride and Et_3N in refluxing dichloromethane. Surprisingly, coupling of dichloride **7** with two equivalents of monomer **3** under standard alkylation conditions (K_2CO_3/DMF or NaH/THF) afforded a considerable amount (66%) of a transesterification product **8** (Scheme 1). This, presumably, derived from reaction of the *p*-toluenesulfonate ester function of the product **7** with the hydroxyl group of the product **3**. Compound **8** can be isolated by column chromatography, and its ^1H NMR characterization is consistent with the assigned structure. As a consequence, an unacceptably low yield of the second generation dendron was obtained.

Removal of the *p*-toluenesulfonate protecting group from **9** using Tesser's procedure[25] gave the corresponding pyridinol **10** in 89% yield (Scheme 3). Hence, coupling of deprotected dendron **10** to the trifunctional core 1,3,5-tris(bromomethyl)benzene, under conditions similar to those used for **11**, gave the G-2 dendrimer **12** bearing **9** specific binding sites in 69% isolated yield. The activated wedge **10** was also reacted with monomer **6** under the same coupling conditions used for the synthesis the second-generation dendron **9**. However, our attempt failed leading to the recovery of the starting product **10**. An alternative coupling procedure was examined for the synthesis of the third-generation dendron. Due to the availability of intermediate **7** containing two benzyl chloride functionalities we reacted **7** with the dendron **10** using DMF/K_2CO_3 coupling conditions.

In accordance with the results obtained for the previous generation the reaction afforded the *p*-toluenesulfonate protected dendron **9** as main product. Therefore, the sulfonate protecting group, which was successfully employed in the convergent synthesis of poly(aryl ether) dendrimers,[26] in our case proved to be only partly useful. Consequently, an alternative protecting group or a new synthetic route should be explored for the synthesis of dendrons of higher generation. However, all our attempts to protect the focal point of the building block **6** by protecting groups compatible with the functionalities on this monomer and the dendron have so far been unsuccessful.

Consistent with our previous studies[27] NMR proved very useful for confirming the structure and assessing the purity of these products. In particular methylene signals can be used to monitor the extent of coupling to either the monomer **6** or the core moiety. As expected, the ^1H NMR spectrum of the second generation dendrimer **12** (Fig. 1) shows six signals for the thiomethylene protons and three signals for the benzylic protons. The ratio of these two



Scheme 3. *Reagents and conditions*: i, PPh_3, DEAD, THF, 24 h, 25°C; ii, dioxane, MeOH, 4 M NaOH, 3 h, 25°C; iii, DMF, K_2CO_3, 24 h, 65°C.

groups of signals is in full agreement with the theoretical ratio. The ^{13}C NMR spectrum also is consistent with the proposed structure for dendrimer **12**. However, not all resonances can be assigned because of the many overlapping signals. Finally, the MALDI-TOF spectrum of the dendrimers **11** and **12** shows the expected molecular ion peaks on the basis of the calculated molecular weights.

Reaction of **11** with three equivalents of $Pd_2(DBA)_3{\cdot}CHCl_3$[28] in an anhydrous acetone–THF mixture in the presence of fumaronitrile afforded the trinuclear complex **13** in 78% yield, which was characterized by NMR spectrometry.

The ^1H NMR spectrum of this metallodendrimer deserves some comments. In particular, upon coordination, the signals ascribable to CH_2S endocyclic and fumaronitrile protons shift downfield ($\Delta\delta$=ca. 0.2–0.3 and 3.2 ppm, respectively) and a general simplification of the spectrum is observed. As a matter of fact, owing to the molecular asymmetry and the planar tetracoordinate arrangement of Pd(0) species, the original six signals of the CH_2S protons should be maintained. Moreover the CH_2S protons contiguous to chiral coordinate sulphur atom should generate an AB system different to those belonging to the uncoordinate wing.

Apparently some sort of fluxional rearrangement which imparts an overall symmetry not compatible with a 'frozen' uncoordinated wing is operative. This behavior which is not unprecedented,[29] arises from the fast (on the NMR time scale) alternating windscreen-wiper motion of the two wing bearing the sulphur coordinating atoms. This rearrangement and the consequent induced symmetry can be used to explain all the observed spectral features. Under these conditions no diasterotopic CH_2S protons nor an AB system ascribable to asymmetric fumaronitrile protons could be observed.[30] The downfield shift ($\Delta\delta$=ca. 100 ppm) of fumaronitrile carbons in the ^{13}C NMR spectrum of **13** is also observed thereby confirming the olefin coordination.

Such a reaction was then extended to dendrimer **12** with a view to encapsulating nine palladium nuclei within the dendritic structure. Addition of nine equivalents of $Pd_2(DBA)_3{\cdot}CHCl_3$ to an acetone–THF solution of **12** in

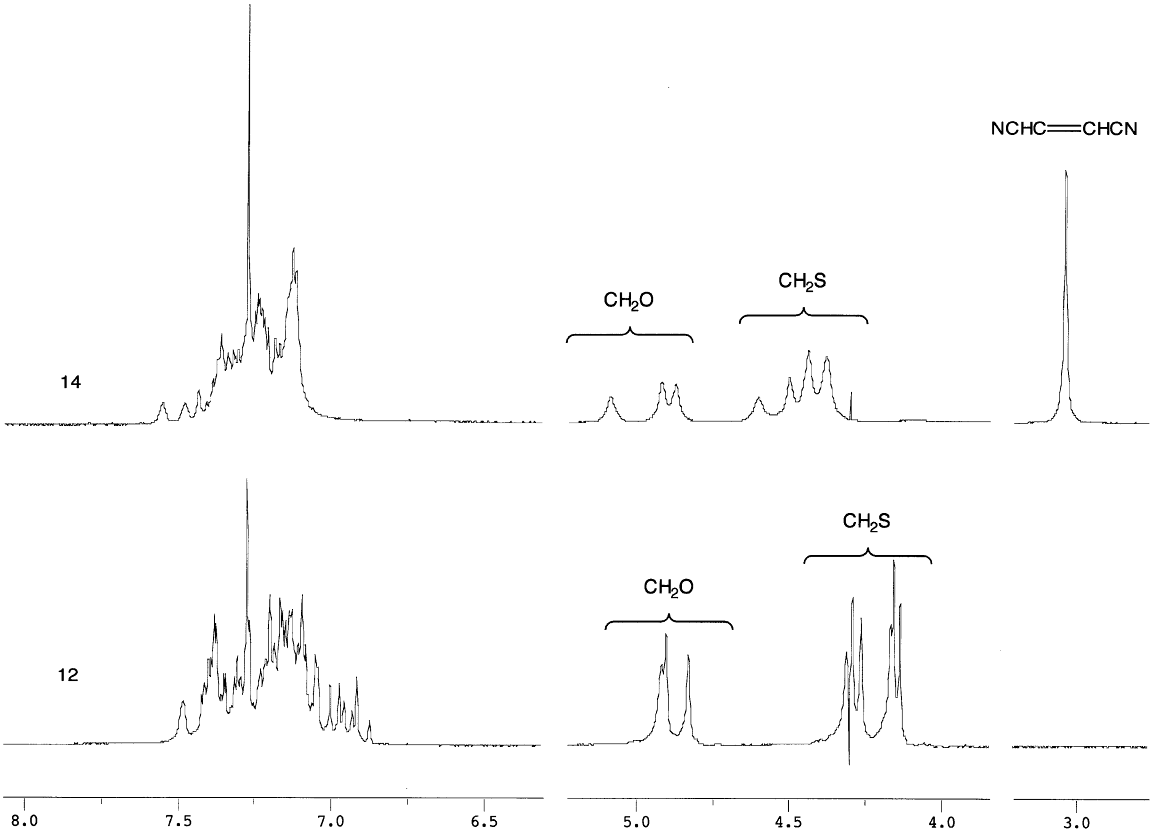
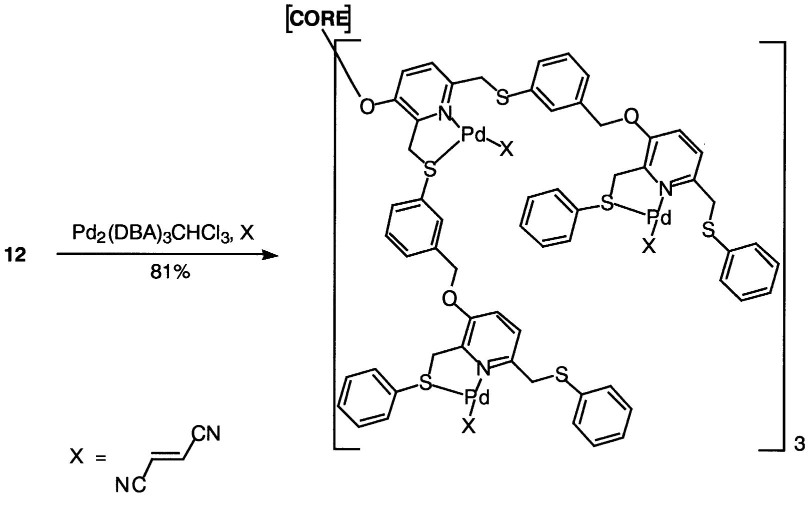


Figure 1. 200 MHz ^{1}H NMR spectrum (CDCl$_3$) of the dendritic system **12** and its Pd(0) complex **14**.

the presence of fumaronitrile gave the expected metallodendrimer **14** in 81% yield (Scheme 4).

Again, the coordination can be inferred from the chemical shift changes in both ^{1}H NMR (Fig. 1) and ^{13}C NMR spectra. Notably, in the NMR spectra there are no signals that could arise from partially metallated dendrimer. Spectroscopic confirmation of the complexation is provided by IR spectroscopy since the characteristic CN stretching vibration of fumaronitrile shifts from 2250 to 2203 cm^{-1} upon coordination.

To further investigate their complexing ability we reacted **11** and **12** with PdCl$_2$(CH$_3$CN)$_2$ in dry DMF. We obtained



Scheme 4. Synthesis of the nonanuclear palladium complex **14**.

the complexes **13a** and **14a** in 83 and 85% yield, respectively. Incorporation of Pd(II) in each available site leads again to a significant downfield shift of the thiomethylene protons ($\Delta\delta$=ca. 1.2 ppm) and carbon ($\Delta\delta$=ca. 11–14 ppm) resonances in NMR spectra of **13a**. Another indication for the coordination of the pyridylthioether units is the broadening of the signals for methylene, pyridine and aromatic protons. This effect is due to sulfur inversion, which was found to be operative in related Pd(II) systems even at low temperature.[31]

Similarly, the ^{1}H NMR and analytical data for **14a** unambiguously indicate the formation of the nonanuclear palladium complex. The metallodendrimer **14a**, not surprisingly, was found to be insoluble or poorly soluble in organic solvents. However, the ^{1}H NMR spectrum of **14a** could be recorded in DMF (d_7). Several attempts have been made to characterize metallodendrimers **13–14a** using both ESI and MALDI-TOF mass spectrometries. Unfortunately, no significative results have been obtained. In particular, any molecular ion has not been detected using the two ionization techniques. The data obtained by ESI-MS show the presence of the dendritic skeleton, while peaks originating from fragmentation processes, already described for pyridine-based dendrimers,[32] are clearly detected by MALDI-MS, even if different experimental conditions (e.g. different matrices, different laser power, different matrix/sample molar ratios) were tested.

3. Conclusion

In this study we have successfully employed a two-step synthetic strategy, based on the construction of a fully organic dendritic structure followed by the complexation with palladium derivatives, to assemble metallodendrimers incorporating palladium.

The dendritic infrastructures were achieved by building blocks having an unsymmetrical arrangement of the coupling functionalities. A recent study[15] indicates that the structure of unsymmetrically branched dendritic wedges is more compact than in the corresponding symmetrical isomers as a result of a coiling effect, which originates from the unsymmetrical substitution pattern in the branching unit.

For this reason future work will be devoted to the synthesis of larger structures and the corresponding symmetrical analogues although, as the size of dendrimers increase they become more difficult to obtain. Further studies will also undertake to explore the applicability of Pd(0) metallodendrimers in cross-coupling catalysis and the field of materials chemistry.

4. Experimental

4.1. Materials and instrumentation

2,6-Bis(hydroxymethyl)-3-hydroxypyridine hydrochloride **1**[17] and 2,6-bis(bromomethyl)-3-hydroxypyridine **2**[18] were prepared according to known synthetic procedures. Tetrahydrofuran (THF) was distilled from Na benzophenone immediately before use. Dimethylsulfoxide (DMSO) and acetone were dried and stored over 3 and 4 Å molecular sieves, respectively. *N*,*N*-Dimethylformamide (DMF) was purified by distillation from CaH_2 and stored over 4 Å molecular sieves in a dark bottle. Dicloromethane was freshly distilled from CaH_2. *p*-Toluenesulfonyl chloride was recrystallized from *n*-hexane. Other solvents and reagents were generally used without further purification. ^{1}H- and ^{13}C NMR spectra were obtained in $CDCl_3$ solutions, unless otherwise indicated, on Bruker AC 200 spectrometer using the solvent signal as internal standard. IR spectra were recorded on a Nicolet Magna-IR™ 750 spectrometer. Melting points were taken in capillary tubes with a Buchi 535 apparatus and are uncorrected.

Mass spectra of dendrimers were measured by Matrix Assisted Laser Desorption Ionisation Mass Spectrometry (MALDI-MS) and Electrospray Mass Spectrometry (ESI-MS). The MALDI data were obtained using a REFLEX™ Time of Flight instrument (Bruker–Franzen Analytik) equipped with a 'Scout' ion source (nitrogen laser λ=337 nm; laser energy=50 μJ; acceleration voltage=30 KV), operating in positive linear mode. 2,5-Dihydroxybenzoic acid (DHB) and 2-(4-hydroxyphenylazo)benzoic acid (HABA) were used as matrices laid down in solution with the sample. ESI measurements were performed on LCQ ion trap instrument (Finnigan, Palo Alto, CA, USA) operating in positive ion mode. The experimental conditions used were sheathgas flow (N_2): 50 a.u.; source voltage: 4 KV; capillary voltage: 3 V; capillary temperature: 200°C. Sample solutions were directly injected into the source by a syringe pump with a flow rate of 8 μL min^{-1}.

4.1.1. 2,6-Bis(phenylthiomethyl)-3-hydroxypyridine (or [G-1]-OH) (3). To a suspension of powdered KOH (11.2 g, 0.2 mol) in anhydrous DMSO (30 mL) was added benzenethiol (6.6 g, 60 mmol) and 2,6-bis(bromomethyl)-3-hydroxypyridine **2** (5.43 g, 15 mmol). After stirring for 1 h at room temperature the reaction mixture was filtered to remove the excess KOH. The resulting solution, after addition of 10% aqueous acetic acid (50 mL), was extracted with CH_2Cl_2 (2×75 mL). The combined extract was washed with saturated NaCl solution (2×50 mL), dried (Na_2SO_4) and concentrated to dryness on a rotary evaporator. The crude product was repeatedly extracted with hot cyclohexane, which afforded a white crystalline solid (4.21 g, 83%) on cooling to room temperature; mp 116–117°C; IR (KBr): ν_{max} (cm^{-1}) 3075, 3055, 2585, 1579, 1481, 1437, 1284, 1104, 847, 735; ^{1}H NMR: δ 4.14 (s, 2H, CH_2S), 4.37 (s, 2H, CH_2S), 6.79 (bs, 1H, OH), 7.03 (d, 1H, J=8.4 Hz, 4-pyH), 7.10 (d, 1H, J=8.4 Hz, 5-pyH), 7.15–7.42 (m, 10H, ArH); ^{13}C NMR: δ 37.0 (CH_2S), 39.5 (CH_2S), 123.3 (5-pyC), 124.9 (4-pyC), 126.3, 127.0, 128.8, 129.0, 129.6, 130.3, 133.9, 143.1 (ArC), 146.6 (2-pyC), 148.6 (6-pyC), 150.5 (3-pyC); [Found: C, 67.05; H, 5.06; N, 4.07; S, 18.77. Anal. calcd for $C_{19}H_{17}NOS_2$: C, 67.22; H, 5.05; N, 4.13; S, 18.89%].

4.1.2. 2,6-Bis(hydroxymethyl)-3-hydroxypyridine *p*-toluenesulfonate (4). To a suspension of 2,6-bis(hydroxymethyl)-3-hydroxypyridine hydrochloride **1** (7.66 g, 40 mmol) in CH_2Cl_2 (80 mL) at 0°C was added Et_3N

(8.1 g, 80 mmol) and then *p*-toluenesulfonyl chloride (7.63 g, 40 mmol). After 24 h at room temperature the reaction mixture was washed with 5% aq. acetic acid (50 mL), twice with equal volumes of water, dried (Na_2SO_4) and evaporated under reduced pressure to give a solid material. The crude product was recrystallized from CH_2Cl_2/diethyl ether yielding a white crystalline solid (10.58 g, 85%), mp 114–115°C; IR (KBr): ν_{max} (cm^{-1}) 3362, 2851, 1595, 1452, 1378, 1180, 1091, 1054, 852, 721, 665; ^{1}H NMR: d 2.48 (s, 3H, CH_3), 4.48 (s, 2H, CH_2O), 4.77 (s, 2H, CH_2O), 7.29 (d, 1H, *J*=8.4 Hz, 4-pyH), 7.37 (d, 2H, *J*=8.3 Hz, CH_3ArH), 7.50 (d, 1H, *J*=8.4 Hz, 5-pyH), 7.75 (d, 2H, *J*=8.3 Hz, SO_2ArH); ^{13}C NMR: δ 21.8 (CH_3), 59.5 (CH_2O), 64.3 (CH_2O), 120.1 (5-pyC), 128.3, 130.2, (TsC), 131.1 (4-pyC), 131.9, 142.1 (TsC), 146.3 (2-pyC), 151.6 (6-pyC), 157.5 (3-pyC); [Found: C, 54.25; H, 4.91; N, 4.50; S, 10.28. Anal. calcd for $C_{14}H_{15}NO_5S$: C, 54.36; H, 4.89; N, 4.53; S, 10.37%].

4.1.3. 2,6-Bis(chloromethyl)-3-hydroxypyridine *p*-toluenesulfonate (5). To a solution of **4** (4.64 g, 15 mmol) in CH_2Cl_2 (100 mL) containing Et_3N (4.55 g, 45 mmol) at 0°C was slowly added methanesulfonyl chloride (5.15 g, 45 mmol). The reaction mixture was gently refluxed overnight, after which water was added. The organic layer was washed with saturated aqueous $NaHCO_3$ (50 mL), water (2×50 mL), dried (Na_2SO_4) and evaporated under reduced pressure. The crude product was recrystallized from ethanol/water to give a pale brown crystalline solid (4.55 g, 88%), mp 63–64°C; IR (KBr): ν_{max} (cm^{-1}) 3131, 1596, 1461, 1378, 1190, 1091, 862, 829, 806, 716, 683; ^{1}H NMR: δ 2.49 (s, 3H, CH_3), 4.46 (s, 2H, CH_2Cl), 4.67 (s, 2H, CH_2Cl), 7.40 (d, 2H, *J*=8.4 Hz, CH_3ArH), 7.51 (d, 1H, *J*=8.5 Hz, 4-pyH), 7.64 (d, 1H, *J*=8.5 Hz, 5-pyH), 7.81 (d, 2H, *J*=8.4 Hz, SO_2ArH); ^{13}C NMR: δ 21.7 (CH_3), 41.0 (CH_2Cl), 45.6 (CH_2Cl), 123.8 (5-pyC), 128.4, 130.2 (TsC), 131.5 (4-pyC), 132.0, 143.8 (TsC), 146.4 (2-pyC), 149.2 (6-pyC), 155.0 (3-pyC); [Found: C, 48.21; H, 3.65; N, 3.95; S, 9.11. Anal. calcd for $C_{14}H_{13}Cl_2NO_3S$: C, 48.57; H, 3.78; N, 4.05; S, 9.26%].

4.1.4. 2,6-Bis[((3-hydroxymethylphenyl)thio) methyl]-3-hydroxypyridine *p*-toluenesulfonate (or $(HOCH_2)_2$-[G-1]-OTs) (6). A solution of 3-mercaptobenzyl alcohol (925 mg, 6.6 mmol) in dry DMF (20 mL) containing anhydrous K_2CO_3 (912 mg, 6.6 mmol) was stirred under reduced pressure at room temperature for 30 min, then 2,6-bis(chloromethyl)-3-hydroxypyridine *p*-toluenesulfonate **5** (1.04 g, 3 mmol) and 18-crown-6 (159 mg, 0.6 mmol) were added. The reaction mixture was allowed to react at 45°C for 24 h under an atmosphere of argon, after which it was evaporated under reduced pressure and the residue was extracted with CH_2Cl_2 (100 mL) The organic extract was washed with saturated NaCl solution (2×50 mL), dried (Na_2SO_4) and concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel eluting with CH_2Cl_2 gradually increasing to 1:1 CH_2Cl_2/ethyl acetate to give a pale yellow oil (1.31 g, 79%); IR (KBr): ν_{max} (cm^{-1}) 3375, 3055, 2926, 2872, 1595, 1456, 1377, 1195, 1180, 1080, 1045, 843, 784; ^{1}H NMR: δ 2.45 (s, 3H, CH_3), 2.53 (bs, 2H, OH), 3.95 (s, 2H, CH_2S), 4.16 (s, 2H, CH_2S), 4.55 (s, 2H, CH_2O), 4.58 (s, 2H, CH_2O), 7.08–7.39 (m, 12H, CH_3ArH, ArH and 4,5-pyH), 7.69 (d, 2H, *J*=8.3 Hz, SO_2ArH); ^{13}C NMR: δ 21.7 (CH_3), 35.2 (CH_2S), 39.4 (CH_2S), 64.6 (CH_2O), 64.8 (CH_2O), 122.7 (5-pyC), 125.1, 125.3, 128.0 (ArC), 128.3 (TsC), 128.7, 128.8, 129.0, 129.3 (ArC), 130.2 (TsC), 130.8 (4-pyC), 132.1 (TsC), 135.3, 135.6, 141.8, 141.9 (ArC), 143.1(TsC), 146.2 (2-pyC), 150.6 (6-pyC), 156.0 (3-pyC); [Found: C, 60.58; H, 4.92; N, 2.56. Anal. calcd for $C_{28}H_{27}NO_5S_3$: C, 60.74; H, 4.91; N, 2.53%].

4.1.5. 2,6-bis[((3-chloromethylphenyl)thio) methyl]-3-hydroxypyridine *p*-toluene sulfonate (or $(ClCH_2)_2$-[G-1]-OTs) (7). To a solution of **6** (1.075 g, 1.94 mmol) in CH_2Cl_2 (50 mL) containing Et_3N (587 mg, 5.82 mmol) at 0°C was slowly added methanesulfonyl chloride (667 mg, 5.82 mmol). The reaction mixture was gently refluxed overnight, after which water was added. The organic layer was washed with water, dried (Na_2SO_4) and evaporated under reduced pressure to give an oil. Purification by flash chromatography on silica gel eluting with CH_2Cl_2 afforded an oil (780 mg, 68%); IR (KBr): ν_{max} (cm^{-1}) 3059, 2960, 1598, 1460, 1387, 1196, 1183, 1084, 841, 665; ^{1}H NMR: δ 2.46 (s, 3H, CH_3), 3.99 (s, 2H, CH_2S), 4.21 (s, 2H, CH_2S), 4.51 (s, 2H, CH_2Cl), 4.52 (s, 2H, CH_2Cl), 7.16–7.37 (m, 11H, CH_3ArH, ArH and 4-pyH), 7.41 (d, 1H, *J*=8.5 Hz, 5-pyH), 7.72 (d, 2H, *J*=8.4 Hz, SO_2ArH); ^{13}C NMR: δ 21.7 (CH_3), 35.0 (CH_2S), 39.4 (CH_2S), 45.7 (CH_2O), 45.8 (CH_2O), 122.6 (5-pyC), 126.5 (ArC), 128.3 (TsC), 129.0, 129.2, 129.3, 129.4, 129.6, 129.7 (ArC), 130.1 (TsC), 130.9 (4-pyC), 132.2 (TsC), 136.1, 136.5, 138.0, 138.2 (ArC), 143.2 (TsC), 146.1 (2-pyC), 150.4 (6-pyC), 155.8 (3-pyC); [Found: C, 56.76; H, 4.19; N, 2.39. Anal. calcd for $C_{28}H_{25}Cl_2NO_3S_3$: C, 56.94; H, 4.27; N, 2.37%].

4.1.6. [G-2]-OTs (9). To a solution of **3** (1.29 g, 3.8 mmol), **6** (1 g, 1.81 mmol) and PPh_3 (1.23 g, 4.71 mmol) in THF (20 mL) was slowly added dropwise a THF solution (20 mL) of DEAD (820 mg, 4.71 mmol). The mixture was stirred at room temperature for 24 h and then evaporated under reduced pressure. The residue was taken up in CH_2Cl_2 (100 mL) washed with saturated aqueous $NaHCO_3$ (2 x 50 mL), water (2×50 mL) and dried (Na_2SO_4). After concentration of the filtered solution under reduced pressure the crude product was purified by flash chromatography on silica gel eluting with 1% diethyl ether in CH_2Cl_2 increasing to 3% to yield a pale yellow oil (1.42 g, 66%); IR (KBr): ν_{max} (cm^{-1}) 3059, 2925, 1588, 1460, 1377, 1268, 1178, 1082, 833, 743, 698; ^{1}H NMR: δ 2.41 (s, 3H, CH_3), 4.03 (s, 2H, CH_2S), 4.19 (m, 6H, CH_2S), 4.33 (s, 4H, CH_2S), 4.94 (s, 4H, CH_2O), 6.95–7.47 (m, 36H, CH_3ArH, ArH and 4,5-pyH), 7.7 (d, 2H, *J*=8.4 Hz, SO_2ArH); ^{13}C NMR: δ 21.5 (CH_3), 34.9 (CH_2S), 35.5 (CH_2S), 39.1 (CH_2S), 69.4 (CH_2O), 69.6 (CH_2O), 119.1 (5′-pyC), 119.2 (5′-pyC), 122.0 (4′-pyC), 122.4 (5-pyC), 124.8, 125.7, 127.4, 127.9, 128.0, 128.4, 125.7, 127.4, 127.9, 128.0, 128.4, 128.6, 129.9, 129.5, 129.6, 129.9 (ArC and TsC), 130.5 (4-pyC), 132.0, 135.9, 136.0, 136.2, 136.4, 136.7, 136.9, 142.9 (ArC and TsC), 145.9 (2-pyC), 146.9 (2′-pyC), 148.2 (6′-pyC), 150.3 (6-pyC), 151.1 (3′-pyC), 155.5 (3-pyC); [Found: C, 65.98; H, 4.67; N, 3.46. Anal. calcd for $C_{66}H_{57}N_3O_5S_7$: C, 66.24; H, 4.80; N, 3.51%].

4.1.7. [G-2]-OH (10). To a solution of [G-2]-OTs (1.41 g, 1.18 mmol) in dioxane/methanol (14:5, 15 mL) was added

15 mL of the same solvent mixture containing 1.5 mL of 4 M NaOH. The reaction mixture was allowed to stir at room temperature until TLC showed no starting material (3 h). Then the reaction mixture was neutralized by the addition of acetic acid, concentrated to dryness and finally dissolved in CH_2Cl_2 (100 mL). The resulting solution was washed with water, dried (Na_2SO_4) and after filtration the solvent was removed under reduced pressure. The crude product was purified by flash chromatography on silica gel eluting sequentially with CH_2Cl_2/diethyl ether (96:4) and CH_2Cl_2/diethyl ether (96:8) affording a clear glassy solid (1.09 g, 89%); IR (KBr): ν_{max} (cm^{-1}) 3445, 3053, 2924, 1578, 1456, 1265, 1087, 737, 689; ^{1}H NMR: δ 4.13 (s, 2H, CH_2S), 4.18 (s, 2H, CH_2S), 4.19 (s, 2H, CH_2S), 4.31 (s, 2H, CH_2S), 4.32 (s, 2H, CH_2S), 4.34 (s, 2H, CH_2S), 4.93 (s, 2H, CH_2O), 4.94 (s, 2H, CH_2O), 6.68 (bs, 1H, OH), 6.86–7.46 (m, 34 H, ArH, and 4,5-pyH); ^{13}C NMR: δ 35.4 (CH_2S), 35.5 (CH_2S), 36.0 (CH_2S), 39.2 (CH_2S), 69.5 (CH_2O), 119.3, 122.0, 122.9, 124.2, 124.6, 124.9, 125.8, 125.9, 127.4, 127.7, 128.4, 128.5, 128.7, 128.8, 128.9, 129.6, 129.7, 135.0, 135.8, 135.9, 136.3, 136.4, 136.5, 136.7, 136.8, 143.0, 146.8 and 146.9 (2-pyC, 2′-pyC), 148.1 and 148.2 (6-pyC, 6′-pyC), 149.8 (3-pyC), 151.1 (3′-pyC); ESI-MS (10^{-5} M solution in $CHCl_3$): $[M+H]^+=1042.3$ *m/z*; calcd=1042.2 *m/z*; [Found: C, 67.71; H, 4.86; N, 3.99. Anal. calcd for $C_{59}H_{51}N_3O_3S_6$: C, 67.98; H, 4.93; N, 4.03%].

4.1.8. [G-1]$_3$-[C] (11). A mixture of **3** (1.12 g, 3.3 mmol) and anhydrous K_2CO_3 (456 mg, 3.3 mmol) in dry DMF (10 mL) was stirred under reduced pressure at room temperature for 30 min, after which 1,3,5-tris(bromomethyl)benzene (375 mg, 1 mmol) was added and the reaction mixture was heated at 65°C for 24 h under an atmosphere of argon. The mixture was evaporated under reduced pressure and the residue was partitioned between CH_2Cl_2 (100 mL) and water (100 mL). The organic extract was washed with water (2×50 mL), dried (Na_2SO_4) and evaporated under reduced pressure to give an oil, which crystallized as a white solid from acetone. On drying under reduced pressure, this solid turned into a clear glassy solid (875 mg, 77%); IR (KBr): ν_{max} (cm^{-1}) 3053, 2912, 1580, 1452, 1271, 741, 690; ^{1}H NMR: δ 4.22 (s, 6H, CH_2S), 4.35 (s, 6H, CH_2S), 5.01 (s, 6H, CH_2O), 7.02 (d, 3H, J=8.4 Hz, 4-pyH), 7.05–7.52 (m, 36H, 5-pyH and ArH); ^{13}C NMR: δ 35.7 (CH_2S), 39.4 (CH_2S), 69.7 (CH_2O), 119.6 (5-pyC), 122.3 (4-pyC), 125.6 (ArC core), 126.0, 128.7, 128.8, 129.1, 129.5, 136.2, 136.8 (ArC), 137.3 (ArC core), 147.0 (2-pyC), 148.6 (6-pyC), 151.3 (3-pyC); MALDI-MS (DHB matrix): $[M+K]^+=1170$ *m/z*; calcd=1171 *m/z*; [Found: C, 69.81; H, 4.99; N, 3.68. Anal. calcd for $C_{66}H_{57}N_3O_3S_6$: C, 69.99; H, 5.07; N, 3.71%].

4.1.9. [G-2]$_3$-[C] (12). 1,3,5-Tris(bromomethyl)benzene (48 mg, 0.135 mmol) was treated with the G-2 dendron **10** (447 mg, 0.429 mmol) in dry DMF (10 mL) with anhydrous K_2CO_3 (62 mg, 0.45 mmol) by the procedure used for **11**. The crude product was purified by flash chromatography on silica gel eluting sequentially with CH_2Cl_2/diethyl ether (96:4) and CH_2Cl_2/diethyl ether (94:6) to give a white glassy solid (303 mg, 69%); IR (KBr): ν_{max} (cm^{-1}) 3053, 2924, 1578, 1454, 1265, 1105, 739, 689; ^{1}H NMR: δ 4.14 (s, 6H, CH_2S), 4.16 (s, 6H, CH_2S), 4.17 (s, 6H, CH_2S), 4.27 (s, 6H, CH_2S), 4.30 (s, 6H, CH_2S), 4.32 (s, 6H, CH_2S), 4.83 (s, 6H, CH_2O), 4.90 (s, 6H, CH_2O), 4.92 (s, 6H, CH_2O), 6.86–7.48 (m, 105 H, ArH and 4,5-pyH); ^{13}C NMR: δ 35.1 (CH_2S), 35.5 (CH_2S), 38.9 (CH_2S), 39.1 (CH_2S), 69.5 (CH_2O), 119.2, 122.0, 122.2, 124.3, 124.4, 125.3, 125.7, 126.9, 127.1, 128.0, 128.2, 128.4, 128.5, 128.7, 128.8, 129.4, 129.5, 136.1, 136.4, 136.6, 136.7, 136.8, 137.0, 137.3, 146.6, 146.7, 146.8, 148.0, 148.1, 151.1; MALDI-MS (HABA matrix): $[M+Na]^+=3263$ *m/z*; calcd=3264 *m/z*; [Found: C, 68.73; H, 4.86; N, 3.87. Anal. calcd for $C_{186}H_{159}N_9O_9S_{18}$: C, 68.92; H, 4.94; N, 3.89%].

4.2. General procedures for the synthesis of palladium complexes

4.2.1. (i) With $Pd_2(DBA)_3\cdot CHCl_3$. To a solution of dendrimer **11** (100 mg, 0.088 mmol) or **12** (97.2 mg, 0.03 mmol) in anhydrous acetone–THF (2:1, v/v, 30 mL) were added three (137 mg, 0.132 mmol) or nine (139.7 mg, 0.135 mmol) equivalents of $Pd_2(DBA)_3\cdot CHCl_3$ and a slight excess of fumaronitrile (24.8 mg, 0.318 mmol) or (25.3 mg, 0.324 mmol), respectively. After 1 h of stirring at room temperature under N_2 activated charcoal was added. The reaction mixture was stirred for 1 h and then filtered through Celite. The resulting solution was evaporated under reduced pressure, and the residue was dissolved in CH_2Cl_2 (5 mL) which was then slowly added to diethyl ether (100 mL) with stirring to give complexes **13** and **14** in 78–81% yield as creamy or white powders.

Complex **13**: Mp 128–129°C (decomp.); IR (KBr): ν_{max} (cm^{-1}) 2203, 1578, 1464, 1273, 743, 690; ^{1}H NMR: δ 3.12 (6H, s, CHCN), 4.45 (s, 6H, CH_2S), 4.61 (s, 6H, CH_2S), 5.03 (s, 6H, CH_2O), 7.15–7.47 (m, 39H, 4,5-pyH and ArH); ^{13}C NMR: δ 23.7 (CCN), 40.7 (CH_2S), 45.1 (CH_2S), 70.2 (CH_2O), 120.5 (5-pyC), 122.0 (CN), 123.4 (4-pyC), 126.0 (ArC core), 128.1, 128.9, 129.2, 129.3, 131.2, 131.3 (ArC), 136.9 (ArC core), 148.7 (2-pyC), 149.4 (6-pyC), 152.2 (3-pyC); [Found: C, 55.48; H, 3.92; N, 7.34. Anal. calcd for $C_{78}H_{63}N_9O_3S_6Pd_3\cdot 0.25(C_2H_5)_2O$: C, 55.67; H, 3.87; N, 7.40%].

Complex **14**: Mp 145°C (decomp.); IR (KBr): ν_{max} (cm^{-1}) 2203, 1575, 1458, 1272, 743, 689; ^{1}H NMR: δ 3.08 (s, 18H, CHCN), 4.39 (s, 12H, CH_2S), 4.45 (s, 12H, CH_2S), 4.51 (s, 6H, CH_2S), 4.61 (s, 6H, CH_2S), 4.88 (s, 6H, CH_2O), 4.92 (s, 6H, CH_2O), 5.09 (s, 6H, CH_2O), 7.11–7.56 (m, 105H, 4,5-pyH and ArH); ^{13}C NMR: δ 23.3 (CCN), 40.7 (CH_2S), 45.1 (CH_2S), 69.8 (CH_2O), 70.1 (CH_2O), 120.5, 120.8, 121.9 (CN), 123.4, 123.6, 125.8, 126.4, 126.7, 128.1, 128.7, 129.0, 129.1, 129.5, 129.9, 130.3, 131.1, 131.5, 132.6, 134.0, 134.2, 136.5, 136.6, 147.8, 148.2, 148.6, 148.8, 148.9, 152.1, 152.2; [Found: C, 54.27; H, 3.74; N, 7.62. Anal. calcd for $C_{222}H_{177}N_{27}O_9S_{18}Pd_9\cdot 0.5(C_2H_5)_2O$: C, 54.48; H, 3.71; N, 7.66%].

4.2.2. (ii) With $PdCl_2(CH_3CN)_2$. A solution of dendrimer **11** (65.9 mg, 0.058 mmol) or **12** (50 mg, 0.015 mmol) in dry DMF (5 mL) was added dropwise to a solution of three (45.3 mg, 0.175 mmol) or nine (36 mg, 0.139 mmol) equivalents of $PdCl_2(CH_3CN)_2$ in DMF (5–25 mL). After 1 h at room temperature, diethyl ether was added to the reaction mixture giving the complexes **13a** and **14a** in 83–85% yield as orange powders.

Complex **13a**: Mp 208–209°C (decomp.); IR (KBr): $\nu_{\max}$ (cm^{-1}) 1575, 1485, 1283, 749, 692; ^{1}H NMR (DMF d$_7$): δ 5.46 (bs, 6H, CH$_2$S), 5.50 (bs, 6H, CH$_2$S), 5.55 (bs, 6H, CH$_2$O), 7.25–8.40 (m, 39H, 4,5-pyH and ArH); ^{13}C NMR (DMF d$_7$): δ 49.9 (3C, CH$_2$S), 50.2 (3C, CH$_2$S), 71.8 (3C, CH$_2$O); [Found: C, 47.32; H, 3.39; N, 2.48. Anal. calcd for $C_{66}H_{57}Cl_6N_3O_3S_6Pd_3$: C, 47.63; H, 3.45; N, 2.52%].

Complex **14a**: Mp 228–230°C (decomp.); IR (KBr): $\nu_{\max}$ (cm^{-1}) 1574, 1474, 1283, 746, 684; ^{1}H NMR (DMF d$_7$): δ 5.49 (bs, 54H, CH$_2$S and CH$_2$O), 7.10–8.30 (m, 105H, 4,5-pyH and ArH); [Found: C, 45.83; H, 3.24; N, 2.54. Anal. calcd for $C_{186}H_{159}Cl_{18}N_9O_9S_{18}Pd_9$: C, 46.18; H, 3.31; N, 2.61%].

Acknowledgements

This work was supported by Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Construction of Solid Supermolecules as Novel Functional Materials Project).

References

1. Gorman, C. *Adv. Mater.* **1998**, *4*, 295–309.
2. van Koten, G.; Jastrzebski, J. T. B. H. *J. Mol. Catal. A: Chem.* **1999**, *146*, 317–323.
3. Cuadrado, I.; Moran, M.; Casado, C. M.; Alonso, B.; Losada, J. *Coord. Chem. Rev.* **1999**, *193–195*, 395–445.
4. Balzani, V.; Campagna, S.; Denti, G.; Juris, A.; Serroni, S.; Venturi, M. *Acc. Chem. Res.* **1998**, *31*, 26–34.
5. Zeng, F.; Zimmerman, S. *Chem. Rev.* **1997**, *97*, 1681–1712.
6. Newkome, G. R.; He, E.; Moorefield, C. N. *Chem. Rev.* **1999**, *99*, 1689–1746.
7. Miedaner, A.; Curtis, C. J.; Barkley, R. M.; DuBois, L. *Inorg. Chem.* **1994**, *33*, 5482–5490.
8. Larré, C.; Donnadieu, B.; Caminade, A. M.; Majoral, J. P. *Chem. Eur. J.* **1998**, *4*, 2031–2036.
9. Petrucci-Samija, M.; Guillemette, V.; Dasgupta, M.; Kakkar, A. K. *J. Am. Chem. Soc.* **1999**, *121*, 1968–1969.
10. Canovese, L.; Chessa, G.; Marangoni, G.; Pitteri, B.; Uguagliati, P.; Visentin, F. *Inorg. Chim. Acta* **1991**, *186*, 79–86.
11. (a) Chessa, G.; Scrivanti, A.; Canovese, L.; Visentin, F.; Uguagliati, P. *Chem. Commun.* **1999**, 959–960. (b) Chessa, G.; Canovese, L.; Visentin, F.; Uguagliati, P. *Inorg. Chem. Commun.* **1999**, *2*, 607–608.
12. Denkewalter, R. G.; Kole, J. F.; Lukasavage, W. J. US Patent 4410688, 1983; *Chem. Abstr.* **1984**, *100*, 103907p.
13. (a) Roy, R.; Zanini, D.; Meunier, S. J.; Romanowska, A. *Chem. Commun.* **1993**, 1869–1872. (b) Maruo, N.; Uchiyama, M.; Kato, T.; Arai, T.; Akisada, H.; Nishino, N. *Chem. Commun.* **1999**, 2057–2058. (c) Grandjeean, C.; Rommens, C.; Gras-Mass, H.; Melnyk, O. *Tetrahedron Lett.* **1999**, *40*, 7235–7238.
14. (a) Twyman, L. J.; Beezer, A. E.; Mitchell, J. C. *Tetrahedron Lett.* **1994**, *35*, 4423–4424. (b) Ranganathan, D.; Kurur, S. *Tetrahedron Lett.* **1997**, *38*, 1265–1268.
15. Weintraub, H. J. G.; Parquette, J. R. *J. Org. Chem.* **1999**, *64*, 3796–3797.
16. Peng, Z.; Pan, Y.; Xu, B.; Zhang, J. *J. Am. Chem. Soc.* **2000**, *122*, 6619–6623.
17. Baldo, M. A.; Chessa, G.; Marangoni, G.; Pitteri, B. *Synthesis* **1987**, 720–723.
18. Chessa, G.; Marangoni, G.; Pitteri, B.; Visentin, F. *React. Polym.* **1992**, *18*, 7–14.
19. Kurita, K. *Chem. Ind. (London)* **1974**, 345.
20. van Oijen, A. H.; Huck, N. P. M.; Kruijtzer, J. A. W.; Erkelens, C.; van Boom, J. H.; Liskamp, R. M. J. *J. Org. Chem.* **1994**, *59*, 2399–2408.
21. Gricen, R.; Owen, L. N. *J. Chem. Soc.* **1963**, 1947–1954.
22. Hawker, C. J.; Fréchet, J. M. J. *J. Am. Chem. Soc.* **1990**, *112*, 7638–7647.
23. Vögtle, F.; Zuber, M.; Lichtenthaler, R. G. *Chem. Ber.* **1973**, *106*, 717–718.
24. Hughes, D. L. *Org. React.* **1992**, *42*, 335–656.
25. Tesser, G. I.; Balvert-Geers, J. C. *Int. J. Peptide Protein Res.* **1975**, *7*, 295–305.
26. (a) Tyler, T. L.; Hanson, J. E. *Chem. Mater.* **1999**, *11*, 3452–3459. (b) Gilat, S.; Andronov, A.; Fréchet, J. M. J. *J. Org. Chem.* **1999**, *64*, 7474–7484.
27. (a) Chessa, G.; Scrivanti, A. *J. Chem. Soc., Perkin Trans. 1* **1996**, 307–311. (b) Chessa, G.; Scrivanti, A. *J. Heterocycl. Chem.* **1997**, 1851–1855.
28. Ukai, T.; Kawazura, H.; Ishii, Y.; Bonnet, J. J.; Ibers, J. A. *J. Organomet. Chem.* **1974**, *65*, 253–266.
29. Canovese, L.; Visentin, F.; Chessa, G.; Gardenal, G.; Uguagliati, P. *J. Organomet. Chem.* **2001**, *602*, 155–165.
30. Slone, C. S.; Weinberger, D. A.; Mirkin, C. A. *Prog. Inorg. Chem.* **1999**, *48*, 233–350.
31. Canovese, L.; Visentin, F.; Chessa, G.; Niero, A.; Uguagliati, P. *Inorg. Chim. Acta* **1999**, *277*, 44–52.
32. Chessa, G.; Scrivanti, A.; Seraglia, R.; Traldi, P. *Rapid Commun. Mass Spectrom.* **1998**, *12*, 1533–1537.