

ACCOUNTS of CHEMICAL RESEARCH[®]

JUNE 2004

Registered in U.S. Patent and Trademark Office; Copyright 2004 by the American Chemical Society

Nanomaterials Based on Phosphorus Dendrimers

ANNE-MARIE CAMINADE* AND
JEAN-PIERRE MAJORAL*

Laboratoire de Chimie de Coordination CNRS,
205 route de Narbonne, 31077 Toulouse cedex 4, France

Received January 24, 2003

ABSTRACT

Dendrimers constitute an increasingly important field of research in chemistry for more than 15 years. After pioneering works concerning synthesis, the interest in dendrimers is now mainly driven by their properties and applications. This Account will emphasize the properties of a special class of dendrimers, that is, phosphorus-containing dendritic macromolecules, as tools for the elaboration of nanomaterials. Indeed, these dendrimers can be considered themselves as materials, or they can be used as an intrinsic constituent of a material or as a modifier of the surface of a material. In this latter case, a fundamental work about surfaces covalently modified by dendrimers recently opened the way to the elaboration of DNA chips.

1. Introduction

The development of nanomaterials, that is, materials based on nanometer-size particles, is one of the major challenges for this new century. For a while, the search for miniaturization was done primarily by an approach of the type top-down, that is, by dividing macroscopic devices. However, it is now recognized that the bottom-up approach from the molecular level should be the next development for future technologies. In this perspective,

Anne-Marie Caminade was born in 1958 in Carmaux (France). She received two Ph.D.s in Toulouse (1984 and 1988). She worked as a Postdoctoral fellow at the Institut Français du Pétrole (1984) and in Prof. M. Veith's group (1988–1989, Saarbrücken, Germany). She has been working since 1985 at the CNRS with Jean-Pierre Majoral, where she has been "Directeur de Recherche" since 1997. Her research interest is in main group elements. She developed several aspects of the chemistry of phosphorus, including low-coordinated compounds, coordination of transition metals, reactivity of metallic hydrides, and synthesis of macrocycles. Her current research interest is on the synthesis, reactivity, and study of properties of dendrimers. She is the coauthor of 200 publications and patents.

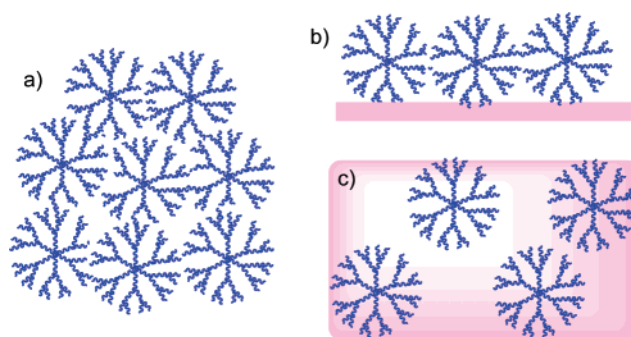


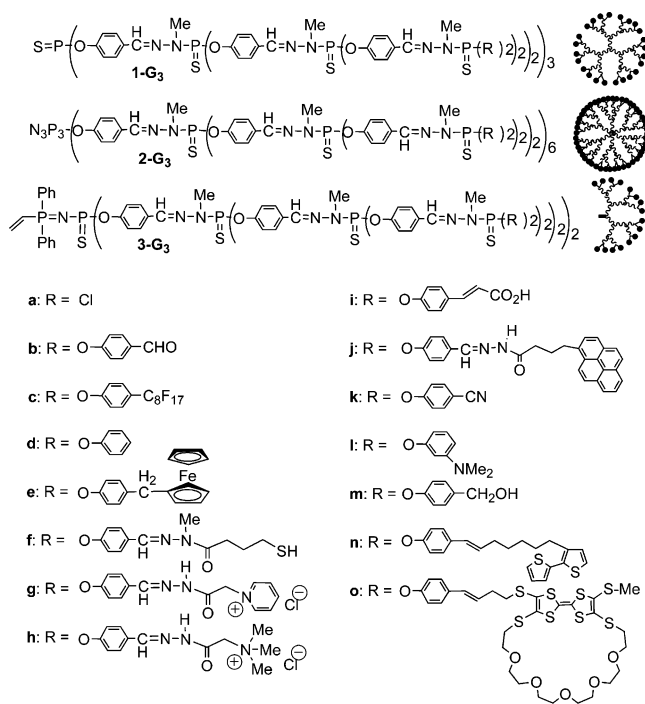
FIGURE 1. Type of uses of dendrimers in materials sciences: (a) in the bulk; (b) on the surface of a material; (c) inside a material.

nanosized molecules are attracting a considerable attention, and a particular emphasis is put on a special class of polymers named dendrimers. Indeed, dendritic macromolecules made of well-defined branching units emanating from a central core undoubtedly constitute a major field of research with more than 6000 reports published within the last 15 years. After pioneering works concerning syntheses, interest in dendrimers is now mainly driven by applications in various fields of chemistry, biology, and physics but also materials science and nanotechnologies.^{1,2} Indeed, dendrimers can be considered themselves as materials when they are in the solid state, or they can be used for creating new materials or for modifying the surface of existing materials (Figure 1). Beside purely

* Fax: (+33) 5 61 55 30 03. E-mail addresses: majoral@lcc-toulouse.fr; caminade@lcc-toulouse.fr.

Jean-Pierre Majoral received his Ph.D. from the Université Paul Sabatier of Toulouse in 1972. In 1972–1973, he worked as a Postdoctoral fellow with Prof. A. Katritzky (University of East Anglia, Norwich, U.K.). He became Directeur de Recherche at the Centre National de la Recherche Scientifique in Toulouse in 1978, where he is presently Directeur de Recherche Classe Exceptionnelle. His research interest is mainly focused on the use of main group elements, especially phosphorus, in different areas of chemistry. Presently, he and his research team are involved in the preparation, properties, and applications of macromolecules such as dendrimers and hyperbranched polymers. Emphasis is also laid on the studies of interactions between heavier main group elements and group 4 elements (titanium, zirconium, hafnium) with applications in organic and organometallic chemistry. He is a member of the Polish Academy of Sciences and of the Academia Europaea and has published more than 360 publications and patents.

Chart 1. Examples of Cores and Examples of End Groups of Phosphorus-Containing Dendrimers



organic dendrimers, phosphorus-containing dendrimers, that is, dendrimers possessing phosphorus atoms at each branching point occupy a special place^{3–5} first because of their simple^{6–8} and sometimes straightforward^{9–12} syntheses and also because of the rich diversity of their chemistry, in most cases due to the presence of highly reactive end groups, either aldehydes or P(S)Cl₂ groups. Their reactivity afforded several hundreds of dendritic macromolecules.^{13–16} This Account will emphasize their applications in the field of materials science. Despite the fact that several groups are synthesizing phosphorus-containing dendrimers,^{17–21} none of them except us are working in materials science; thus, this paper will emphasize our contribution, but comparisons will be done with purely organic dendrimers. Chart 1 displays the chemical structure of the dendrimers of which the properties or applications in this field will be described.

II. Phosphorus Dendrimers in the Solid State

A very important characteristic of any substance for applicative purposes concerns its thermal stability specially when considering uses in materials science. A large study was carried out for several dendrimers and dendrons shown in Chart 1, having various types of end groups, various cores, and different generations. Studying **1b-G₁-G₅** shows that the generation has practically no influence on the thermal stability. On the other hand, the type of end groups has a dramatic influence. Figure 2 displays the thermogravimetric analyses (TGA) of various dendrimers obtained from **1-G₅** after modifications of the end groups.²² The thermal stability varies from 225 °C for the least stable (**1g-G₅**) to 376 °C for the most stable (**1e-G₅**), showing a strong dependence on the type of end

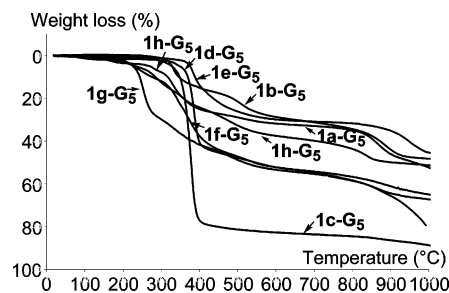


FIGURE 2. Thermal stability (TGA analyses under helium) for dendrimers **1a–1h-G₅** (see Chart 1).

groups. This last result indicates that the internal skeleton of these dendrimers is stable up to at least this temperature and may be over. In several cases, the amount of material remaining at very high temperature is substantial, more than 50% at 1000 °C. This fact could be related to the known fire-proof properties of polyphosphazene derivatives.²³ The presence of a vinyl group at the core of dendron **3b-G₂** induces a spectacular difference in the percentage of mass remaining at high temperature (70% at 1000 °C for **3b-G₂** versus 47% for **1b-G₂**). This particular behavior is presumably due to the polymerization of the vinyl group located at the core. In general, these phosphorus dendrimers are more stable than polyamidoamine (PAMAM) dendrimers²⁴ and less stable than polyphenylene dendrimers,²⁵ but they offer an excellent compromise between thermal stability and ease of functionalization.

Another property in the solid state concerns the evolution of molecular mobility with increasing generations. It was analyzed for **1b-G₀-G₂** using dielectric techniques (thermostimulated currents and dynamic dielectric spectroscopy). The narrow relaxation mode observed for **1b-G₀** indicates that there is a single mobile dipolar species (the aldehydes), whereas a submode of relaxation is observed for **1b-G₂**, which might be ascribed to a structural relaxation.^{26,27} Temperature-modulated calorimetry and standard differential scanning calorimetric techniques applied to dendrimers **1b-G₁-G₅** show the metastability of their physical structure. These techniques indicate that for low generation (1–3) the molecular mobility gives rise to a physical aging that decreases upon increasing generation and that the higher generations have a higher rigidity.²⁸

Dendrimers of series **1a** and **1b** were also analyzed by IR and Raman spectroscopies.²⁹ A good correlation of the theoretical spectra with the experimental spectra was obtained, which allowed an estimation of their heat capacities. The value approximately doubles each time when going to the next generation and varies from 0.31 kJ/(mol·°C) for **1b-G₀** to 1547.85 kJ/(mol·°C) for **1b-G₁₁**.³⁰ The same series of dendrimers was also characterized in the bulk by X-ray photoelectron spectroscopy, and the atomic composition was found to be in good agreement with the theoretical one.³¹

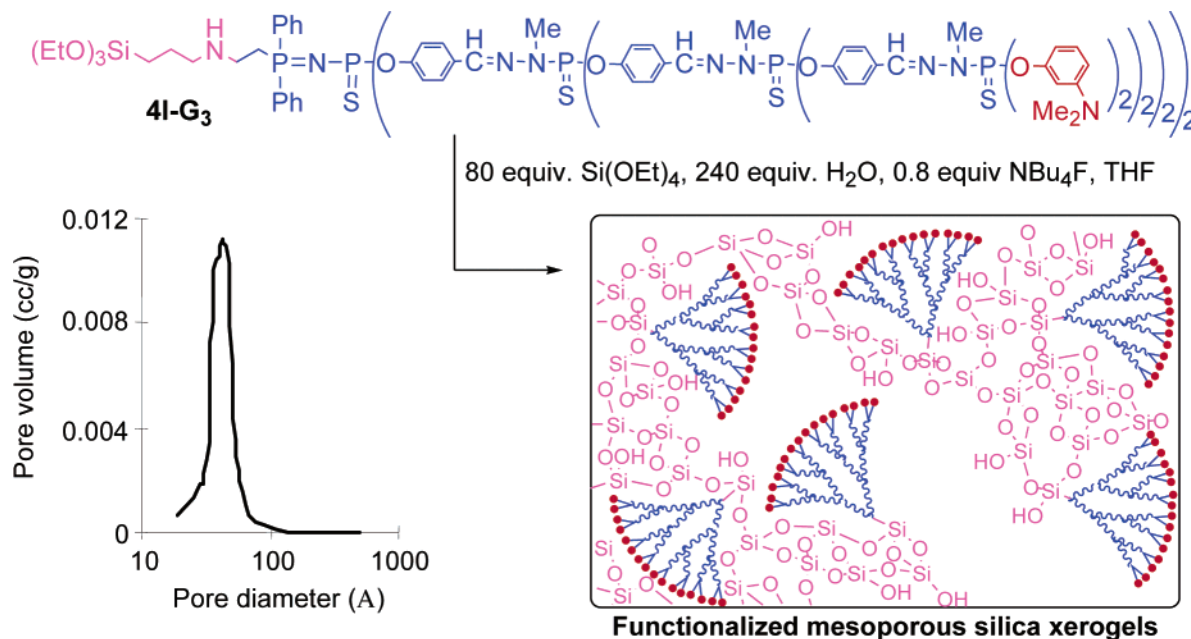


FIGURE 3. One of the dendrons used for obtaining functionalized silica xerogels and the corresponding BJH pore size distribution.

III. Phosphorus Dendrimers as Building Blocks of Materials

Dendrimers can play a key role in the chemical construction of organized matter. Our first attempts in this field concern the cohydrolysis and polycondensation of dendrons bearing a hydrolyzable Si(OEt)₃ group at the core with an adequate number of equivalents of Si(OEt)₄ and water. Various sizes of dendrons (generations 1, 2, and 3) possessing various types of end groups (**b**, **j**, **k**, and **l**, Chart 1) were reacted with various amounts of Si(OEt)₄. A large variety of dendron-silica xerogels were obtained, and some of them were found to be mesoporous with a narrow pore size distribution. Figure 3 shows the Barrett, Joyner, and Halenda (BJH) pore size distribution (mean value 45 Å) for the xerogel obtained from dendron **4I-G₃**.³²

An analogous sol-gel process can be applied to dendrimers possessing triethoxysilyl end groups and Si(OEt)₄ to afford hybrid organic-inorganic solids. Such a process was already applied, in particular, to dendrimers having silicon at each branching point, but the highly flexible skeleton of these dendrimers induces a poor homogeneity of the size of pores.^{33,34} The use of phosphorus-containing dendrimers also affords hybrid solids, which give, after heating at 550 °C for several hours, a highly porous material with a good reproducibility, which could be related to the expected semirigidity of these dendrimers; these materials might be used as absorbents or insulating materials.³⁵

In contrast to silicate materials, the elaboration of organic-inorganic hybrid materials built from nonsilicate precursors is often difficult to control, but strategies based on the assembly of nano building blocks (ANBB) with well-defined structures are useful. This concept was applied to the reaction of the small dendrimers **1i-G₁** and **1m-G₁** with the cluster [Ti₁₆O₁₆(OEt)₃₂], which gives a hybrid gel made of dendrimers and clusters of which the indi-

vidual internal structure is conserved. The organic-inorganic interfaces are obtained by transalcoholysis between some ethoxy groups of the cluster and some alcoholic groups of dendrimer **1m-G₁** or by nucleophilic substitutions coupled with a proton transfer from the acid end groups of **1i-G₁** giving bridging carboxylates (Figure 4). These solid gels are mesostructured hybrid materials in which clusters are regularly spaced by the dendrimers.³⁶

If larger dendrimers are used, such as the fifth generation **1i-G₅** or the seventh generation **1i-G₇** with titanium or cerium alkoxides, the complexation of the metal centers by the acidic functions of the dendrimers occurs first through bridging carboxylates; then these sites act as anchoring points for the development of the inorganic network all around the dendrimer, which acts as a template, affording a hybrid material. After thermal decomposition, the pore packing observed by TEM is spongelike with mesopores of 9–30 Å; macroporosities are also detected.³⁷ Control of porosity in all these hybrid organic-inorganic materials should lead to several applications in various fields such as catalysis, separation techniques, or coatings.

The formation of another type of network is responsible for an astonishing and up to now unique property of dendrimers having Girard-P or Girard-T reagents as end groups such as **1g-G_n**, **2g-G_n**, **1j-G_n**, and **2j-G_n**; they form hydrogels when dissolved in water at relatively low concentrations (0.25%–1.8% in weight) and left several days at room temperature or heated several hours at 60–65 °C.³⁸ A single molecule of the fourth generation of the dendrimer is able to gel about 500 000 molecules of water! These hydrogels are rigid, they do not flow, and they can even be crushed into pieces. Freeze-fracture electron microscopy of the gels shows fragments of chains made of dendrimers, imprisoning large pockets of water. The dendrimer network is likely due to supramolecular inter-

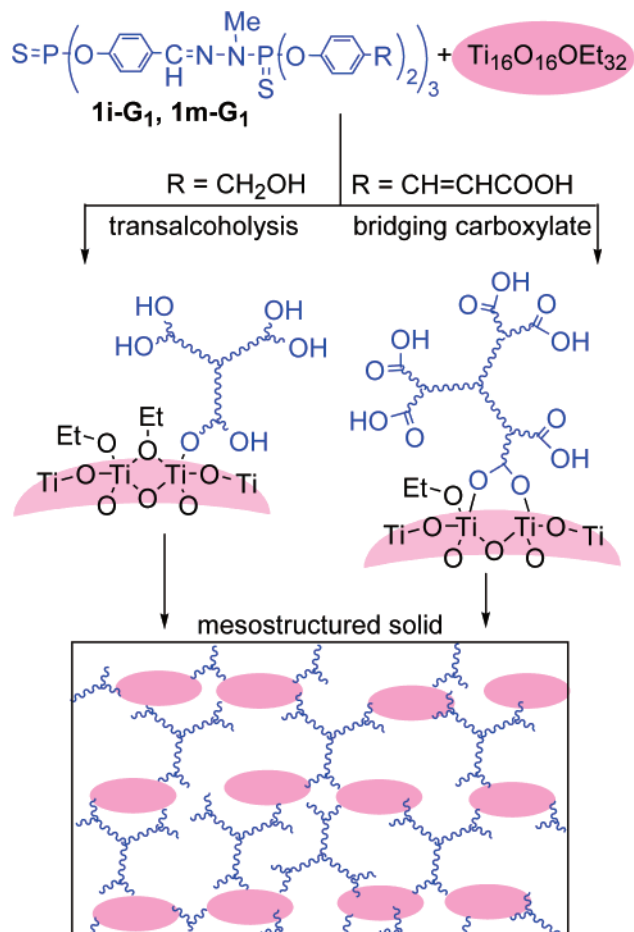


FIGURE 4. Mesostructured solids obtained by assembly of dendrimer **1i-G₁** or **1m-G₁** with the cluster $\text{Ti}_{16}\text{O}_{16}(\text{OEt})_{32}$.

actions between the end groups of the dendrimers: hydrogen bonds, π -stacking, and hydrophilic/hydrophobic interactions can occur, since these phosphorus dendrimers have a hydrophobic interior and a hydrophilic surface (Figure 5). These gels are able to encapsulate a large amount of various substances (up to 30% in weight for nickel acetate) during their formation; these gels could be used for the controlled delivery of active substances.³⁹

IV. Phosphorus Dendrimers on the Surface of Materials

Depending on the type of end groups, we have shown that phosphorus-containing dendrimers may create various types of networks by supramolecular assemblies. The thiol-terminated dendrimers **1f-G_n** and **2f-G_n** may serve as matrix for generating crystals of naked Au_{55} clusters starting from $\text{Au}_{55}(\text{PPh}_3)_{12}\text{Cl}_6$. A thin layer of dendrimers induces the formation and the growing of the crystals of clusters and protects them against decomposition (Figure 6).⁴⁰ It must be emphasized that numerous previous attempts to generate such crystals failed. These crystals of gold clusters might be promising candidates for future nanoelectronic devices working with quantum dots.

The surface of electrodes can be also modified by dendrimers possessing electroactive end groups. We have

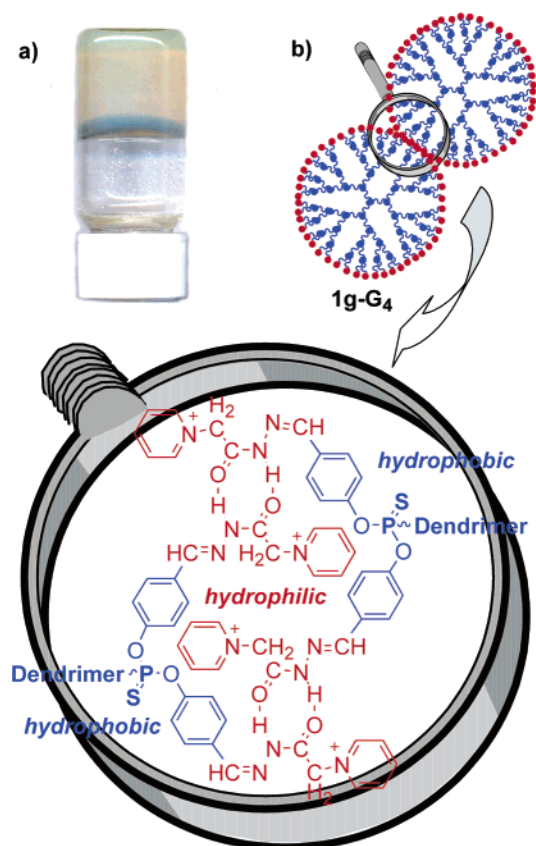


FIGURE 5. Hydrogel (a) in a reversed flask obtained with 1% in weight of **1g-G₄** in water and (b) possible supramolecular associations of dendrimers **1g-G₄** creating the network, which imprisons water.

used various ferrocenes^{41–43} such as **1e-G_n**, bithiophene (**1n-G₀-G₄**),⁴⁴ or TTF (**1o-G₃**)⁴⁵ derivatives and studied their electrochemical behavior by cyclic voltammetry. A deposition of a conducting film of dendrimers onto the electrode is often observed during the oxidation step, whatever the type of dendrimer used.^{46–49} This deposit is generally reversible during the reduction step, and the dendrimers are recovered intact in solution. Nevertheless, repeated cycling allows growth of the film on the electrode, thus modifying it. The electrode reversibly modified by electrodeposition of the TTF-crown-ether dendrimer **1o-G₃** can be used as electrochemical sensor for barium; the crown-ether part of the film made of dendrimers is able to control the reversible complexation/expulsion sequence of Ba^{2+} .⁴⁵ On the other hand, the oxidation is irreversible with the bithiophene derivatives (**1n-G_n**) due to an electropolymerization process of these groups with an increasing efficiency when the dendrimer is larger.⁴⁴ These electrodes modified by the polymerized dendrimers are highly electroactive in aqueous media, whereas electrodes modified by poly(bithiophene) are almost inactive in these conditions. Such behavior should open interesting perspectives in the field of electrochemically controlled release or electroanalysis.

Dendrimers may also be used to modify the surface of existing materials. These modifications can be irreversible (covalent anchorage) or reversible (ionic anchorage). The surface of quartz plates previously modified by amino-

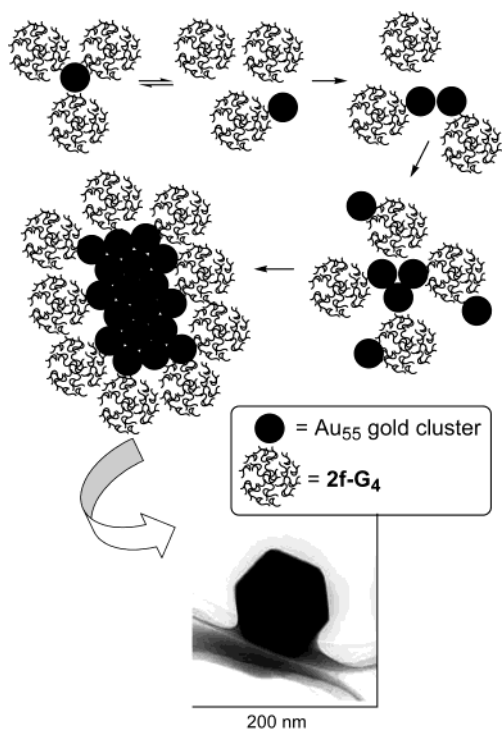


FIGURE 6. Method of synthesis of crystals of naked Au_{55} gold clusters using dendrimers $2f\text{-G}_4$ and shape of the crystals obtained.

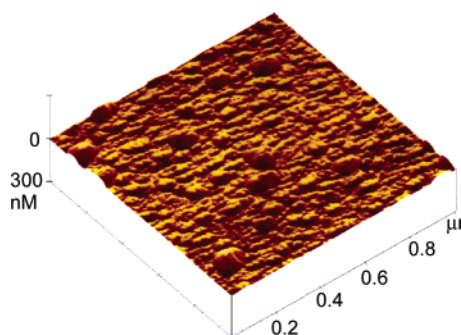


FIGURE 7. Atomic force microscopy (AFM) view of a quartz surface covered by dendrimers $1b\text{-G}_5$, and used for the immobilization of human serum albumin (see clusters).

silane reacts with aldehyde-terminated dendrimers such as $1b\text{-G}_5$. Several aldehyde groups of each dendrimer are involved in the covalent grafting to the quartz surface; thus dendrimers are strongly bound.⁵⁰ A significant lowering of the wettability of the modified plates is observed compared to the untreated plates, showing the hydrophobic character of these dendrimers.⁵¹ Furthermore, many aldehyde functions remain available for further reactions, as shown by the covalent grafting of a second layer of dendrimers having NH_2 end groups. Interestingly, the plate modified by aldehydic dendrimers can be used for the immobilization of proteins, as shown by the attachment of human serum albumin (Figure 7).⁵⁰ A four-generation dendrimer with 96 thiol functions at its periphery was used to generate densely packed monolayers on various substrates such as silicon, by using a special experiment set up.⁵² Several monolayers of dendrimers, eventually with other components, can be su-

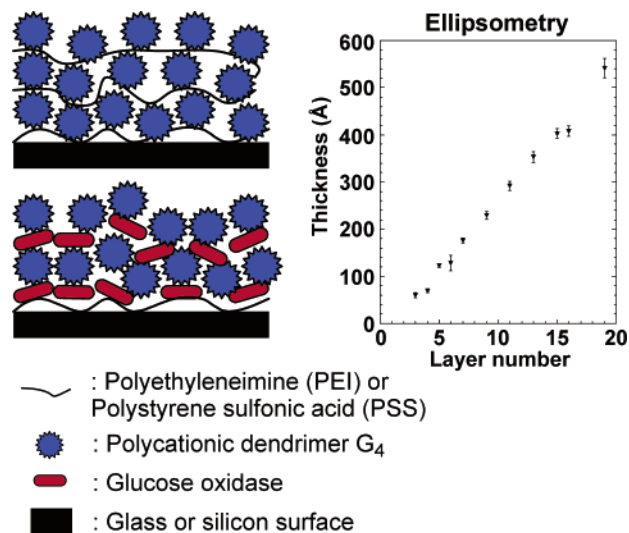


FIGURE 8. Multilayers composed of monolayers of polycationic dendrimers and polystyrene sulfonic acid or glucose oxidase and thickness measured by ellipsometry.

perimposed step by step on a surface, either covalently as shown above or even by ionic interactions when dendrimers having charges on the surface are used.⁵³ Indeed, hybrid layered assemblies with a control of the internal supramolecular structure at the nanometer level can be built. Surface plasmon field-enhanced fluorescence spectroscopy is used to monitor the luminescent properties of dendrimers with a phthalocyanine core integrated into such a multilayer assembly.⁵⁴ Moreover, the build-up of multilayers composed of polycationic phosphorus dendrimers and polystyrenesulfonic acid (PSS) in an alternate way was realized, as well as that of multilayers formed alternately of polycationic dendrimers and glucose oxidase (Figure 8).⁵³

We recently applied these results to the elaboration of biochips for the immobilization of biomolecules such as oligonucleotides (Figure 9). Dendrimers are first covalently grafted to the surface of the material in the way described above; then modified oligonucleotides (NH_2 attached to the 5'-terminus) are grafted to the dendrimer, using the remaining functional groups, to afford the Dendri-chip. If another oligonucleotide having complementary bases and a fluorophore at one end is added, the hybridization is detected by fluorescence. Applying a classical deshybridization process affords again the Dendri-chip. These biochips have two main advantages: first, these chips are particularly stable with time and temperature, in contrast to what was previously reported for DNA chips manufactured with PAMAM dendrimers;^{55,56} thus, they can be reused several times (more than 10 times) without any modification of the signal/noise ratio.⁵⁷ In addition, the signal/noise ratio is very high and allows a very good detection for amounts of complementary oligonucleotides lower than 1 pmol. This sensitivity is 10- to 100-fold higher than with all the other functionalized glass slides we tested (11 examples).⁵⁸ Figure 10 illustrates the comparison between the slides obtained with phosphorus dendrimers having aldehyde end groups, and a commercially available

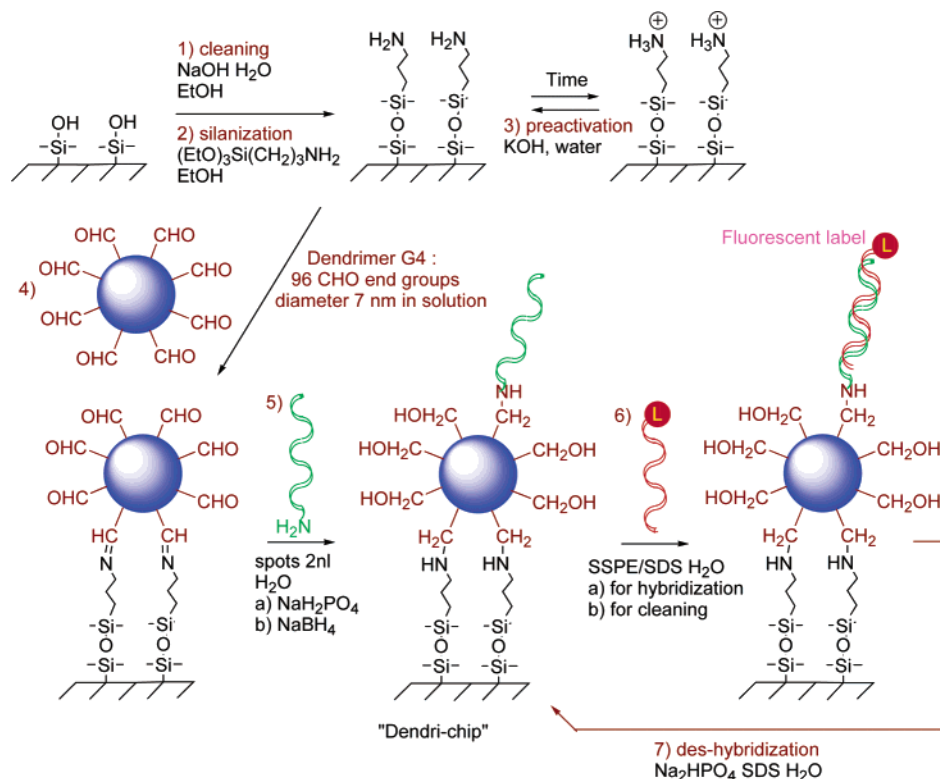


FIGURE 9. Principle of synthesis of biochips using dendrimers and oligonucleotides and the hybridization/deshybridization process.

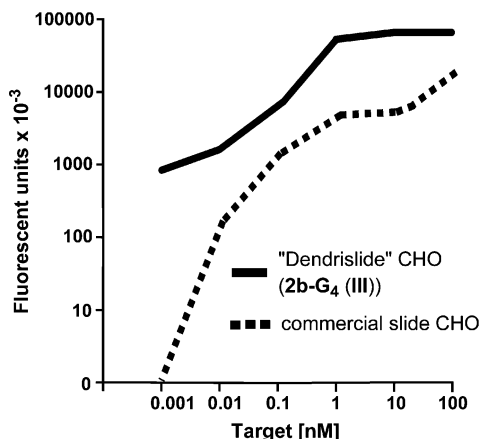


FIGURE 10. Detection sensitivity of a slide having dendrimer **2b-G₄** as linker (dendrislide) compared with a commercially available slide having small aldehyde-functionalized linkers. A single-stranded 35-mer oligonucleotide (10 μ M) was spotted on the functionalized slides, then the target Cy-5-labeled 15-mer oligonucleotide was hybridized at concentrations from 0.001 to 100 nM.

aldehyde slide, of which the results are representative of all 11 glass slides tested.

Conclusion

The extraordinarily versatile behavior of phosphorus gave rise to several hundreds of dendritic macromolecules, and many of them possess interesting properties and applications. Most of them are thermally stable over 300 °C, and some of them exhibit original supramolecular properties, giving thin layers on materials or hydrogels. Applications are already demonstrated in the field of modified surfaces giving sensitive and reliable biochips. Other applications

can be anticipated for the delivery of active substances, as insulating materials, or in the fields of nanoelectronics and (electro)chemical (bio)sensors. In all these cases, the nanometric size of the dendrimers plays a key role, which should be important for future nanotechnologies. Furthermore, the phosphorus dendrimers that we described here bring specific properties in terms of thermal stability, semirigidity of the structure, and ease of functionalization, not only of the end groups but also in all parts of the structure. In addition to the uses related to materials sciences, which were emphasized in this Account, phosphorus-containing dendrimers possess also properties potentially important in catalysis,^{59–61} biology, and life science, in particular as transfecting agents^{62,63} and anti-proliferation species.⁶⁴

In conclusion, this Account demonstrates that phosphorus-containing dendrimers are not simple curiosities in the field of dendrimers but that they are useful tools for many applications from materials science to biology.

We are greatly indebted to all our co-workers, postdoctoral fellows, graduate students, and also collaborative scientists who have contributed to the research on phosphorus-containing dendrimers for their enthusiasm, devoted efforts, ideas, and friendship. Their names can be found in the numerous papers cited herein. We also thank the Centre National de la Recherche Scientifique (France) for financial support.

References

- (1) Fréchet, J. M. J.; Tomalia, D. A. *Dendrimers and other dendritic polymers*; John Wiley and Sons: Chichester, U.K., 2001.
- (2) Newkome, G. R.; Vögtle, F.; Moorefield, C. N. *Dendrimers and dendrons*; John Wiley and Sons: Weinheim, Germany, 2001.
- (3) Majoral, J.-P.; Caminade, A.-M. Dendrimers containing heteroatoms (Si, P, B, Ge, or Bi). *Chem. Rev.* **1999**, *99*, 845–880.

- (4) Majoral, J.-P.; Caminade, A.-M. Divergent approaches to phosphorus-containing dendrimers and their functionalization. *Top. Curr. Chem.* **1998**, *197*, 79–124.
- (5) Majoral, J.-P.; Caminade, A.-M.; Maraval, V. The specific contribution of phosphorus in dendrimer chemistry. *Chem. Commun.* **2002**, 2929–2942.
- (6) Launay, N.; Caminade, A.-M.; Lahana, R.; Majoral, J.-P. General synthetic strategy for neutral phosphorus-containing dendrimers. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1589–1592.
- (7) Galliot, C.; Prevote, D.; Caminade, A.-M.; Majoral, J.-P. Polyaminophosphine containing dendrimers. Syntheses and characterization. *J. Am. Chem. Soc.* **1995**, *117*, 5470–5476.
- (8) Launay, N.; Caminade, A.-M.; Majoral, J.-P. Synthesis and reactivity of unusual phosphorus dendrimers. A useful divergent growth approach up to the seventh generation. *J. Am. Chem. Soc.* **1995**, *117*, 3282–3283.
- (9) Brauge, L.; Magro, G.; Caminade, A.-M.; Majoral, J.-P. First divergent strategy using two AB₂ unprotected monomers for the rapid synthesis of dendrimers. *J. Am. Chem. Soc.* **2001**, *123*, 6698–6699. Erratum: *J. Am. Chem. Soc.* **2001**, *123*, 8446.
- (10) Maraval, V.; Laurent, R.; Donnadiou, B.; Mauzac, M.; Caminade, A.-M.; Majoral, J.-P. Rapid synthesis of phosphorus-containing dendrimers with controlled molecular architectures: First example of surface-block, layer-block, and segment-block dendrimers issued from the same dendron. *J. Am. Chem. Soc.* **2000**, *122*, 2499–2511.
- (11) Maraval, V.; Caminade, A.-M.; Majoral, J.-P.; Blais, J. C. Dendrimer design. How to circumvent the dilemma of a reduction of steps or an increase of function multiplicity? *Angew. Chem., Int. Ed.* **2003**, *42*, 1822–1826.
- (12) Maraval, V.; Pyzowski, J.; Caminade, A.-M.; Majoral, J.-P. "Lego" chemistry for the rapid synthesis of dendrimers. *J. Org. Chem.* **2003**, *68*, 6043–6046.
- (13) Galliot, C.; Larre, C.; Caminade, A.-M.; Majoral, J.-P. Regioselective stepwise growth of dendrimer units in the internal voids of a main dendrimer. *Science* **1997**, *277*, 1981–1984.
- (14) Larre, C.; Caminade, A.-M.; Majoral, J.-P. Chemoselective polyalkylations of phosphorus-containing dendrimers. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 596–598.
- (15) Larre, C.; Donnadiou, B.; Caminade, A.-M.; Majoral, J.-P. Phosphorus-containing dendrimers: chemoselective functionalization of internal layers. *J. Am. Chem. Soc.* **1998**, *120*, 4029–4030.
- (16) Larre, C.; Bressolles, D.; Turrin, C.; Donnadiou, B.; Caminade, A.-M.; Majoral, J.-P. Chemistry within megamolecules: regiospecific functionalization after construction of phosphorus dendrimers. *J. Am. Chem. Soc.* **1998**, *120*, 13070–13082.
- (17) Rengan, K.; Engel, R. Phosphonium cascade molecules. *J. Chem. Soc., Chem. Commun.* **1990**, 1084–1085.
- (18) Miedaner, A.; Curtis, C. J.; Barkley, R. M.; DuBois, D. L. Electrochemical reduction of CO₂ catalyzed by small organophosphine dendrimers containing palladium. *Inorg. Chem.* **1994**, *33*, 5482–5490.
- (19) Petrucci-Samija, M.; Guillemette, V.; Dasgupta, M.; Kakkar, A. K. A new divergent route to the synthesis of organophosphine and metallodendrimers via simple acid–base hydrolytic chemistry. *J. Am. Chem. Soc.* **1999**, *121*, 1968–1969.
- (20) Schneider, R.; Kollner, C.; Weber, I.; Togni, A. Dendrimers based on cyclophosphazene units and containing chiral ferrocenyl ligands for asymmetric catalysis. *Chem. Commun.* **1999**, 2415–2416.
- (21) Salamonczyk, G. M.; Kuznikowski, M.; Poniatowska, E. Synthesis and oxygenation of selenophosphate dendrimers. *Chem. Commun.* **2001**, 2202–2203.
- (22) Turrin, C.-O.; Maraval, V.; Leclaire, J.; Dantras, E.; Lacabanne, C.; Caminade, A.-M.; Majoral, J.-P. Surface, core, and structure modifications of phosphorus-containing dendrimers. Influence on the thermal stability. *Tetrahedron* **2003**, *59*, 3965–3973.
- (23) Allcock, H. R. *Phosphorus–Nitrogen Compounds*; Academic Press: New York, 1972.
- (24) Balogh, L.; de Leuze-Jallouli, A.; Dvornic, P.; Kunugi, Y.; Blumstein, A.; Tomalia, D. A. Architectural copolymers of PAMAM dendrimers and ionic polyacetylenes. *Macromolecules* **1999**, *32*, 1036–1042.
- (25) Miller, T. M.; Neenan, T. X.; Zayas, R.; Bair, H. E. Synthesis and characterization of a series of monodisperse 1,3,5-phenylene-based hydrocarbon dendrimers including C276H186 and their fluorinated analogues. *J. Am. Chem. Soc.* **1992**, *114*, 1018–1025.
- (26) Dantras, E.; Lacabanne, C.; Caminade, A. M.; Majoral, J. P. TSC and broadband dielectric spectroscopy studies of β -relaxation in phosphorus-containing dendrimers. *Macromolecules* **2001**, *34*, 3808–3811.
- (27) Dantras, E.; Caminade, A. M.; Majoral, J. P.; Lacabanne, C. Dielectric study of local relaxations in dendritic macromolecules. *J. Phys. D: Appl. Phys.* **2002**, *35*, 5–8.
- (28) Dantras, E.; Dandurand, J.; Lacabanne, C.; Caminade, A. M.; Majoral, J. P. Enthalpy relaxation in phosphorus-containing dendrimers. *Macromolecules* **2002**, *35*, 2090–2094.
- (29) Furer, V. L.; Kovalenko, V. I.; Vanduykov, A. E.; Majoral, J. P.; Caminade, A. M. Calculation of IR spectra of the elementoorganic dendrimers. *Spectrochim. Acta, Part A* **2002**, *58*, 2905–2912.
- (30) Furer, V. L.; Kovalenko, V. I.; Vanduykov, A. E.; Majoral, J. P.; Caminade, A. M. The vibrational analysis of the starting "monomer" and first generation of the starburst elementoorganic dendrimer. *Vib. Spectrosc.* **2003**, *31*, 71–79.
- (31) Demathieu, C.; Chehimi, M. M.; Lipskier, J.-F.; Caminade, A.-M.; Majoral, J.-P. Characterization of dendrimers by X-ray photoelectron spectroscopy. *Appl. Spectrosc.* **1999**, *53*, 1277–1281.
- (32) Turrin, C.-O.; Maraval, V.; Caminade, A.-M.; Majoral, J.-P.; Mehdi, A.; Rey, C. Organic–inorganic hybrid materials incorporating phosphorus-containing dendrimers. *Chem. Mater.* **2000**, *12*, 3848–3856.
- (33) Boury, B.; Corriu, R. J. P.; Nunez, R. Hybrid Xerogels from Dendrimers and Arborols. *Chem. Mater.* **1998**, *10*, 1795–1804.
- (34) Kriesel, J. W.; Tilley, T. D. Dendrimers as Building Blocks for Nanostructured Materials: Micro- and Mesoporosity in Dendrimer-Based Xerogels. *Chem. Mater.* **1999**, *11*, 1190–1193.
- (35) Chane Ching, J. Y.; Reinert, P.; Bull, L.; Caminade, A.-M. Sol–gel preparation of silica ceramics with high-porosity from silica-precursors, dendritic organic polymers and non-ionic surfactant. French Patent FR 2833936, December 26, 2001.
- (36) Soler-Illia, G. J. d. A. A.; Rozes, L.; Boggiano, M. K.; Sanchez, C.; Turrin, C.-O.; Caminade, A.-M.; Majoral, J.-P. New mesotextured hybrid materials made from assemblies of dendrimers and titanium(IV)-oxo-organo clusters. *Angew. Chem., Int. Ed.* **2000**, *39*, 4249–4254.
- (37) Bouchara, A.; Rozes, L.; Soler-Illia, G. J. d. A. A.; Sanchez, C.; Turrin, C. O.; Caminade, A.-M.; Majoral, J.-P. Use of functional dendritic macromolecules for the design of metal oxo based hybrid materials. *J. Sol-Gel Sci. Technol.* **2003**, *26*, 629–633.
- (38) Marmillon, C.; Gauffre, F.; Gulik-Krzywicki, T.; Loup, C.; Caminade, A.-M.; Majoral, J.-P.; Vors, J.-P.; Rump, E. Organophosphorus dendrimers as new gelating materials for hydrogels. *Angew. Chem., Int. Ed.* **2001**, *40*, 2626–2629.
- (39) Caminade, A.-M.; Majoral, J.-P.; Rump, E.; Zerouk, R.; Gauffre-Guirardel, F.; Marmillon, C.; Vors, J.-P. Pesticide and/or plant growth regulating compositions. World Patent No. WO0053009, 2000.
- (40) Schmid, G.; Meyer-Zaika, W.; Pugin, R.; Sawitowski, T.; Majoral, J.-P.; Caminade, A.-M.; Turrin, C.-O. Naked Au₅₅ clusters: Dramatic effect of a thiol-terminated dendrimer. *Chem.–Eur. J.* **2000**, *6*, 1693–1697.
- (41) Turrin, C.-O.; Chiffre, J.; de Montauzon, D.; Daran, J.-C.; Caminade, A.-M.; Manoury, E.; Balavoine, G.; Majoral, J.-P. Phosphorus-containing dendrimers with ferrocenyl units at the core, within the branches, and on the periphery. *Macromolecules* **2000**, *33*, 7328–7336.
- (42) Turrin, C. O.; Chiffre, J.; Daran, J.-C.; de Montauzon, D.; Caminade, A.-M.; Manoury, E.; Balavoine, G.; Majoral, J.-P. New chiral phosphorus-containing dendrimers with ferrocenes on the periphery. *Tetrahedron* **2001**, *57*, 2521–2536.
- (43) Turrin, C.-O.; Chiffre, J.; de Montauzon, D.; Balavoine, G.; Manoury, E.; Caminade, A.-M.; Majoral, J.-P. Behavior of an Optically Active Ferrocene Chiral Shell Located within Phosphorus-Containing Dendrimers. *Organometallics* **2002**, *21*, 1891–1897.
- (44) Sebastian, R.-M.; Caminade, A.-M.; Majoral, J.-P.; Levillain, E.; Huchet, L.; Roncali, J. Electrogenerated poly(dendrimers) containing conjugated poly(thiophene) chains. *Chem. Commun.* **2000**, 507–508.
- (45) Le Derf, F.; Levillain, E.; Trippe, G.; Gorgues, A.; Salle, M.; Sebastian, R.-M.; Caminade, A.-M.; Majoral, J.-P. Immobilization of redox-active ligands on an electrode: the dendrimer route. *Angew. Chem., Int. Ed.* **2001**, *40*, 224–227.
- (46) Casado, C. M.; Cuadrado, I.; Moran, M.; Alonso, B.; Garcia, B.; Gonzalez, B.; Losada, J. Redox-active ferrocenyl dendrimers and polymers in solution and immobilised on electrode surfaces. *Coord. Chem. Rev.* **1999**, *185–186*, 53–76.
- (47) Casado, C. M.; Gonzalez, B.; Cuadrado, I.; Alonso, B.; Moran, M.; Losada, J. Mixed ferrocene-cobaltocenium dendrimers/the most stable organometallic redox systems combined in a dendritic molecule. *Angew. Chem., Int. Ed.* **2000**, *39*, 2135–2138.
- (48) Nlate, S.; Ruiz, J.; Blais, J. C.; Astruc, D. Ferrocenylsilylation of dendrons: a fast convergent route to redox-stable ferrocene dendrimers. *Chem. Commun.* **2000**, 417–418.
- (49) Nlate, S.; Ruiz, J.; Sartor, V.; Navarro, R.; Blais, J. C.; Astruc, D. Molecular batteries: ferrocenylsilylation of dendrons, dendritic cores and dendrimers: new convergent and divergent routes to ferrocenyl dendrimers with stable redox activity. *Chem.–Eur. J.* **2000**, *6*, 2544–2553.

- (50) Slomkowski, S.; Miksa, B.; Chehimi, M. M.; Delamar, M.; Cabet-Deliry, E.; Majoral, J.-P.; Caminade, A.-M. Inorganic-organic systems with tailored properties controlled on molecular, macromolecular and microscopic level. *React. Funct. Polym.* **1999**, *41*, 45–57.
- (51) Miksa, B.; Slomkowski, S.; Chehimi, M. M.; Delamar, M.; Majoral, J.-P.; Caminade, A.-M. Tailored modification of quartz surfaces by covalent immobilization of small molecules (γ -(aminopropyl)-triethoxysilane), monodisperse macromolecules (dendrimers), and poly(styrene/acrolein/divinylbenzene) microspheres with narrow diameter distribution. *Colloid Polym. Sci.* **1999**, *277*, 58–65.
- (52) Emmrich, E.; Franzca, S.; Schmid, G.; Majoral, J.-P. Monolayer of a fourth-generation thiol-terminated dendrimer. *Nano Lett.* **2002**, *2*, 1239–1242.
- (53) Caminade, A.-M.; Majoral, J.-P.; Eckle, M.; Pointu, D.; Decher, G., manuscript in preparation.
- (54) Hernandez-Lopez, J. L.; Bauer, R. E.; Chang, W.-S.; Glasser, G.; Grebel-Koehler, D.; Klapper, M.; Kreiter, M.; Leclaire, J.; Majoral, J.-P.; Mittler, S.; Müllen, K.; Vasilev, K.; Weil, T.; Wu, J.; Zhu, T.; Knoll, W. Functional polymers as nanoscopic building blocks. *Mater. Sci. Eng.* **2003**, *C23*, 267–274.
- (55) Benters, R.; Niemeyer, C. M.; Wohrle, D. Dendrimer-activated solid supports for nucleic acid and protein microarrays. *Chem. Biochem.* **2001**, *2*, 686–694.
- (56) Benters, R.; Niemeyer, C. M.; Drutschmann, D.; Blohm, D.; Wohrle, D. DNA microarrays with PAMAM dendritic linker systems. *Nucleic Acid Res.* **2002**, *30*, No. e10.
- (57) Trévisiol, E.; Leberre-Anton, V.; Leclaire, J.; Prativiel, G.; Caminade, A.-M.; Majoral, J.-P.; François, J. M.; Meunier, B. Dendrilsides, dendrichips: a simple chemical functionalization of glass slides with phosphorus dendrimers as an effective mean for the preparation of biochips. *New J. Chem.* **2003**, *27*, 1713–1719.
- (58) Le Berre, V.; Trévisiol, E.; Dagkessamanskaia, A.; Sokol, S.; Caminade, A. M.; Majoral, J. P.; Meunier, B.; François, J. Dendrimeric coating of glass slides for sensitive DNA microarrays analysis. *Nucleic Acid Res.* **2003**, *31*, No. e88.
- (59) Caminade, A.-M.; Maraval, V.; Laurent, R.; Majoral, J.-P. Organometallic derivatives of phosphorus-containing dendrimers. Synthesis, properties and applications in catalysis. *Curr. Org. Chem.* **2002**, *6*, 739–774.
- (60) Maraval, V.; Laurent, R.; Caminade, A.-M.; Majoral, J.-P. Phosphorus-containing dendrimers and their transition metal complexes as efficient recoverable multicenter homogeneous catalysts in organic synthesis. *Organometallics* **2000**, *19*, 4025–4029.
- (61) Koprowski, M.; Sebastian, R.-M.; Maraval, V.; Zablocka, M.; Cadierno, V.; Donnadieu, B.; Igau, A.; Caminade, A.-M.; Majoral, J.-P. Iminophosphine palladium complexes in catalytic Stille coupling reactions: From monomers to dendrimers. *Organometallics* **2002**, *21*, 4680–4687.
- (62) Loup, C.; Zanta, M.-A.; Caminade, A.-M.; Majoral, J.-P.; Meunier, B. Preparation of water-soluble cationic phosphorus-containing dendrimers as DNA transfecting agents. *Chem.–Eur. J.* **1999**, *5*, 3644–3650.
- (63) Maszewska, M.; Leclaire, J.; Cieslak, M.; Nawrot, B.; Okruszek, A.; Caminade, A.-M.; Majoral, J.-P. Water-soluble polycationic dendrimers with a phosphoramidothioate backbone: preliminary studies of cytotoxicity and oligonucleotide/plasmid delivery in human cell culture. *Oligonucleotides* **2003**, *13*, 193–207.
- (64) Majoral, J.-P.; Caminade, A.-M.; Leclaire, J.; Loup, C.; Solassol, J.; Lehmann, S.; Meunier, B. Uses of phosphorylated dendrimers as drugs. French Patent FR 2834988, January 21, 2002.

AR020077N