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Design and Structural Analysis of the First Spherical Monodendron Self-Organizable in a Cubic Lattice

Virgil Percec,*,† Wook-Dong Cho,† Martin Möller,‡
Svetlana A. Prokhorova,‡ Goran Ungar,§ and
Duncan J. P. Yeardley§

Roy & Diana Vagelos Laboratories
Department of Chemistry, University of Pennsylvania
Philadelphia, Pennsylvania 19104-6323
Organische Chemie II, Makromolekulare Chemie
Universität Ulm, D-89069 Ulm, Germany
Department of Engineering Materials and
Center for Molecular Materials
University of Sheffield, Sheffield S1 3JD, U.K.

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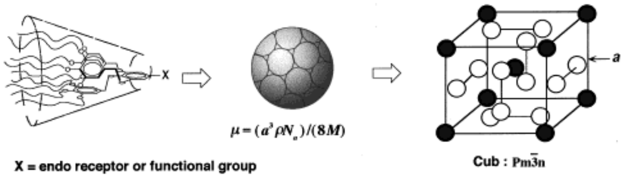
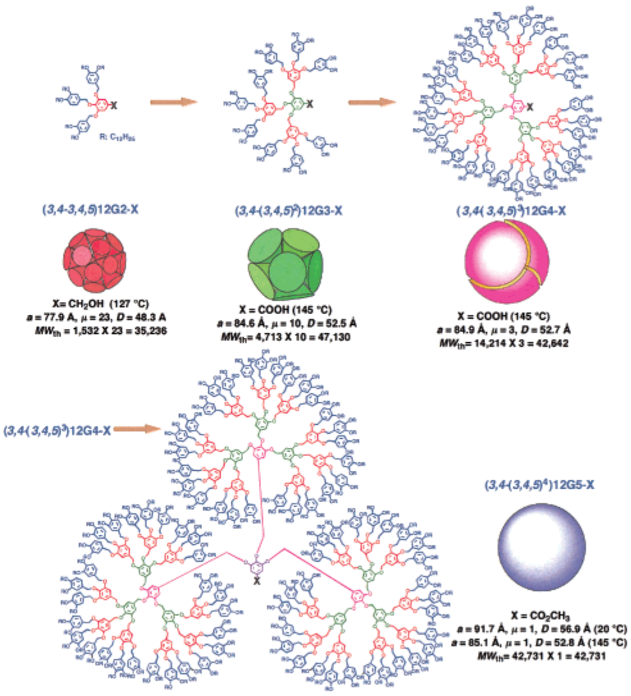
Monodendrons[1] synthesized by a convergent method and dendrimers (prepared by a divergent[1] method or by the covalent[1,2] or supramolecular[3] assembly of monodendrons to a multiple molecular[1] or macromolecular[2] core) are valuable building blocks used in the construction of object-like nanosystems with novel functions and properties.[1,2,4] Recently, we have elaborated a novel approach to the design, shape, and size analysis of self-assembling monodendrons[5−7] and of self-organizable supramolecular and macromolecular dendrimers (Scheme 1).[2,5−7] This strategy involves the quantitative analysis by X-ray diffraction (XRD) of the thermotropic liquid crystalline (LC) 2-D hexagonal columnar $p6mm$[5] and 3-D cubic $Pm\bar{3}n$[6a,b] and $Im\bar{3}m$[6c] lattices self-organized from cylindrical and respectively spherical supramolecular dendrimers. These building blocks are subsequently employed in the construction of more complex functional architectural motives.[2,8]

This contribution reports the design, synthesis, and the structural analysis by XRD of the first spherical functional monodendron that self-organizes in a cubic $Pm\bar{3}n$ lattice. The direct visualization by scanning force microscopy (SFM) of the spherical monodendron both as a single molecule and in disordered monolayers is also reported. Previous examples of spherical dendritic objects self-organizable in a cubic lattice were obtained only by the self-assembly of conical and hemispherical monodendrons.[6,7] Dendrimers obtained by a divergent synthesis, that have a spherical shape in solution but lack the shape perfection required for self-organization in a lattice, were also reported.[9] Their spherical shape was estimated, in solution, by SAXS and TEM[9a,b] and on a surface by AFM or SFM.[9c−f]

Scheme 1. Self-assembly of Conical Monodendrons into Supramolecular Spherical Dendrimers and the Subsequent Self-Organization of the Supramolecular Dendrimers in a $Pm\bar{3}n$ Cubic Lattice



Scheme 2. Synthesis of **(3,4-(3,4,5)$^{n-1}$)12Gn-X** (n = 1 to 5) Monodendrons and Determination of Shape and Size by XRD Analysis of the $Pm\bar{3}n$ Cubic Lattice



Reagents and Conditions : i) **X = CH_2OH**: X = CO_2CH_3, $LiAlH_4$, THF, 20 °C; ii) **X = CH_2Cl**: X = CH_2OH, $SOCl_2$, DTBMP, CH_2Cl_2, 20 °C; iii) **X = CO_2CH_3**: X = CH_2Cl, methyl 3,4,5-trihydroxy benzoate, K_2CO_3, DMF, THF, 70 °C; iv) **X = COOH**: X = CO_2CH_3, KOH, THF, EtOH, reflux.

Scheme 2 and Table 1 summarize the synthesis and the results of the structural analysis by a combination of differential scanning calorimetry (DSC), thermal optical polarized microscopy (TOPM), XRD, and SFM of the first five generations of **(3,4-(3,4,5)$^{n-1}$)-12Gn-X** (where n is the generation number, n = 1 to 5) monodendrons. The difference between the GPC and theoretical molecular weights of these monodendrons is in agreement with previously reported data, demonstrating the decrease in hydrodynamic volume with the increase of Gn.[6a] The $Pm\bar{3}n$ cubic lattice dimension (a, in Å), the diameter of the supramolecular or molecular dendritic sphere (D, in Å), the number of monodendrons (μ) that self-assemble into a sphere, the temperature at which the XRD analysis was performed, the functional group X, and the theoretical molar mass of the monodendron are also shown in

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† University of Pennsylvania.

‡ Universität Ulm.

§ University of Sheffield.

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Table 1. Theoretical and Experimental Molecular Weights Determined by GPC, Experimental Densities,[a] and Thermal Transitions of Selected Examples of $(3,4\text{-}(3,4,5)^{n-1})$12Gn-X (X = CH_2OH, COOH, and CO_2CH_3) Monodendrons

monodendron	MW_t	M_n (GPC)	$M_{w/}M_n$ (GPC)	ρ_{20}[a] (g/cm3)	thermal transitions (°C) and corresponding enthalpy changes (kcal/mol)[b] heating	cooling
(*3,4*)12G1-CH_2OH	477	830	1.02	1.00	k[c]12 (4.23) k 53 (16.06) i	i 27 (10.91) k
second heating					k 37 (0.53) −k 39 (2.32) k 52 (14.26) i	
(*3,4-3,4,5*)12G2-CH_2OH	1532	2069	1.04	1.00	k 0 (2.42) k 60 (39.14) Cub[d]133 (4.45) i	i 128 (4.31) Cub 15 (20.49) k
second heating					k 42 (18.32) Cub 133 (4.30) i	
(*3,4-(3,4,5*)^2)12G3-COOH	4713	5067	1.07	0.99	k −7 (42.87) −k 12 (6.84) k 131 (15.74) Cub 190 (0.71) i[e]	
(*3,4-(3,4,5*)^3)12G4-COOH	14214	10112	1.06	0.99	k −10 (25.72) k 101 (56.90) Cub 200 (4.68) i[e]	
(*3,4-(3,4,5*)^4)12G5-CO_2CH_3	42731	13450	1.06	0.98	k −15 (56.51) k 48 (20.91) Cub 194 (7.34) i	i 175 (7.34) Cub −15 (169.41) k
second heating					k −9 (231.64) Cub 191 (5.51) i	

[a] Densities were measured at 20 °C. [b] Data from the first DSC heating and cooling scans are on the first line, and data from the DSC second heating are on the second line. [c] k = crystalline. [d] Cub = Cubic $Pm\bar{3}n$. [e] Decomposition after first heating.

Scheme 2. Both their synthesis and structural analysis were carried out as reported previously for the first four generations of **$(3,4,5\text{-}(3,4,5)^{n-1})$12Gn-X**[6a] and the first three generations of **$(4\text{-}(3,4,5)^{n})$-12Gn-X**[6b] monodendrons. **$(3,4\text{-}(3,4,5)^{n-1})$12Gn-X** represents the third series from a library of self-assembling monodendrons based on 3,4,5-trisubstituted AB_3 benzyl ether repeat units.[6] They are functionalized on the periphery with 3,4-bis(*n*-dodecan-1-yloxy)-benzyl ether groups. **$(3,4,5\text{-}(3,4,5)^{n-1})$12Gn-X** series is functionalyzed on the periphery with 3,4,5-tris(*n*-dodecan-1-yloxy)-benzyl ether,[6a] while the series **$(4\text{-}(3,4,5)^{n})$12Gn-X** contains 3,4,5-tris[*p*-(*n*-dodecan-1-yloxy)benzyloxy]benzyl ether groups on the periphery.[6b]

The rational for the selection of the series of experiments described in Scheme 2 is as follows. The analysis of **$(3,4,5\text{-}(3,4,5)^{n-1})$12Gn-X**[6a] and **$(4\text{-}(3,4,5)^{n})$12Gn-X**[6b] demonstrated that for the same internal repeat unit the shape and size of the monodendron is determined by the structure of the first generation monodendron attached on the periphery. The fourth generation monodendron **$(3,4,5\text{-}(3,4,5)^{3})$12G4-COOH** has a hemispherical shape and a theoretical molar mass of 19 191.[6a] Attempts to synthesize its fifth generation did not succeed due to the low molar concentration of its X group and the steric hindrance induced by its shape. The third generation of **$(4\text{-}(3,4,5)^{3})$12G3-CO_2CH_3** has a shape that is equivalent with a sixth of a sphere and a theoretical molar mass of 9252.[6b] Therefore, two additional generations would have been required to accomplish a spherical monodendron. This would have produced an even larger molar mass and similar steric constrains as **$(3,4,5\text{-}(3,4,5)^{3})$12G4-X**. Therefore, we have advanced the hypothesis that the experiments summarized in Scheme 2 could alleviate some of these problems since this series of monodendrons would be expected to have shapes, sizes, and molar masses between those of the two series reported previously.[6]

The results presented in Scheme 2 can be summarized as follows. **(3,4)12G1-X** (not shown in Scheme 2) is only crystalline.[8a] Twenty three **(3,4-3,4,5)12G2-CH_2OH** monodendrons and respectively 10 **$(3,4\text{-}(3,4,5)^{2})$12G3-COOH** monodendrons self-assemble into a sphere. Therefore, we hypothesize that each has a conical shape. Only three **$(3,4\text{-}(3,4,5)^{3})$12G4-COOH** monodendrons of molar mass 14214 are required to self-assemble into a sphere. Finally, a single **$(3,4\text{-}(3,4,5)^{4})$12G5-CO_2CH_3** monodendron forms a sphere. This functional single monodendron−single sphere has a single X functionality isolated in its core (Scheme 2). The most significant difference between a spherical monodendron and a spherical dendrimer is that the last one does not have a single functional group in its core.

According to the results outlined in Scheme 2, a single **$(3,4\text{-}(3,4,5)^{4})$12G5-CO_2CH_3** monodedron of theoretical molar mass 42 731, most probably the largest synthesized so far, exhibits a spherical shape when the molecule is self-organized in a cubic $Pm\bar{3}n$ lattice. The most intriguing question is what is the shape of this molecule in a disordered assembly or as a single molecule? Does it display the same shape as in its $Pm\bar{3}n$ lattice? Single molecules and disordered molecules within islands of several hundred were visualized by SFM on mica (Figure 1). Within islands, the average diameter of the molecule is 60 Å, and the average height is 50 Å (Figure 1a). These results are in excellent agreement with the diameter determined by XRD in a lattice (57 Å). If we consider that the resolution of the SFM is ±5 Å, these data may suggest that on a surface, a monolayer of densely packed monodendrons could adopt only a slightly oblate spherical shape (Figure 1a). The average diameter of the single monodendron is 100 Å, and its height is 25 Å (Figure 1b). The distortion of the shape of the single monodendron on a surface is in agreement with previous reports.[9c−e] However, in these reports the dendrimers did not assemble into a lattice. Therefore, these authors could not offer information on the shape of the dendrimers within such a lattice. This distortion is most probably due to the interaction of the single monodendron with the surface and/or its soft structure.[9c−e] The most dramatic shape change reported so far is from spherical in solution to "windscreen wiper" in a lattice.[9g] Experiments to quantitatively elucidate the similarities and differences between monodendrons in a lattice, in the disordered bulk state, in solution, and as single molecules together with the elaboration of novel single molecule-based functional nanosystems[1,4,10] are in progress.

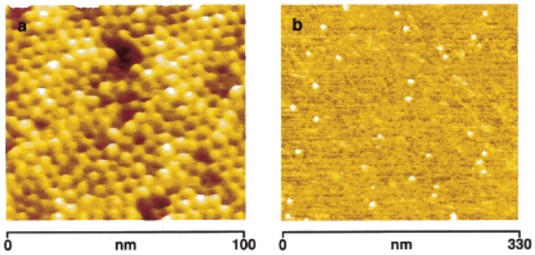

Figure 1. Visualization of spherical **$(3,4\text{-}(3,4,5)^{4})$12G5-CO_2CH_3** monodendrons by SFM on mica. Samples were prepared by dipping mica in a dodecane solution of the monodendron with c = 0.01 mg/mL. The height of monodendrons in disorded monolayer (a) is 50 Å and diameter is 60 Å. The height and diameter of single monodendrons are 25 and 100 Å, respectively (b).

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Supporting Information Available: Reaction schemes, experimental procedures, analytical data, tables with characterization results, and references (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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