

Dendritic encapsulation of amino acid–metal complexes. Synthesis and studies of dendron-functionalized L-tyrosine–metal (Zn^{II}, Co^{II}) complexes

Thatavarathy Rama Krishna and Narayanaswamy Jayaraman *

Department of Organic Chemistry, Indian Institute of Science, Bangalore 560 012, India.
E-mail: jayaraman@orgchem.iisc.ernet.in; Fax: 080 360 0529; Tel: 080 394 2578

Received (in Cambridge, UK) 9th November 2001, Accepted 28th January 2002
First published as an Advance Article on the web 15th February 2002

This paper describes the synthesis, characterization and studies of dendrimers possessing an amino acid–metal complex as the core. Using Fréchet-type polyaryl ether dendrons, L-tyrosine–metal (Zn^{II} and Co^{II}) complex cored dendrimers of 0–4 generations were synthesized. The metal complexation of the tyrosine unit at the focal point of these dendrons took place smoothly, in excellent yields, even though the sizes of the dendrons increase as the generations advance. Spectrophotometric titrations with Co^{II} metal ion confirmed the formation of a 2 : 1 dendritic ligand to metal complex and the existence of a pseudotetrahedral geometry at the metal centre is also inferred. Cyclic voltammetric studies of dendrimer–Co^{II} complexes showed that while the electron transfer of Co^{II} to Co^I was facile for generations 0–2, such a process was difficult with generations 3 and 4, indicating a rigid encapsulation of the metal ion centre by proximal dendron groups. Further reduction of Co^I to Co⁰ and the corresponding oxidation processes appear to be limited by adsorption at the surfaces of the electrodes.

Introduction

Architectural, structural and topological features of dendrimers continue to be the focus of a wide range of investigations, ever since these macromolecules became prominent over a decade ago.¹ The flexibility to modify the dendrimer structures has allowed the synthesis and study of a large number of different types of functional dendrimer.² Primary among covalent modifications of dendrimers are those involving either the core or the periphery of these macromolecules. While the functional group cored dendrimers exhibit properties as a result of evolution of ‘microenvironments’ and ‘site isolations’,³ a precise and periodic functionalization of the peripheries of a series of dendrimers is used often to understand the collective properties of such functional groups placed on a dendritic framework.⁴ In relevance to these features, a variety of dendrimers incorporating ligand–metal complexes, biologically active molecules, chromophores, fluorophores, electroactive and photoactive units have been synthesized and their properties examined.⁵

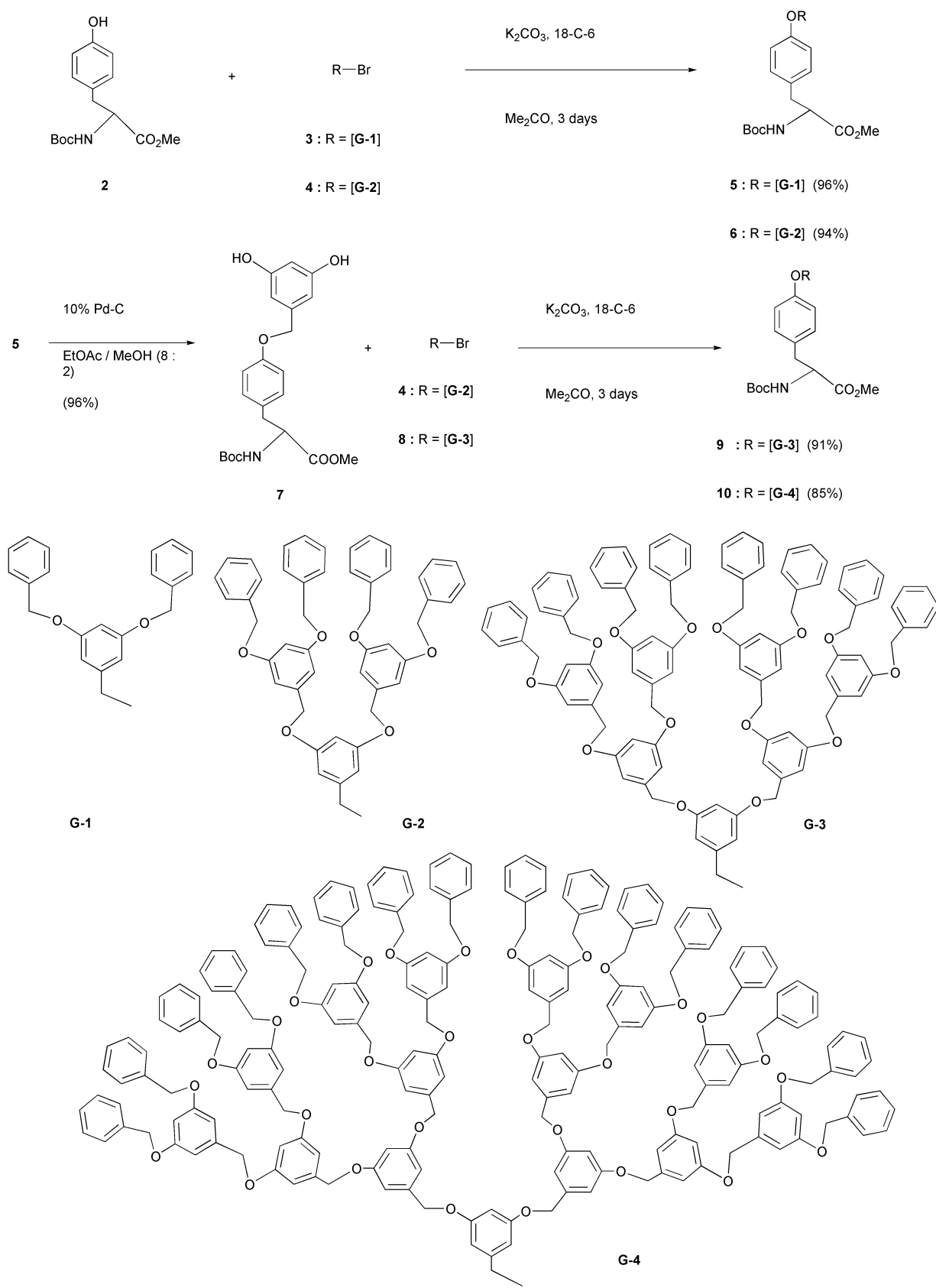
Of the two modifications mentioned previously, it has been suggested and tested that core modifications give rise to properties that are very different from those of the species under consideration in the bulk environments.³ Pioneering contributions by several groups on different types of dendrimer have demonstrated consistently that solution and solid state properties of the so-called ‘cored dendrimers’ can best be described in terms of their ‘site isolations’ and ‘microenvironmental effects’ that are attributable to dendritic architecture.⁶ As a result of our desire to study these phenomena in other types of cored dendrimer, we describe, in this report, the synthesis and studies of a series of homologous dendrimers that are ‘cored’ with amino acid–metal complexes. Amino acid–metal complexes are one of the most well-studied among metal complexes of biomolecules.⁷ Several facets of amino acid and peptide–metal complexes in selective organic reactions and biological studies have been reviewed recently.⁸ In amino acids, the amine and carboxylic acid functionalities take part invariably in metal coordination and form a stable five-membered chelate ring with the metal ion. Additionally, the side chain functionality,

wherever present, may also participate in metal coordination. In this report, we describe the synthesis of dendronized tyrosine amino acid functionalized with 0–4 generations of polyaryl ether dendrons and their Zn^{II} and Co^{II} metal complexes, followed by spectroscopic and electrochemical studies of these metal complexes.

Results and discussion

Synthesis of dendronized tyrosine derivatives

We chose to employ Fréchet-type polyaryl ether dendrons⁹ in order to functionalize the tyrosine amino acid. The convergent growth methodology developed for the synthesis of these dendrons is flexible enough to enable the incorporation of almost any type of functionalized core unit. An iterative procedure consisting of phenolic-*O*-alkylation and conversion of a benzylic hydroxy group into a benzylic bromide is often a standard synthetic protocol to obtain these polyaryl ether dendrons.⁹ Dendrons of generations 0–4, consisting of 1, 3, 7, 15 and 31 benzyloxy groups, respectively, were used to functionalize the phenolic hydroxy group of Boc-Tyr-OMe. While the zero generation dendron, Bn-Tyr (1) was prepared according to a known procedure,¹⁰ synthesis of 1–4 generation functionalized tyrosine was carried out by *O*-alkylation of either Boc-Tyr-OMe (2)¹¹ or 3,5-dihydroxybenzyl-Boc-Tyr-OMe (7) with bromide functionalized dendrons 3, 4 and 8⁹ (Scheme 1). Thus, *O*-alkylation of 2 with first generation (3) and second generation (4) bromides, under basic conditions, afforded the G-1-Boc-Tyr-OMe (5) and G-2-Boc-Tyr-OMe (6) in 96% and 94% yields, respectively. Similarly, the reaction of 7 with second generation (4) and third generation (8) bromides led to the isolation of G-3-Boc-Tyr-OMe (9) and G-4-Boc-Tyr-OMe (10) in 91% and 85% yields, respectively. All the dendronized tyrosine amino acid derivatives 5, 6, 9, 10 were purified by column chromatography (SiO₂) using hexane–EtOAc as the eluant system. Their structures were confirmed by routine physical methods (¹H NMR, ¹³C NMR, MS and elemental analysis). Deprotections of –OMe and Boc– groups were carried out on 5, 6, 9 and 10 by treatment with aq. KOH, followed by addition of



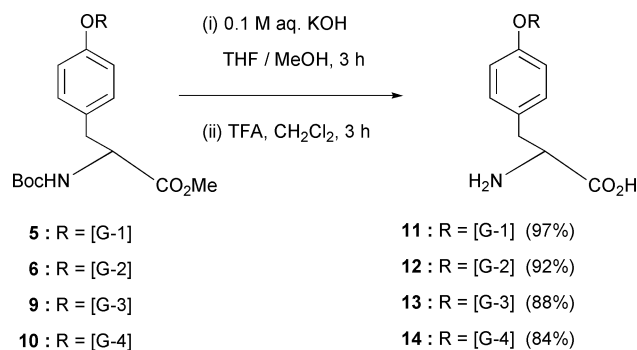
Scheme 1

TFA to obtain dendron-functionalized free amino acids **11** to **14**, again in excellent yields (Scheme 2).

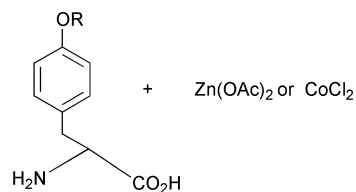
Synthesis of dendronized tyrosine–metal complexes

Metal ion complexations of G-0- to G-4-Tyr dendrons (**1**, **11**–**14**) were carried out mainly with Zn^{II} and Co^{II} metal ions. Both of these metal ions are known generally to assume tetrahedral

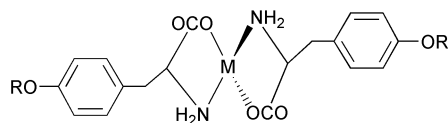
coordination geometry, although they are also known to adopt other coordination geometries.¹² Further, Co^{II} derivatives absorb radiation in the visible region, thereby rendering this metal a good environmental probe to access coordination geometries by UV–VIS spectroscopic techniques.¹³ Zn^{II} and Co^{II} complexes were prepared by treatment of free amino acids **1** and **11** to **14** with either $\text{Zn}(\text{OAc})_2$ or CoCl_2 (0.5 mol equiv.) in THF at 50–60 °C for 3 h and the metal complexes (Zn^{II} : **15**–**19**



Scheme 2



- 1** : R = Bn [G-0]
11 : R = [G-1]
12 : R = [G-2]
13 : R = [G-3]
14 : R = [G-4]



- 15** : M = Zn : R = Bn [G-0] (63%) **20** : M = Co : R = Bn [G-0] (90%)
16 : M = Zn : R = [G-1] (94%) **21** : M = Co : R = [G-1] (90%)
17 : M = Zn : R = [G-2] (87%) **22** : M = Co : R = [G-2] (94%)
18 : M = Zn : R = [G-3] (96%) **23** : M = Co : R = [G-3] (95%)
19 : M = Zn : R = [G-4] (89%) **24** : M = Co : R = [G-4] (97%)

Scheme 3

and Co^{II}: **20–24**) were obtained in excellent yields (Scheme 3). The facile formation of the metal complexes indicates that the amine and carboxylic acid functionalities of the Tyr moiety are freely available for metal complexation, even though it is tethered to the bulky dendron pendant groups. The Zn^{II} complexes **15–19** were colorless, whereas the Co^{II} complexes **20–24** exhibited a characteristic blue colour. While the Zn^{II} complexes were stable for prolonged periods, the Co^{II} complexes were only moderately stable and upon air exposure, these complexes changed colour from blue to red, possibly due to oxidation at the metal centre.

Structural characterization

With the exception of Bn-Tyr (**1**) and its metal complexes **15** and **20**, higher generation amino acids **11** to **14** and the corresponding metal complexes **16–19** and **21–24** were freely soluble in non-polar solvents such as CH₂Cl₂, CHCl₃, and Me₂CO. Melting point measurements showed that while G-0-Tyr (**1**) and G-1-Tyr (**11**) were solids with melting points 286–290 °C and 92–94 °C, respectively, G-2-Tyr (**12**) melted at 63–65 °C and G-3-Tyr (**13**), G-4-Tyr (**14**) were foamy powders at room temperature. A decreasing trend in the melting points of the metal complexes was observed as the number of generations increased. The higher generation metal complexes **18**, **19**, **23**

Table 1 Optical rotation data^a of dendrons and Zn^{II}-dendrimer complexes

	[α]/10 ⁻¹ deg cm ² g ^{-1b}	[φ]/degrees
2	52	153.4
5	26	155.2
6	13	242.9
7	30	125.1
9	15	153.2
10	4	142.8
11	-19	-110.4
12	-15	-153.3
13	-13	-243.2
14	-4	-145.1
16	-15	-154.5
17	-9	-169.11
18	-10	-357.7
19	-9	-627.75

^a The optical rotation was recorded at the D-line of Na. ^b In CHCl₃ (*c* = 1) unless otherwise specified.

and **24** exhibited melting points of *ca.* 100 °C, compared with the corresponding metal-free dendrons **13** and **14**, which were foamy powders. It appears that the solid state packing arrangement of free Tyr dendrons can be altered considerably upon metal coordination and this effect is significant for higher-generation metal complexes **18**, **19**, **23** and **24**, in which the metal ions constitute less than 1.6% of the overall molecular mass of the complexes.

Specific and molar optical rotations

Optical rotation measurements were carried out for solutions in CHCl₃ for all the dendronized Tyr derivatives (**11–14**) and their Zn^{II} complexes (**16–19**). The data are given in Table 1. The specific rotation values arising from chiral centre of the Tyr unit were observed to decrease monotonously as the dendron size increased. The corresponding molar rotations had a reverse trend, which increased from G-1-Tyr (**11**) to G-4-Tyr (**14**). A decreasing trend in specific rotation values has been observed previously for polyaryl ether dendrons, containing a single chiral unit at the core and this trend was attributed generally to 'optical dilution effects'.¹⁴ In these instances, the molar rotations remained essentially constant. It appears that steric crowding as well as higher rigidity of the Tyr unit in the dendrons reported herein are likely to contribute to the increasing trend of molar rotations as the generations increase. Optical rotation measurements of Zn^{II} complexes (**16–19**) also showed a similar trend, in that while the specific rotation values decreased, the corresponding molar rotation values increased considerably with the higher generation dendrimer-metal complexes.

Characterizations of dendrons and the metal complexes

The G-*n*-Tyr dendrons and their metal complexes were characterized by FT-IR, ¹H NMR and ¹³C NMR spectroscopic methods and elemental composition analyses. Mass spectrometric and atomic absorption analyses were also performed in order to ascertain the constitution and metal content of the complexes. Additionally, UV-VIS spectroscopy was employed to confirm the coordination geometry of the metal-ion core and to study the stoichiometric complexation behaviour of the ligand and the metal ion.

Pertinent changes in the IR spectrum of each metal complex (**15–24**), when compared with the corresponding metal-free dendrons (**1**, **11–14**), were the disappearance of absorptions at 1678 cm⁻¹ and 1240 cm⁻¹ in the spectrum of the metal complexes, which corresponded to their -NH₂ (δ) and -OC-OH (δ) frequencies. Apart from these changes, a comparison of the IR spectrum also showed that vibrational frequencies due to the

polyaryl ether dendron moiety became more prominent than that of the Tyr unit as the generations increased. This behaviour was observed in both G-*n*-Tyr dendrons as well as their metal complexes.

^1H and ^{13}C NMR spectroscopic characterizations of the dendronized Tyr derivatives and the Zn^{II} metal complexes were performed for solutions in CDCl_3 . Proton and carbon nuclei associated with the Tyr residue as well as the dendron portion could be observed clearly for dendronized Boc-Tyr-OMe (**5**, **6**, **9** and **10**). However, the resonances due to these nuclei became broad for dendronized free Tyr derivatives **11–14**, as well as Zn^{II} metal complexes **15–19**. The diastereotopic Tyr- CH_2 - protons resonated as two broad peaks in the ^1H NMR spectrum of these compounds. The severity of the crowding around the Tyr residue and the higher intensities of the polyaryl ether portion led to almost negligible appearance of protons and carbons in the NMR spectrum of higher generation dendrons and the corresponding metal complexes. Due to the paramagnetic nature of Co^{II} , NMR spectroscopic methods could not be routinely applied for the Co^{II} -dendrimer complexes. For these complexes **19–22**, other methods of characterization allowed us to confirm the structures.

Elemental composition analyses were obtained satisfactorily for all compounds. The composition of nitrogen was very low for higher generations and thus the nitrogen content for higher generation ligands and metal complexes could not be obtained reliably. Mass spectroscopic analyses were performed to confirm the constitution of dendrons **5**, **6**, **9**, **10**, **12** and **13** and the metal complexes **16** and **22**. Lower generation dendrons and metal complexes were susceptible to the FAB-MS technique, whereas the higher generation dendrons were analysed by the MALDI-TOF technique. Mass spectrometric analysis of higher generation metal complexes was unsuccessful and thus the metal ion content of these metal complexes was confirmed through atomic absorption analysis. While the atomic absorption values for the Zn^{II} complex **18** and Co^{II} complexes **23** and **24** were close to the calculated values, no reliable value for the fourth generation Zn^{II} complex **19** could be obtained.

UV-VIS spectroscopic studies of Co^{II} metal complexes

The nature of coordination geometry around the metal ion in dendrimers **20–24** was probed through the UV-VIS spectroscopic technique. Complexes of Co^{II} exhibit characteristic d-d transitions in the visible region of the spectrum; such transitions are dependent on the ligand geometry and other immediate environments of the metal centre.¹⁵ These properties of Co^{II} ion have been used widely in many metalloprotein structural studies.¹³ The UV-VIS spectra of complexes **20–24** were recorded for THF solutions. The visible absorption range of the spectrum showed two major bands (~ 670 and 592 nm) and two shoulders (~ 651 and 630 nm), indicating the presence of four distinguishable electronic d-d transitions (Fig. 1). In addition, a charge transfer band at ~ 330 nm ($\epsilon > 20000 \text{ l M}^{-1} \text{ cm}^{-1}$), typical of $\text{NH}_2 \rightarrow \text{Co}^{\text{II}}$ and $\text{O}^- \rightarrow \text{Co}^{\text{II}}$, along with aromatic $\pi-\pi^*$ transitions were also observed for all the metal complexes. Absorption maxima in the visible region are often used to assign the coordination geometry of a complex. The presence of distinguishable absorption maxima in the case of dendronized Tyr-Co complexes **20–24** indicated that a tetracoordinate geometry at the metal centre can be assigned in these complexes. The ϵ values, however, remained in the range $50\text{--}65 \text{ M}^{-1} \text{ cm}^{-1}$ at the absorption maximum (~ 670 nm). From the intensity considerations, it appears that these complexes may adopt either a pseudotetrahedral geometry or a pentacoordinate geometry. We can rule out the latter possibility on account of the fact that pentacoordinate Co^{II} complexes exhibit absorptions between 833 and 714 nm, which is considerably higher than the observed absorption range of between 730 and 545 nm for the dendronized metal complexes. Further, in the absence of

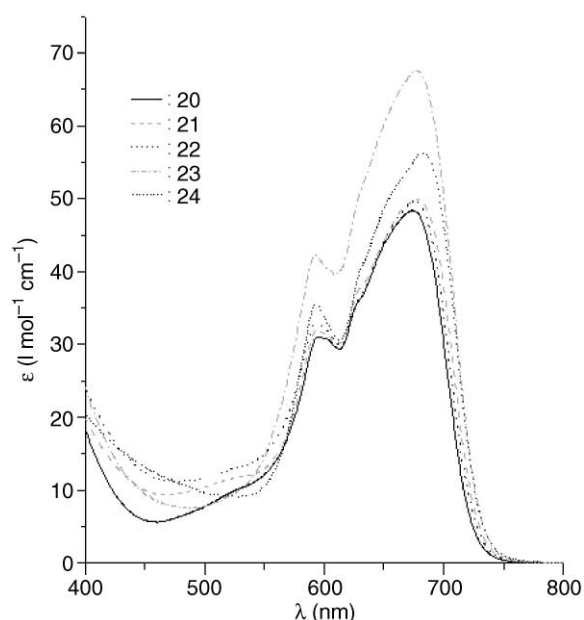


Fig. 1 UV-VIS absorption spectra of dendronized Tyr ligand- Co^{II} complexes (**20–24**) in THF.

absorptions at ~ 500 nm, a six-coordinate complex formation can be discounted. Thus, considering the presence of structured bands and their intensities, it appears that these complexes **20–24** are most likely to exist in a pseudotetrahedral geometry. It was also decided to ascertain the metal-ligand ratio in the complexes **20–24** and for this purpose, spectrophotometric titrations were performed for each complex.

An optically monitored titration of G-1-Tyr (**21**) with Co^{II} is shown in Fig. 2. A slightly red-shifted ligand field band was

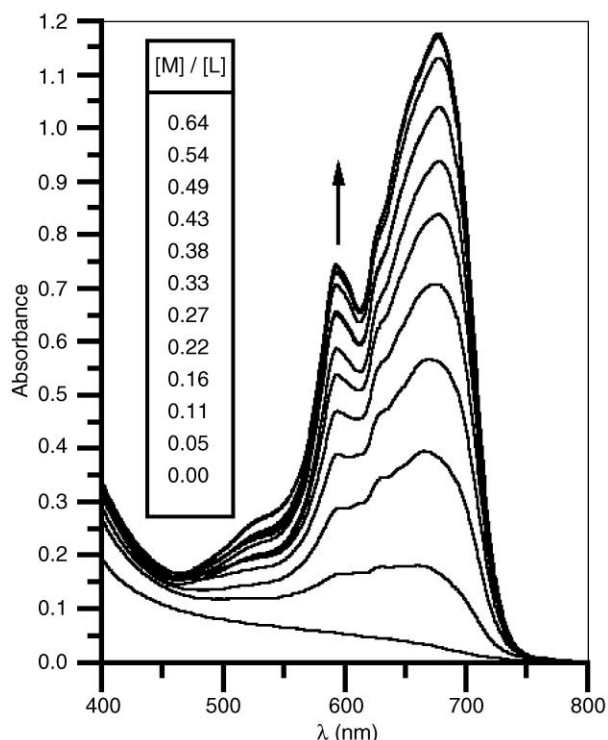


Fig. 2 A series of absorption spectra of a solution of **11** (~ 16.5 mM) in THF with various amounts of a solution of Co^{2+} in MeOH.

observed in the spectra at lower [metal] : [dendron] ratio. This spectrum saturated eventually, giving rise to the spectrum as shown in Fig. 1. A similar pattern was observed for other dendronized Tyr-Co complexes **20** and **22–24**. A combined plot of increase in absorbance with increasing ratios of [metal] :

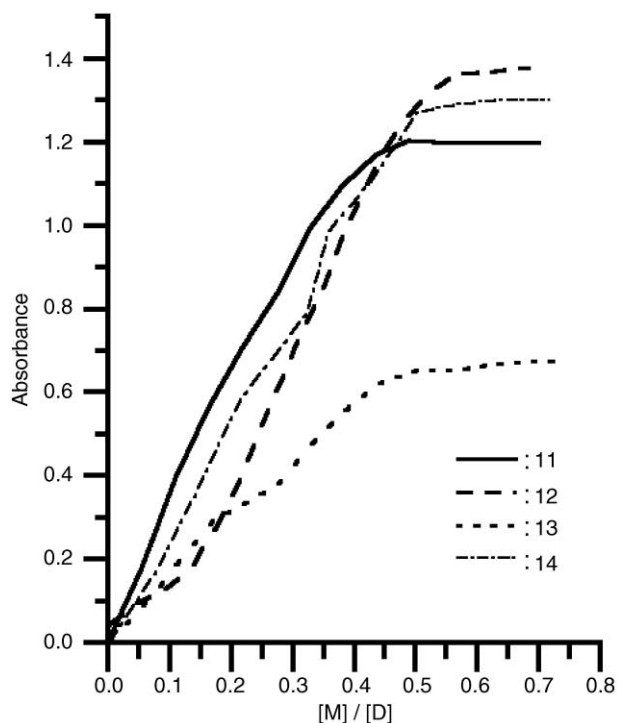


Fig. 3 A plot of the level of saturation of dendronized Tyr ligands (**11–14**) with Co^{2+} as a function of metal to ligand ratio.

[dendron] is shown in Fig. 3. From this plot, it is evident that the ratio of [metal] : [dendron] is close to 0.5, confirming the formation of a 2 : 1 ligand–metal complex in each of the complex studied. No further change in the absorption spectrum occurred beyond this ratio, even when an excess of metal ion was added. Thus, while the relative band intensities reflect a pseudotetrahedral geometry, the complementary results of the metal ion titration experiments confirm the formation of 2 : 1 dendron–metal complexes. The changes in the shape of the spectrum may be explained on the basis of the formation of other complex species during the early part of the titration. As the ratio of dendron : metal is decreased by the addition of free metal ion, which corresponds to later part of the spectrum, the formation of 2 : 1 dendron–metal complex is favoured, wherein the tetracoordination is assisted by the amine/carboxylate functionalities present in the dendron ligand. The notion that intermediate complex species may form is supported by the presence of an isosbestic point at ~ 730 nm in the spectra of the titration experiments. Further, the extent of 2 : 1 dendron–metal complex formation remained very similar for all the complexes **20–24**, indicating that the complex formation was not affected severely by increasing sizes of dendron pendant groups on the Tyr moiety. These results suggest that the dendronized amino acid has its amine and carboxylic acid functionalities in unhindered locations. This also indicates that the coordination of these dendronized amino acid ligands with other desired metal ions is distinctly possible.

Electrochemical characterization of dendronized Tyr– Co^{II} complexes

Cyclic voltammetric (CV) methods were used to characterize the redox potentials of Co^{II} bound to Tyr residue in dendrimers **20–24**, primarily to assess the effect of periodic increases in the size of the ligands on the metal electron transfer properties at the core in these dendrimers. Studies of electroactive dendrimers incorporating transition metal ions have been performed previously on different types of such metal ion containing dendrimers.¹⁶ Specific interest in the study of electron transfer properties in electroactive dendrimers relates largely to the unique molecular architecture of dendritic macromolecules and

Table 2 Cyclic voltammetric data^a for dendrimer– Co^{II} metal complexes

	$E^{\circ}_{\text{red(I)}/\text{V}}$	$E^{\circ}_{\text{red(II)}/\text{V}}$	$E^{\circ}_{\text{ox(I)}/\text{V}}$	$E^{\circ}_{\text{ox(II)}/\text{V}}$
20	–0.78 ^b	–1.17	0 ^b	0.16
21	–0.69 ^b	–1.31	0	0.07
22	–0.58	–1.36	0.08	0.16
23	–0.83	–1.24	–0.10	0
24	–0.88 ^b	–1.45 ^c		0.18 ^c

^a Ar-purged DMF solutions (2.5 mM), room temperature, TBAP supporting electrolyte; 100 mV s^{-1} sweep rate; glassy carbon working electrode; Ag reference electrode; Pt counter electrode. ^b Weakly resolved signal. ^c Broad signal.

their influence on the properties of the bound metal. Dendrimers **20–24**, having the metal ion as core, can be considered as metal complexes of Tyr amino acid ligands surrounded with dendritic substituents of different generations. From this consideration, the most commonly studied metal complex cored dendrimers previously are those derived from porphyrins,¹⁷ polypyridines,¹⁸ ferrocenes¹⁹ and iron–sulfur clusters.²⁰ CV experiments on dendrimers **20–24** were carried out in DMF solution with $\text{Bu}_4\text{N}^+ \text{ClO}_4^-$ (0.1 M) as the supporting electrolyte. The zero generation Co^{II} complex **20**, which represents the earliest of the series of Co^{II} complexes, exhibited two reduction (–0.78 and –1.17 V) and two oxidation (0 and 0.16 V) waves. The first reduction wave was rather weak and it appeared that in this two-electron transfer process, the first process, namely, Co^{II} to Co^{I} was not as prominent as that of the second reduction process, *i.e.*, Co^{I} to Co^0 . Similarly, in the oxidation process of Co^0 to Co^{II} , represented by two waves, one of the waves was weaker compared with the other. When Co^{II} as CoSO_4 was tested in the solution phase under identical conditions, it exhibited only one set of redox waves: one corresponding to a reduction (–1.1 V) and the other corresponding to an oxidation (–0.2 V) process. Thus, the Co^{II} to Co^0 conversion occurred in a single step in the case of uncomplexed Co^{II} as CoSO_4 , whereas the Co^{II} – Co^{I} – Co^0 conversion was observed as two distinct processes in the case of the zero generation Co^{II} complex. The redox potentials measured for dendritic Co^{II} complexes **20–24**, in the range –1.6 V to +1.2 V, are presented in Table 2 and the voltammograms corresponding to **22** and **23** are shown in Fig. 4. All the Co^{II} complexes exhibited quasi-reversible voltammograms in general. Similar to the case of zero generation **20**, generations 1–4 exhibited two waves during the reduction process Co^{II} to Co^0 . The first wave, which was weaker in magnitude, could be assigned to Co^{II} to Co^{I} [$E_{\text{red(I)}}$]. A comparison across generations revealed that this electron transfer process was affected severely by the structural changes. The observed order of the $E_{\text{red(I)}}$ (in V) process was **20** (–0.78) > **21** (–0.69) > **22** (–0.58) < **23** (–0.83) < **24** (–0.88). This trend can be attributed to the first electron transfer becoming more facile in the order zero to second generation dendrimer. However, the electron transfer process shows the opposite effect in the case of **23** and **24** (–0.83 and –0.88 V, respectively), probably due to increased encapsulation of the metal ion and the greater distance between the metal ion and the electrode surface. The higher reduction potentials of $E_{\text{red(I)}}$ reflect a slower and more difficult electron transfer in these two higher generation metal complexes (**23** and **24**) and thus this process is very likely to be kinetically controlled. In contrast, the second reduction potential [$E_{\text{red(II)}}$], namely Co^{I} to Co^0 , was comparable across the lower to the higher generation dendrimer–metal complexes. One possibility for this trend in $E_{\text{red(II)}}$ is that this process involves adsorption of the intermediate Co^{I} complex and the subsequent reduction of this complex to Co^0 , as opposed to the reduction of freely diffusing complex. Alternatively, there could be ligand dissociation during the reduction of Co^{I} to Co^0 ,

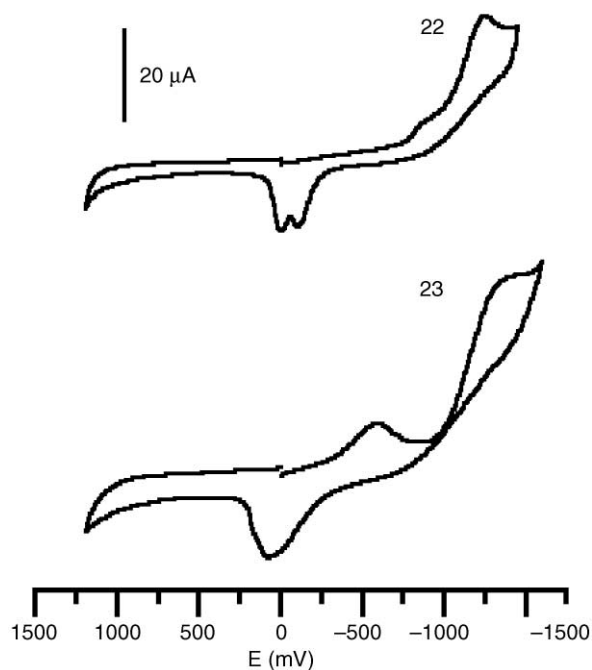


Fig. 4 Cyclic voltammograms of a solution of **22** (5 mM) and **23** (5 mM) in DMF (0.1 M Bu₄NClO₄). Scan rate = 100 mV s⁻¹.

which leads to the reduction occurring at similar potentials, regardless of the nature of the ligand.

The oxidative processes of Co⁰ to Co^{II} were also observed to have two potentials and the peak potentials were comparable for all the compounds studied (Table 2). There were very few changes in the metal oxidative properties upon dimeric complexation with Tyr residues coated with dendrons of different generations, the exception being that the oxidative waves were shifted within a limited range of -0.16 V to +0.16 V for the individual dendrimer-metal complex. This may be due to adsorption on the surfaces of the electrodes. Further, the CV behaviour was pronounced in the case of the fourth generation-Co^{II} complex **24**, wherein both reductive and oxidative waves were broad and the corresponding cathodic and anodic currents were found to be very high, for the same concentration of analyte. It is possible that there could be a ligand dissociation when Co exists as Co⁰ and the oxidation Co⁰-Co^I-Co^{II} may have occurred without reformation of dendrimeric ligand-metal complex. Fréchet-type polyaryl ether dendrons have been used previously to build dendrimers around a [Ru(bpy)₃]²⁺ core by Vögtle, Balzani and coworkers.^{18c} As reported in this work, the oxidation processes at more positive potentials (+1.76 V and +1.50 V), relating to the ligand-centred oxidation of dioxybenzene- and oxybenzene-type units of the dendritic branches, were also observed in the CV voltammograms of **21-24** when the experiment was carried out at a more positive potential (up to 2.0 V).

Conclusions

In conclusion, we have extended dendritic synthetic principles to the synthesis of a number of dendron-encapsulated tyrosine amino acid-metal complexes. In this metal ion-ligand self-assembly, a fine degree of structural control exists such that an ideal metal coordination of the amino acid at the focal point of dendrons is possible, irrespective of the sizes of dendrons. Spectrophotometric studies confirmed the 2 : 1 dendronized ligand to metal ratio for the 0-4 generations of Fréchet-type polyaryl ether dendron encapsulated tyrosine-metal (Zn^{II}, Co^{II}) complexes. In this manner, we may consider that an artificial environment is created around the metal complex in which the dendrons act as a permanent trap for the metal ion. We observe an effect of such encapsulation on the

electrochemical behaviour of the Co^{II} metal ion. Specifically, the one-electron reduction of Co^{II} to Co^I becomes facile in the order 0-generation Tyr-Co^{II} complex (**20**) to second generation Tyr-Co^{II} complex (**22**). However, this reduction process becomes more difficult with third- and fourth-generation Tyr-Co^{II} complexes (**23** and **24**), probably due to increased encapsulation of the metal ion and the attendant lesser proximity of the metal ion to the electrode surface. To the extent that these amino acid-metal complexes are encapsulated inside the bulky dendrons, they may exhibit altered properties such as catalytic properties, when compared with the parent Bn-Tyr-metal complex. Exploring such properties will form the basis of our future work with these dendron-encapsulated amino acid-metal complexes.

Experimental

Chemicals were purchased from commercial sources and were used without further purification. K₂CO₃ (AR grade) was dried at 120 °C for 24 h before being used. Solvents were dried and distilled according literature procedures.²¹ Analytical TLC was performed on commercial Merck plates coated with silica gel GF₂₅₄ (0.25 mm). Silica gel (100-200 mesh) (Acme) was used for column chromatography. Melting points were determined on a Büchi B-540 apparatus and are uncorrected. Infrared spectra were recorded on a JASCO FT-IR-410 spectrophotometer for either KBr discs or neat samples. UV-VIS spectra of metal-dendrimer complexes were run on a Shimadzu 2100 UV-VIS spectrophotometer. Matrix-assisted laser desorption ionization-time-of-flight mass spectra (MALDI-TOF-MS) were recorded on a Kratos Kompact MALDI-III instrument using gentisic acid matrix. Metal content analysis was performed on a Thermo Jarrell Ash Video 11E atomic absorption spectrometer. Aqueous solutions of metal ions for these analyses were prepared by digesting the metal-dendrimer complex in HNO₃-H₂SO₄ followed by complete removal of acidic solutions. Electrochemical characterizations of cobalt-dendrimer complexes were performed on a CH 660A electrochemical workstation, equipped with glassy carbon as working electrode and an Ag wire as a reference electrode. The experiments were carried out at ambient temperature, on DMF solutions (5 mM) that contained tetrabutylammonium perchlorate as the supporting electrolyte (0.1 M). Dry Ar gas was passed through the solutions for ~5 min before the cyclic voltammograms were recorded. Optical rotation measurements were recorded on a JASCO DIP 370 polarimeter at ambient temperature. Microanalyses were performed on a Carlo-Erba automated C, H, N analyser. ¹H and ¹³C NMR spectral analysis was performed on a JEOL JNM LA 300 spectrometer operating at 300 MHz and 75 MHz, respectively, with the residual solvent signal acting as the internal standard. The following abbreviations were used to denote the multiplicities: s, singlet; d, doublet; t, triplet; m, multiplet; band, several overlapping signals; br, broad. The following notations were used to describe the nuclei of NMR spectra: Ph, peripheral phenyl rings, Ar, inner phenyl rings, Tyr, tyrosine residue.

General procedure of *O*-alkylation of Boc-Tyr-OMe

A mixture of a dendron⁹ (**3**, **4**, **8**) (1.05 mol equiv.), Boc-Tyr-OMe (**2**)¹¹ (1.00 mol equiv.), K₂CO₃ (2.5 mol equiv) and 18-C-6 (0.2 molar equiv) in Me₂CO was refluxed, under a N₂ blanket, until the bromide disappeared (~24-72 h). The solvents were then evaporated off and the residue that remained was partitioned between CH₂Cl₂ and H₂O. The organic portion was separated and the aqueous portion was extracted further with CH₂Cl₂ (3 × ~15 ml). The combined organic portions were dried (Na₂SO₄) and evaporated to afford a crude product, which was purified by column chromatography (SiO₂).

G-1-Boc-Tyr-OMe (5). G-1-Br (**3**) (3.83 g, 10 mmol) was added to a stirred mixture of **2** (2.95 g, 10 mmol), K_2CO_3 (3.45 g, 25 mmol) and 18-C-6 (0.53 g, 2 mmol) in Me_2CO (45 ml). The reaction mixture was refluxed for 24 h. The solvents were then evaporated off, and the residue was worked up as described in the general procedure and purified by column chromatography (hexane–EtOAc 5 : 1) to obtain **5** as a colourless gum (5.74 g, 96%). FT-IR (neat) ν/cm^{-1} : 3376, 1745, 1715, 1595, 1243, 1160; EI-MS m/z : 597 $[M]^+$; 1H NMR ($CDCl_3$): δ 1.42 (s, 9 H, Me), 3.00–3.07 (br, 2 H, CH_2), 3.70 (s, 3 H, OMe), 4.54 (br, 1 H, CH), 4.96 (br, 3 H, $ArCH_2$ & NH), 5.02 (s, 4 H, $PhCH_2$), 6.57 (t, 1 H, $J = 2.1$ Hz, Ar), 6.67 (d, 2 H, $J = 2.1$ Hz, Ar), 6.87 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.03 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.29–7.43 (m, 10 H, Ph); ^{13}C NMR ($CDCl_3$): δ 28.2 (Me), 37.4 (Tyr CH_2), 52.1 (OMe), 54.5 (TyrCH), 60.3 (CMe_3), 69.8 ($ArCH_2$), 70.0 ($PhCH_2$), 101.4, 106.3, 114.9 (Ar), 127.5, 127.9, 128.5 (Ph), 128.2, 130.3, 139.4, 136.7 (Ar), 155.0 (NHCO), 157.7 (Tyr), 160.1 (Ar), 172.4 (COO); Anal. calcd. for: $C_{36}H_{39}NO_7$; C, 72.36; H, 6.50. Found: C, 72.22; H, 6.71%.

G-2-Boc-Tyr-OMe (6). G-2-Br (**4**) (0.85 g, 1.05 mmol) was added to a stirred mixture of **2** (0.30 g, 1 mmol), K_2CO_3 (0.35 g, 2.5 mmol) and 18-C-6 (0.053 g, 0.2 mmol) in Me_2CO (30 ml). The reaction mixture was refluxed for 24 h. The solvents were then evaporated off, and the residue was worked up as described in the general procedure and purified by column chromatography (hexane–EtOAc 4 : 1) to obtain **6** as a colourless gum (1.01 g, 94%). FT-IR (neat) ν/cm^{-1} : 3429, 1715, 1595, 1246, 1159, 1056; EI-MS m/z : 1021 $[M]^+$; 1H NMR ($CDCl_3$): δ 1.40 (s, 9 H, Me), 2.99 (br, 2 H, CH_2), 3.74 (s, 3 H, OMe), 4.51 (br, 1 H, CH), 4.95 (s, 7 H, $ArCH_2$ & NH), 5.01 (s, 8 H, $PhCH_2$), 6.52 (t, 1 H, $J = 2.1$ Hz, Ar), 6.55 (t, 2 H, $J = 2.1$ Hz, Ar), 6.64 (d, 2 H, $J = 2.1$ Hz, Ar), 6.69 (d, 4 H, $J = 2.1$ Hz, Ar), 6.86 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.01 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.27–7.413 (m, 20 H, Ph); ^{13}C NMR ($CDCl_3$): δ 28.3 (Me), 37.5 (Tyr CH_2), 52.2 (OMe), 54.5 (TyrCH), 69.8, 69.9 ($ArCH_2$), 70.1 ($PhCH_2$), 101.5, 101.6, 106.4 (Ar), 114.9 (Tyr), 127.5, 127.9, 128.6 (Ph), 128.2, 130.3 (Tyr), 136.7 (Ph), 139.2, 139.4, 160.0, 160.1 (Ar), 172.4 (NHCO); Anal. calcd. for: $C_{64}H_{63}NO_{11}$; C, 75.22; H, 6.17. Found: C, 75.17; H, 5.98%.

3,5-Dihydroxybenzyl-Boc-Tyr-OMe (7). To a solution of **5** (1 g, 2.4 mmol) in EtOAc–MeOH (80 : 20, 25 ml) was added Pd–C (10%) (0.1 g) and the mixture was stirred under a positive pressure of H_2 for 6 h. The reaction mixture was then filtered and the filtrate concentrated to obtain **7** as a white crystalline solid (0.4 g, 96%). Mp 178–180 °C; FT-IR (KBr) ν/cm^{-1} : 3370, 1729, 1686, 1511, 1300, 1243, 1159, 1055; EI-MS m/z : 417 $[M]^+$; 1H NMR ($CDCl_3$): δ 1.40 (s, 9 H, Me), 3.00–3.07 (br, 2 H, CH_2), 3.62 (s, 3 H, OMe), 4.45 (br, 1 H, CH), 4.81 (s, 2 H, $ArCH_2$), 4.95 (d, 1 H, NH), 6.21 (t, 1 H, $J = 2.1$ Hz, Ar), 6.34 (d, 2 H, $J = 2.1$ Hz, Ar), 6.75 (d, 2 H, $J = 8.4$ Hz, Tyr), 6.92 (d, 2 H, $J = 8.4$ Hz, Tyr); ^{13}C NMR ($CDCl_3$): δ 28.2 (Me), 37.5 ($ArCH_2$), 52.3 (OMe), 54.5 (TyrCH), 69.7 ($ArCH_2$), 102.4, 106.6 (Ar), 115.1, 128.2, 130.3 (Tyr), 139.8 (Ar), 155.5 (NHCO), 157.3 (Ar), 157.7 (Tyr), 172.7 (COO); Anal. calcd. for: $C_{22}H_{27}NO_7$; C, 63.31; H, 6.47; N, 3.36. Found: C, 63.68; H, 6.64; N, 3.68%.

G-3-Boc-Tyr-OMe (9). G-2-Br (**4**) (1.00 g, 1.24 mmol) was added to a stirred mixture of **7** (0.26 g, 0.62 mmol), K_2CO_3 (0.21 g, 1.54 mmol) and 18-C-6 (0.032 g, 0.12 mmol) in Me_2CO (30 ml). The reaction mixture was refluxed for 72 h. The solvents were then evaporated off, and the residue was worked up as described in the general procedure and purified by column chromatography (PhMe–EtOAc = 19 : 1) to obtain **9** as a colourless foamy solid (0.45 g, 91%, on the basis of recovered starting materials). FT-IR (KBr) ν/cm^{-1} : 3431, 1745, 1715, 1595, 1295, 1157; MS (MALDI-TOF) m/z : 1909.4 $[M + K]^+$, 1893.7 $[M + Na]^+$; 1H NMR ($CDCl_3$): δ 1.40 (s, 9 H, Me), 2.99 (br, 2 H, CH_2), 3.67 (s, 3 H, OMe), 4.52 (br, 1 H, CH), 4.92 (s, 2

H, $ArCH_2$), 4.94 (s, 13 H, $ArCH_2$ & NH), 5.00 (s, 16 H, $PhCH_2$), 6.52–6.55 (m, 7 H, Ar), 6.64–6.66 (m, 14 H, Ar), 6.86 (d, 2 H, $J = 8.4$ Hz, Tyr), 6.99 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.22–7.40 (m, 40 H, Ph); ^{13}C NMR ($CDCl_3$): δ 28.3 (Me), 69.9 ($ArCH_2$), 70.0 ($PhCH_2$), 101.6, 106.4 (Ar), 114.9 (Tyr), 127.5, 127.9, 128.6 (Ph), 128.2, 130.3 (Tyr), 136.7 (Ph), 139.2, 160.1, 160.0 (Ar); Anal. calcd. for: $C_{120}H_{111}NO_{19}$; C, 77.05; H, 5.94. Found: C, 77.17; H, 5.98%.

G-4-Boc-Tyr-OMe (10). (G-3-Br (**8**) (1.00 g, 0.60 mmol) was added to a stirred mixture of **7** (0.12 g, 0.30 mmol), K_2CO_3 (0.10 g, 0.74 mmol) and 18-C-6 (0.032 g, 0.12 mmol) in Me_2CO (30 ml). The reaction mixture was refluxed for 72 h. The solvents were then evaporated off, and the residue was worked up as described in the general procedure and purified by column chromatography (PhMe–EtOAc 4 : 1) to obtain **10** as a white foamy solid (0.38 g, 85%, on the basis of recovered starting materials). FT-IR (KBr) ν/cm^{-1} : 3436, 1743, 1715, 1595, 1295, 1157; MS (MALDI-TOF) m/z : 3608.3 $[M + K]^+$, 3594.3 $[M + Na]^+$, 3545.3 $[M]^+$; 1H NMR ($CDCl_3$): δ 1.41 (s, 9 H, Me), 2.89 (br, 2 H, CH_2), 3.57 (s, 3 H, OMe), 4.44 (br, 1 H, CH), 4.83 (s, 31 H, $ArCH_2$ & NH), 4.88 (s, 32 H, $PhCH_2$), 6.43–6.46 (m, 15 H, Ar), 6.56 (m, 30 H, Ar), 6.86 (d, 2 H, $J = 8.4$ Hz, Tyr), 6.99 (d, 2 H, $J = 8.4$ Hz, Tyr), 7.19–7.30 (m, 80 H, Ph); ^{13}C NMR ($CDCl_3$): δ 28.3 (Me), 69.9 ($ArCH_2$), 70.0 ($PhCH_2$), 101.6, 106.3, 106.4 (Ar), 114.9 (Tyr), 127.5, 127.9, 128.5 (Ph), 128.2, 130.3 (Tyr), 136.7 (Ph), 139.2, 160.0, 160.1 (Ar); Anal. calcd. for: $C_{232}H_{207}NO_{35}$; C, 78.07; H, 5.84. Found: C, 78.04; H, 5.74%.

General procedure for the deprotection of dendronized tyrosine

A solution of a dendronized Boc-Tyr-OMe (**5**, **6**, **9**, **10**) in THF–MeOH was treated with aqueous KOH (0.1 M) and stirred for 3 h. The solution was acidified (pH ~ 4) with aqueous HCl (1 M) and the volume of solvent was reduced *in vacuo*. The resulting suspension was extracted with CH_2Cl_2 , and the organic layer was dried (Na_2SO_4) and filtered. A few drops of TFA were added to this solution, which was stirred until the starting material disappeared (TLC). The solvents were then removed *in vacuo* to obtain dendronized tyrosine as its TFA salt. The TFA salt was subjected to purification by column chromatography (SiO_2).

G-1-Tyr (11). A solution of **5** (0.90 g, 1.86 mmol) in EtOH (50 ml) was treated with aq. KOH (1 M) (1.8 ml) and stirred for 3 h, then acidified with aq. HCl (1 M). The volume of solvent was reduced *in vacuo* and the resulting suspension was extracted with CH_2Cl_2 (3×10 ml). The organic portions were combined, dried and filtered. A few drops of TFA were added to this solution, which was then stirred for 3 h. The solvents were evaporated off *in vacuo* and the resulting crude product was purified by column chromatography ($CHCl_3$ –MeOH 19 : 1) to obtain **11** as a white amorphous solid (0.85 g, 96.7%). Mp 92–94 °C; FT-IR (KBr) ν/cm^{-1} : 3437, 1725, 1673, 1596, 1292, 1162; 1H NMR ($CDCl_3$): δ 2.96 (br, 1 H, CH_2), 3.19 (br, 1 H, CH_2), 4.10 (br, 1 H, CH), 4.77 (s, 2 H, $ArCH_2$), 4.88 (s, 4 H, $PhCH_2$), 6.48 (br, 1 H, Ar), 6.56 (br, 2 H, Ar), 6.82 (br, 2 H, Tyr), 7.06 (br, 2 H, Tyr), 7.29–7.43 (m, 10 H, Ph).

G-2-Tyr (12). A solution of **6** (0.71 g, 0.69 mmol) in THF–MeOH (1 : 1) (25 ml) was treated with aq. KOH (0.1 M) (4 ml) and stirred for 3 h. The resulting suspension was extracted with CH_2Cl_2 (3×10 ml), and the organic portions were combined, dried and filtered. A few drops of TFA were added to the solution, which was then stirred for 3 h. The solvents were evaporated off *in vacuo* and the resulting crude product was purified by column chromatography ($CHCl_3$ –MeOH 16 : 1) to obtain **12** as a white foamy powder (0.65 g, 92%). Mp 63–65 °C; FT-IR (neat) ν/cm^{-1} : 3066, 1724, 1676, 1596, 1296, 1157; MS

(MALDI-TOF) m/z : 908 [M + H]⁺; ¹H NMR (CDCl₃): δ 2.89 (br, 1 H, CH₂), 3.14 (br, 1 H, CH₂), 3.97 (br, 1 H, CH), 4.74 (s, 7 H, ArCH₂), 4.84 (s, 8 H, PhCH₂), 6.29 (s, 1 H, Ar), 6.42 (s, 2 H, Ar), 6.55 (s, 6 H, Ar), 6.81 (br, 2 H, Tyr), 7.07 (br, 2 H, Tyr), 7.23–7.52 (m, 20 H, Ph); ¹³C NMR (CDCl₃): δ 69.9 (ArCH₂), 101.5, 106.4 (Ar), 127.5, 127.9, 128.5, 136.7 (Ph), 139.1, 159.9, 160.1 (ArC); Anal. calcd. for C₆₀H₅₄NO₁₁F₃: C, 70.51; H, 5.28. Found: C, 69.23; H, 5.31%.

G-3-Tyr (13). A solution of **9** (0.25 g, 0.13 mmol) in THF–MeOH (20 : 9) (15 ml) was treated with aq. KOH (0.1 M) (1.3 ml) and stirred for 3 h. The resulting suspension was extracted with CH₂Cl₂ (3 × 10 ml), and the organic portions were combined, dried and filtered. A few drops of TFA were added to the solution, which was stirred for 3 h. The solvents were evaporated off *in vacuo* and the resulting crude product was purified by column chromatography (CHCl₃–MeOH 13 : 1) to obtain **13** as a white foamy powder (0.22 g, 88%). FT-IR (KBr) ν/cm^{-1} : 3430, 1678, 1595, 1295, 1156; MS (MALDI-TOF) m/z : 1757.4 [M]⁺, 1780.1 [M + Na]⁺, 1796.2 [M + K]⁺; ¹H NMR (CDCl₃): δ 2.87 (br, 1 H, CH₂), 3.18 (br, 1 H, CH₂), 3.94 (br, 1 H, CH), 4.76 (s, 15 H, ArCH₂), 4.85 (s, 16 H, PhCH₂O), 6.43–6.45 (m, 7 H, Ar), 6.55 (s, 14 H, Ar), 6.80 (d, 2 H, Tyr), 7.03 (d, 2 H, Tyr), 7.22–7.27 (m, 40 H, Ph); ¹³C NMR (CDCl₃): δ 69.9 (ArCH₂), 70.0 (PhCH₂), 101.4, 106.3 (Ar), 127.4, 127.8, 128.4, 136.7 (Ph), 139.1, 159.9, 160.0 (Ar); Anal. calcd. for C₁₁₆H₁₀₂NO₁₉F₃: C, 74.48; H, 5.45. Found: C, 74.90; H, 5.72%.

G-4-Tyr (14). A solution of **10** (0.37 g, 0.1 mmol) in THF–MeOH (5 : 3) (18 ml) was treated with aq. KOH (0.1 M) (1 ml) and stirred for 3 h. The resulting suspension was extracted with CH₂Cl₂ (3 × 10 ml), and the organic portions were combined, dried and filtered. A few drops of TFA were added to the solution, which was then stirred for 3 h. The solvents were evaporated off *in vacuo* and the resulting crude product was purified by column chromatography (CHCl₃–MeOH 9 : 1) to obtain **14** as a white foamy powder (0.31 g, 84%). FT-IR (KBr) ν/cm^{-1} : 3064, 1713, 1595, 1295, 1151; ¹H NMR (CDCl₃): δ 2.84 (br, 1 H, CH₂), 3.23 (br, 1 H, CH₂), 3.88 (br, 1 H, CH), 4.79 (s, 30 H, ArCH₂), 4.87 (s, 32 H, PhCH₂), 6.46 (s, 14 H, Ar), 6.57 (s, 31 H, Ar), 6.82 (br, 2 H, Tyr), 7.04 (br, 2 H, Tyr), 7.26–7.28 (m, 80 H, Ph); ¹³C NMR (CDCl₃): δ 69.9 (ArCH₂), 70.0 (PhCH₂), 101.5, 106.3 (Ar), 127.4, 127.8, 128.4, 136.7 (Ph), 139.1, 159.9, 160.0 (Ar); Anal. Calcd. for C₂₂₈H₁₉₈NO₃₅F₃: C, 76.73; H, 5.48. Found: C, 76.87; H, 5.77%.

General procedure for the preparation of metal complexes

A solution of the dendronized tyrosine ligands (**11–14**) in CH₂Cl₂ was treated with aq. NH₄OH for 30 min, after which the organic portion was separated, evaporated *in vacuo* and dried thoroughly. The resulting ligand (2.0 mol equiv.) in THF was then added to either Zn(OAc)₂ or CoCl₂ (1.0 mol equiv.) and the solution was stirred for 3 h at 50–60 °C. The solvents were then removed and the resulting residue washed several times with Et₂O, MeOH and H₂O to obtain the desired metal complex.

G-0-Zn complex (15). A solution of **1** (0.135 g, 0.5 mmol) in MeOH (20 ml) was added to 0.1 M aqueous NaOH (2.5 ml) and Zn(OAc)₂ (0.055 g, 0.25 mmol), and the mixture was stirred at 50–60 °C for 3 h and then worked up as described in the general procedure to obtain **15** as a white amorphous solid (0.096 g, 63%). Mp 345–350 °C; FT-IR (KBr) ν/cm^{-1} : 3430, 1630, 1511, 1251, 1105; Anal. Calcd. for C₃₂H₃₂N₂O₆Zn: C, 63.46; H, 5.33. Found: C, 61.91; H, 5.21%.

G-1-Zn complex (16). G-1-Tyr (**11**) (0.12 g, 0.25 mmol) in THF (10 ml) was mixed with Zn(OAc)₂ (0.023 g, 0.08 mmol)

and stirred at 50–60 °C for 3 h. The reaction mixture was worked up as described in the general procedure to obtain **16** as a white amorphous solid (0.11 g, 94%). Mp 176–177 °C; FT-IR (KBr) ν/cm^{-1} : 3439, 1595, 1510, 1296, 1156, 1052; EI-MS m/z : 1051 (22%), 1053 (11%), 1055 (10%) [M + Na]⁺, 1030 [M + 1]⁺; ¹H NMR (CDCl₃): δ 2.94 (br, 2 H, CH), 3.47 (m, 4 H, CH₂), 4.91 (s, 4 H, ArCH₂), 4.99 (s, 8 H, PhCH₂), 6.55 (s, 2 H, Ar), 6.66 (s, 4 H, Ar), 6.90 (d, 4 H, Tyr), 7.15 (d, 4 H, Tyr), 7.25–7.61 (m, 20 H, Ph); ¹³C NMR (CDCl₃): δ 54.4 (TyrCH), 69.8 (ArCH₂), 101.4, 106.3 (Ar), 114.9 (Tyr), 127.5, 127.9, 128.5 (Ph), 128.2, 130.3 (Tyr), 139.4, 136.7 (Ar), 155.0 (C=O), 157.7 (Ar), 160.1 (Ar), 172.4 (CO); Anal. calcd. for C₆₀H₅₆N₂O₁₀Zn: C, 69.94; H, 5.44; N, 2.72. Found: C, 69.91; H, 5.35; N, 2.70%.

G-2-Zn complex (17). G-2-Tyr (**12**) (0.13 g, 0.14 mmol) in THF (10 ml) was mixed with Zn(OAc)₂ (0.013 g, 0.07 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **17** as a white amorphous solid (0.12 g, 87%). Mp 139–141 °C; FT-IR (neat) ν/cm^{-1} : 3439, 1595, 1510, 1296, 1156, 1052; ¹H NMR (CDCl₃): δ 2.89 (br, 2 H, CH₂), 3.14 (br, 2 H, CH₂), 3.97 (br, 2 H, CH), 4.74 (s, 12 H, ArCH₂), 4.84 (s, 16 H, PhCH₂), 6.29 (s, 2 H, Ar), 6.42 (s, 4 H, Ar), 6.55 (s, 12 H, Ar), 6.81 (br, 4 H, Tyr), 7.07 (br, 4 H, Tyr), 7.23–7.52 (m, 40 H, Ph); ¹³C NMR (CDCl₃): δ 69.9 (ArCH₂), 101.5, 106.4 (Ar), 127.5, 127.9, 128.5, 136.7 (Ph), 139.1, 159.9, 160.1 (Ar); Anal. calcd. for C₁₁₆H₁₀₄N₂O₁₈Zn: C, 74.13; H, 5.54. Found: C, 74.06; H, 5.48%.

G-3-Zn complex (18). G-3-Tyr (**13**) (0.05 g, 0.02 mmol) in THF (10 ml) was mixed with Zn(OAc)₂ (0.0026 g, 0.014 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **18** as a white amorphous solid (0.049 g, 96%). Mp 94–96 °C; FT-IR (KBr) ν/cm^{-1} : 3439, 1595, 1510, 1296, 1156, 1052; ¹H NMR (CDCl₃): δ 2.85 (br, 2 H, CH₂), 3.22 (br, 2 H, CH₂), 3.94 (br, 2 H, CH), 4.78 (s, 28 H, ArCH₂), 4.88 (s, 32 H, PhCH₂), 6.49 (s, 14 H, Ar), 6.59 (s, 28 H, Ar), 6.86 (br, 4 H, Tyr), 7.03 (br, 4 H, Tyr), 7.27–7.40 (m, 80 H, Ph); ¹³C NMR (CDCl₃): δ 69.8, 69.9 (ArCH₂), 101.5, 106.3 (Ar), 127.5, 127.9, 128.5, 136.7 (Ph), 139.1 (Ar), 159.9, 160.0 (Ar); Anal. calcd. for C₂₂₈H₂₀₀N₂O₃₄Zn: C, 76.56; H, 5.68; Zn, 1.63. Found: C, 76.20; H, 5.69; Zn, 1.61%.

G-4-Zn complex (19). G-4-Tyr (**14**) (0.05 g, 0.014 mmol) in THF (10 ml) was mixed with Zn(OAc)₂ (0.0012 mg, 0.007 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **19** as a white amorphous solid (0.045 g, 89%). Mp 100–102 °C; FT-IR (KBr) ν/cm^{-1} : 3430, 1595, 1509, 1296, 1156, 1051; ¹H NMR (CDCl₃): δ 2.82 (br, 2 H, CH₂), 3.10 (br, 2 H, CH₂), 3.96 (br, 2 H, CH), 4.73 (s, 60 H, ArCH₂), 4.82 (s, 64 H, PhCH₂), 6.43 (s, 30 H, Ar), 6.53 (s, 60 H, Ar), 6.72 (br, 4 H, Ar), 7.00 (br, 4 H, Ar), 7.19–7.36 (m, 160 H, Ph); ¹³C NMR (CDCl₃): δ 69.9 (ArCH₂), 101.5, 106.3 (Ar), 127.5, 127.9, 128.5, 128.6, 136.7 (Ph), 139.1 (Ar), 159.9, 160.0 (Ar); Anal. calcd. for C₄₅₂H₃₉₂N₂O₆₆Zn: C, 77.85; H, 5.69. Found: C, 76.76; H, 5.71%.

G-0-Co complex (20). A solution of **1** (0.1 g, 0.37 mmol) in THF (10 ml) was admixed with CoCl₂ (0.024 g, 0.18 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **20** as a blue amorphous solid (0.095 g, 90%). Mp 240–250 °C; FT-IR (neat): ν/cm^{-1} : 3438, 1623, 1513, 1251, 1116; UV λ_{max}/nm (MeOH–THF 1 : 1): 666 ($\epsilon = 49$), 644 ($\epsilon = 49$), 627 ($\epsilon = 49$); Anal. Calcd. for C₃₂H₃₂N₂O₆Co: C, 64.10; H, 5.38. Found: C, 62.34; H, 5.24%.

G-1-Co complex (21). G-1-Tyr (**11**) (0.1 g, 0.21 mmol) in THF (10 ml) was mixed with CoCl₂ (0.014 g, 0.11 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up

as described in the general procedure to obtain **21** as a blue amorphous powder (0.095 g, 90%). Mp 138–140 °C; FT-IR (KBr) ν/cm^{-1} : 3423, 1595, 1510, 1296, 1243, 1156, 1052; UV $\lambda_{\text{max}}/\text{nm}$ (CHCl_3): 666 ($\epsilon = 50$), 644 ($\epsilon = 38$), 627 ($\epsilon = 32$); Anal. calcd. for $\text{C}_{60}\text{H}_{56}\text{N}_2\text{O}_{10}\text{Co}$: C, 70.37; H, 5.51; N, 2.72. Found: C, 69.94; H, 5.26; N, 2.80%.

G-2-Co complex (22). G-2-Tyr (**12**) (0.03 g, 0.033 mmol) in THF (10 ml) was mixed with CoCl_2 (0.002 g, 0.016 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **22** as a blue amorphous solid (0.029 g, 94%). Mp 139–141 °C; FT-IR (neat): ν/cm^{-1} : 3431, 1595, 1510, 1296, 1156, 1052; UV $\lambda_{\text{max}}/\text{nm}$ (CHCl_3): 666 ($\epsilon = 50$), 644 ($\epsilon = 37$), 627 ($\epsilon = 33$); LSI-MS m/z : 1872 $[\text{M} + 1]^+$; Anal. calcd. for $\text{C}_{116}\text{H}_{104}\text{N}_2\text{O}_{18}\text{Co}$: C, 74.40; H, 5.57. Found: C, 74.61; H, 5.82%.

G-3-Co complex (23). G-3-Tyr (**13**) (0.026 g, 0.0148 mmol) in THF (10 ml) was mixed with CoCl_2 (0.001 g, 0.0074 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **23** as a blue amorphous solid (0.075 g, 95%). Mp 97–99 °C; FT-IR (KBr) ν/cm^{-1} : 3431, 1510, 1295, 1156, 1052; UV $\lambda_{\text{max}}/\text{nm}$ (CHCl_3): 666 ($\epsilon = 67.7$), 644 ($\epsilon = 52$), 627 ($\epsilon = 42$); Anal. calcd. for $\text{C}_{228}\text{H}_{200}\text{N}_2\text{O}_{34}\text{Co}$: C, 76.70; H, 5.65; Co, 1.62. Found: C, 75.84; H, 5.73; Co, 1.59%.

G-4-Co complex (24). G-4-Tyr (**14**) (0.055 g, 0.0154 mmol) in THF (10 ml) was mixed with CoCl_2 (0.001 g, 0.0077 mmol) and stirred for 3 h at 50–60 °C. The reaction mixture was worked up as described in the general procedure to obtain **24** as a blue amorphous solid (0.054 g, 97%). Mp 99–101 °C; FT-IR (KBr) ν/cm^{-1} : 3064, 1713, 1682, 1595, 1295, 1151, 1051; UV $\lambda_{\text{max}}/\text{nm}$ (CHCl_3): 666 ($\epsilon = 57$), 644 ($\epsilon = 40$), 627 ($\epsilon = 37$); Anal. calcd. for $\text{C}_{452}\text{H}_{392}\text{N}_2\text{O}_{66}\text{Co}$: C, 77.92; H, 5.67; Co, 0.831. Found: C, 77.17; H, 5.98; Co, 0.78%.

Acknowledgements

We are very grateful to Ms Smitha Sarkar and Professor S. Sampath (Inorganic and Physical Chemistry department) for their guidance and assistance in carrying out the electrochemical studies presented in this work and Professor S. Subramanian (Department of Metallurgy) for his kind help in the atomic absorption analyses of the metal complexes. We are grateful to Department of Science and Technology (New Delhi) for financial support. T.R. thanks UGC for a research fellowship.

References

- (a) E. Buhleier, W. Wehner and F. Vögtle, *Synthesis*, 1978, 155; (b) D. A. Tomalia, H. Baker, J. Dewald, M. Hall, C. Kallos, S. Martin, J. Roeck, J. Ryder and P. Smith, *Polym. J. (Tokyo)*, 1985, **17**, 117; (c) G. R. Newkome, Z.-Q. Yao, G. R. Baker and V. K. Gupta, *J. Org. Chem.*, 1985, **50**, 2003.
- (a) D. A. Tomalia, A. M. Naylor and W. A. Goddard III, *Angew. Chem., Int. Ed. Engl.*, 1990, **29**, 138; (b) J. M. J. Fréchet, *Science*, 1994, **263**, 1710; (c) F. Zeng and S. C. Zimmerman, *Chem. Rev.*, 1997, **97**, 1681; (d) H. Chow, T. K. T. Mong, M. F. Nongrum and W. Chi-Wai, *Tetrahedron*, 1998, **54**, 8543; (e) O. A. Matthews, A. N. Shipway and J. F. Stoddart, *Prog. Polym. Sci.*, 1998, **23**, 1; (f) A. W. Bosman, H. M. Jansen and E. W. Meijer, *Chem. Rev.*, 1999, **99**, 1665; (g) J.-P. Majoral and A.-M. Caminade, *Chem. Rev.*, 1999, **99**, 845; (h) K. Inoue, *Prog. Polym. Sci.*, 2000, **25**, 453.
- (a) D. K. Smith and F. Diederich, *Chem. Rev.*, 1998, **4**, 1353; (b) S. Hecht and J. M. J. Fréchet, *Angew. Chem., Int. Ed.*, 2001, **40**, 74; (c) C. B. Gorman and J. C. Smith, *Acc. Chem., Res.*, 2001, **34**, 60.
- (a) G. R. Newkome, X. Lin and C. D. Weis, *Tetrahedron: Asymmetry*, 1991, **2**, 957; (b) J. F. G. A. Jansen, E. M. M. de B. Berg and E. W. Meijer, *Science*, 1994, **266**, 1226; (c) P. M. Saville, P. A. Reynolds, J. W. White, C. J. Hawker, J. M. J. Fréchet, K. L. Wooley, J. Penfold and J. R. P. Webster, *J. Phys. Chem.*, 1995, **99**, 8283; (d) T. D. James, T. M. Shinmori and S. Shinkai, *Chem. Commun.*, 1996, 705; (e) R. Roy, *Polym. News*, 1996, **21**, 226; (f) N. Jayaraman, S. A. Nepogodiev and J. F. Stoddart, *Chem. Eur. J.*, 1997, **3**, 1193; (g) J. H. Cameron, A. Facher, G. Lattermann and S. Diele, *Adv. Mater.*, 1997, **9**, 398; (h) C. Valério, J.-L. Fillaut, J. Ruiz, J. Guittard, J. C. Blais and D. Astruc, *J. Am. Chem. Soc.*, 1997, **119**, 2588; (i) J. Losada, I. Cuadrado, M. Moran, C. M. Casado, B. Alonso and M. Barranco, *Anal. Chim. Acta*, 1997, **338**, 191; (j) C. Wang, M. R. Bryce, A. S. Batsanov, L. M. Goldenberg and J. A. K. Howard, *J. Mater. Chem.*, 1997, **7**, 1189; (k) J. F. Stoddart and T. Welton, *Polyhedron*, 1999, **18**, 3575; (l) E. Oosterom, J. N. H. Reek, P. C. J. Kamer and P. W. N. M. Van Leeuwen, *Angew. Chem., Int. Ed.*, 2001, **40**, 1828.
- Many aspects of functional dendrimers have been covered in: (a) *Top. Curr. Chem.*, 1998, **197**; (b) *Top. Curr. Chem.*, 2000, **210**; (c) *Top. Curr. Chem.*, 2001, **212**.
- (a) A. M. Naylor, W. A. Goddard III, G. E. Kiefer and D. A. Tomalia, *J. Am. Chem. Soc.*, 1989, **111**, 2339; (b) C. J. Hawker, P. J. Farrington, M. E. Mackay, K. L. Wooley and J. M. J. Fréchet, *J. Am. Chem. Soc.*, 1995, **117**, 4409; (c) J. Jansen, R. A. J. Janssen, E. M. de Brabender-van den Berg and E. W. Meijer, *Adv. Mater.*, 1995, **7**, 561; (d) H. Brunner, *J. Organomet. Chem.*, 1995, **500**, 39; (e) G. M. Stewart and M. A. Fox, *J. Am. Chem. Soc.*, 1996, **118**, 4354; (f) C. Bolm, N. Derrien and A. Seger, *Synlett*, 1996, 387; (g) C. B. Gorman, *Adv. Mater.*, 1997, **9**, 1117; (h) C. Devadoss, P. Bharathi and J. S. Moore, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 1633; (i) M. Kawa and J. M. J. Fréchet, *Chem. Mater.*, 1998, **10**, 286; (j) G. E. Oosterom, R. J. van Haaren, J. N. H. Reek, P. C. J. Kamer and P. van Leeuwen, *Chem. Commun.*, 1999, 1119; (k) M. J. Hannon, P. C. Mayers and P. C. Taylor, *J. Chem. Soc., Perkin Trans. 1*, 2000, 1881; (l) M. J. Hannon, P. C. Mayers and P. C. Taylor, *Angew. Chem., Int. Ed.*, 2001, **40**, 1081.
- H. C. Freeman, in *Inorganic Biochemistry*, ed. E. L. Eichhorn, Elsevier, Amsterdam, 1973, p. 121.
- K. Severin, R. Bergs and W. Becks, *Angew. Chem., Int. Ed. Engl.*, 1998, **37**, 1634.
- C. J. Hawker and J. M. J. Fréchet, *J. Am. Chem. Soc.*, 1990, **112**, 7638.
- E. Wünsch, G. Fries and A. Zwick, *Chem. Ber.*, 1958, **91**, 542.
- A. Kolodziejczyk and M. Manning, *J. Org. Chem.*, 1981, **46**, 1944.
- S. H. Laurie, in *Comprehensive Coordination Chemistry*, eds. G. Wilkinson, R. D. Gillard and J. A. McCleverty, Pergamon, Oxford, 1987, vol. 2, pp. 739–776.
- (a) B. L. Vallee and R. J. P. Williams, *Proc. Natl. Acad. Sci. USA*, 1968, **59**, 498; (b) I. Bertini, M. Ciampolini and L. Sacconi, *J. Coord. Chem.*, 1971, **1**, 73.
- (a) D. Seebach, J.-M. Lapierre, K. Skobridis and G. Greiveldinger, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 440; (b) D. Seebach, J.-M. Lapierre, G. Greiveldinger and K. Skobridis, *Helv. Chim. Acta*, 1994, **77**, 1673.
- (a) A. B. P. Lever, *Inorganic Electronic Spectroscopy*, Elsevier, Amsterdam, 1968; (b) R. L. Carlin, *Transition Metal Chem.*, 1965, **1**, 1.
- (a) I. Cuadrado, C. M. Casado, B. Alonso, M. Morán, J. Losada and V. Belsky, *J. Am. Chem. Soc.*, 1997, **119**, 7613; (b) T. D. Selby and S. C. Blackstock, *J. Am. Chem. Soc.*, 1998, **120**, 12155; (c) M. Kimura, Y. Sugihara, T. Muto, K. Hanabusa, H. Shirai and N. Kobayashi, *Chem. Eur. J.*, 1999, **5**, 3495; (d) L. Derf, E. Levillain, G. Trippé, A. Gorgues, M. Sallé, R. Sebastain, A. Caminade and J. Majoral, *Angew. Chem., Int. Ed.*, 2001, **40**, 224.
- (a) P. J. Dandliker, F. Diederich, J. P. Gisselbrecht, A. Louati and M. Gross, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 2725; (b) P. J. Dandliker, F. Diederich, A. Zingg, J. P. Gisselbrecht, M. Gross, A. Louati and E. Sanford, *Helv. Chim. Acta*, 1997, **80**, 1773; (c) P. Weyermann, J. P. Gisselbrecht, C. Boudon, F. Diederich and M. Gross, *Angew. Chem., Int. Ed.*, 1999, **38**, 3215.
- (a) H. F. Chow, I. Y. K. Chan, D. T. W. Chan and R. W. M. Kwok, *Chem. Eur. J.*, 1996, **9**, 1085; (b) M. Haga, M. M. Ali and R. Arakawa, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 76; (c) F. Vögtle, M. Plevoets, M. Nieger, G. C. Azzellini, A. Credi, L. D. Cola, V. D. Marchis, M. Venturi and V. Balzani, *J. Am. Chem. Soc.*, 1999, **121**, 6290; (d) G. R. Newkome, H. Enfei and L. A. Godínez, *Macromolecules*, 1998, **31**, 4382.
- (a) G. R. Newkome, A. K. Patri and L. A. Godínez, *Chem. Eur. J.*, 1999, **5**, 1445; (b) C. Valério, J. L. Fillaut, J. Ruiz, J. Guittard, J. C. Blais and D. Astruc, *J. Am. Chem. Soc.*, 1997, **119**, 2588.
- (a) C. B. Gorman, B. L. Parkhurst, W. Y. Su and K. Y. Chen, *J. Am. Chem. Soc.*, 1997, **119**, 1141; (b) C. B. Gorman, J. C. Smith, M. W. Hager, B. L. Parkhurst, H. Sierzputowska-Grac and C. A. Haney, *J. Am. Chem. Soc.*, 1999, **121**, 9958.
- D. D. Perrin and W. L. F. Armarego, *Purification of Laboratory Chemicals*, 3rd edn., Pergamon Press, Oxford, 1988.