Phosphate-, Phosphite-, Ylide-, and Phosphonate-Terminated Dendrimers

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Many types of tri- and tetracoordinated phosphorus derivatives have been grafted on the surface of dendrimers, starting from aldehyde terminal functions. Depending on the solubility of the resulting phosphorylated dendrimers, these experiments have been carried out on generation 1 (six end groups) for phosphate- (**4-[G$_1$]**), phosphinite- (**6-[G$_1$]**), and ylide-terminated (**11-[G$_1$]**) dendrimers and up to generation 5 (96 end groups) for aminophosphate- (**8-[G$_1$]**, **8-[G$_5$]**), aminophosphite (**10-[G$_1$]**, **10-[G$_5$]**), and functionalized phosphonate-terminated (**14-[G$_1$]**−**14-[G$_5$]**, **15-[G$_1$]**, **15-[G$_5$]**, **17-[G$_1$]**, **19-[G$_1$]**, **19-[G$_5$]**) dendrimers. Most of the phosphonate-terminated dendrimers present an unexpected long-range phosphorus−phosphorus coupling constant through seven bonds ($3.8 < {}^7J_{PP} < 4.5$ Hz).

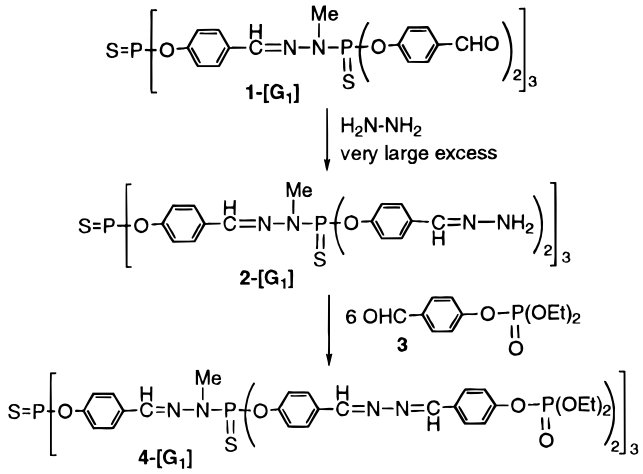
Introduction

Tetracoordinated organophosphorus derivatives such as phosphates and phosphonates offer a wide range of applications as pesticides, insecticides, herbicides, catalysts, lubricants, adhesives, flame retardants, etc. For many uses, these compounds are grafted on polymers or are polymerized themselves. Owing to their potential applications, we decided to graft several types of tetracoordinated organophosphorus derivatives on a new class of monodisperse and highly branched polymers, namely dendrimers.[1] Our efforts were first directed toward the grafting of phosphates and then mainly toward the grafting of phosphonates, since both types of compounds generally have similar properties, but differ in that phosphonates have a different solubility and a greater stability toward hydrolysis. We have also grafted on dendrimers several other types of organophosphorus derivatives such as aminophosphates, phosphinites, aminophosphites, and even ylides.

Results and Discussion

The family of dendrimers we used is built from P(S)Cl_3 as core by the repetition of two reactions, which creates $OC_6H_4CH{=}NN(Me)P(S)$ linkages.[2] These compounds possess 6, 12, 24, 48, or 96 terminal functions for generations 1, 2, 3, 4, or 5, respectively. These functions are either Cl or benzaldehyde groups, the latter being the starting groups for the synthesis of all the organophosphorus-terminated dendrimers described in this paper (Figure 1).

Scheme 1



In first attempts, we tried to graft phosphate groups in two steps from the dendrimer **1-[G$_1$]**. The first step is a condensation with hydrazine, used in very large excess, to afford compound **2-[G$_1$]**.[2d,f] The second step is another condensation, with the phosphate **3**, easily obtained by reaction of hydroxybenzaldehyde sodium salt with $(EtO)_2P(O)Cl$ (Scheme 1). The synthesis of dendrimer **4-[G$_1$]** is monitored by ^{31}P NMR, which shows a slight deshielding of the signal corresponding to the $(EtO)_2P(O)R$ moieties on going from **3** ($\delta^{31}P = -7$ ppm) to **4-[G$_1$]** ($\delta^{31}P = -6.7$ ppm). Additional proofs of the condensation reaction are given by ^1H NMR, with the total disappearance of signals corresponding to CHO and NH_2 groups. Furthermore, ^{13}C NMR indicates the presence of two very close singlets ($\delta^{13}C = 160.5$ and 160.8 ppm) corresponding to the azine −CH═NN═CH− linkages of the dendrimer **4-[G$_1$]**.

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(1) For reviews on dendrimers, see, for example: (a) Tomalia, D. A.; Naylor, A. M.; Goddart, W. A., III. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 138. (b) Tomalia, D. A.; Durst, H. D. In *Topics in Current Chemistry*; Weber, E., Ed.; Springer Verlag: Berlin, Heidelberg, 1993; Vol. 165, p 193. (c) Issberner, J.; Moors, R.; Vögtle, F. *Angew. Chem.* **1994**, *106*, 2507; *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2413. (d) Moorefield, C. N.; Newkome, G. R. In *Advances in Dendritic Molecules*; Newkome, G. R., Ed.; JAI Press: Greenwich, CT, 1994; Vol. 1, p 1. (e) Caminade, A.-M.; Majoral, J.-P. *Main Group Chem. News* **1995**, *3*, 14. (f) Ardoin, N.; Astruc, D. *Bull. Soc. Chim. Fr.* **1995**, *132*, 876. (g) Majoral, J.-P.; Caminade, A.-M. *Acta Chim.* **1996**, *4*, 13. (h) Fréchet, J. M. J.; Hawker, C. J. In *Comprehensive Polymer Science*; Aggarwal, S. L., Russo, S., Eds.; Pergamon Press: Oxford, 1996; pp 140−201.

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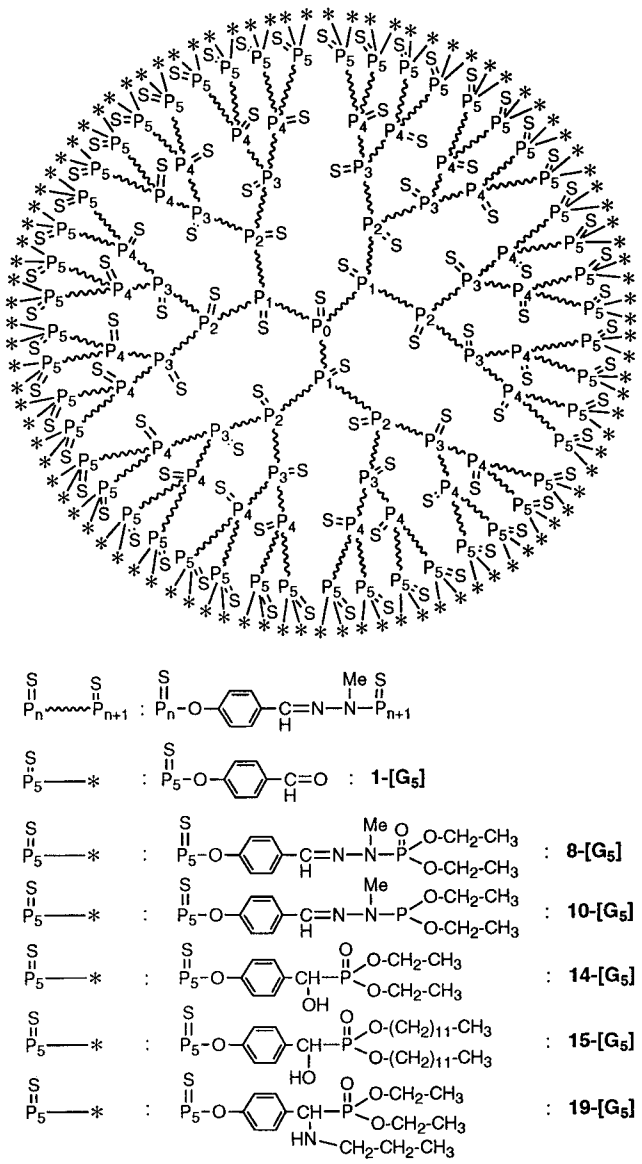
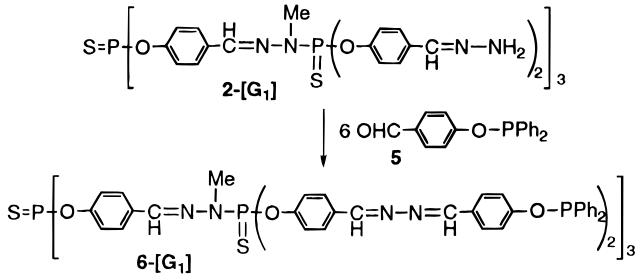


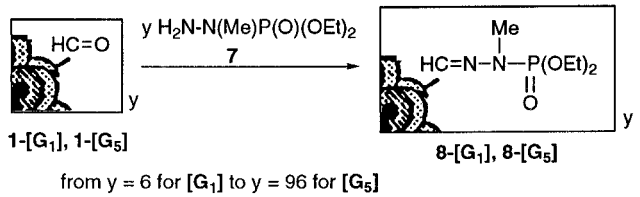
Figure 1. Fifth generation of the dendrimer with various end groups.

We tried to extend this reaction to higher generations **4-[G$_n$]** (***n***: generations 2−5). Unfortunately, the condensation results in all cases in the formation of powders, insoluble in water and in common organic solvents. However, the same condensation reaction can be applied to graft other phosphorus derivatives such as phosphinites. Indeed, the phosphinite **5**, obtained by reaction of hydroxybenzaldehyde and triethylamine and diphenylchlorophosphine, is easily condensed with dendrimer **2-[G$_1$]** to afford the phosphinite-terminated dendrimer **6-[G$_1$]** (Scheme 2). The condensation induces a slight shielding of the signal corresponding to the Ph_2PO moieties in ^{31}P NMR on going from **5** ($\delta^{31}P = 112.3$ ppm) to **6-[G$_1$]** ($\delta^{31}P = 111.5$ ppm) and the total disappearance of signals corresponding to CHO and NH_2 groups in ^1H NMR. In this case also, we tried to obtain higher generations of the phosphinite-terminated dendrimers, for instance **6-[G$_3$]**, but we observed the same phenomenon of insolubility that we already noted for dendrimers **4-[G$_n$]** (***n*** > 1), probably due to the presence of many diarylazine groups. To overcome this problem, we decided to avoid the formation of this linkage and, therefore,

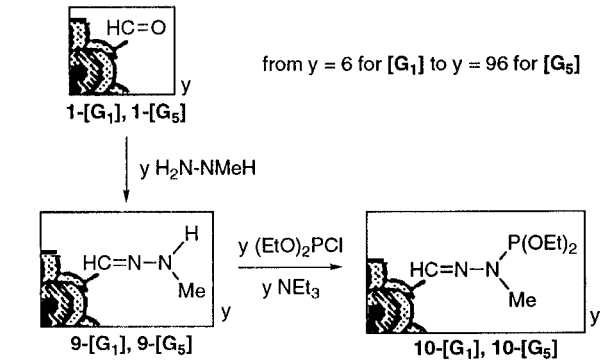
Scheme 2



Scheme 3



Scheme 4

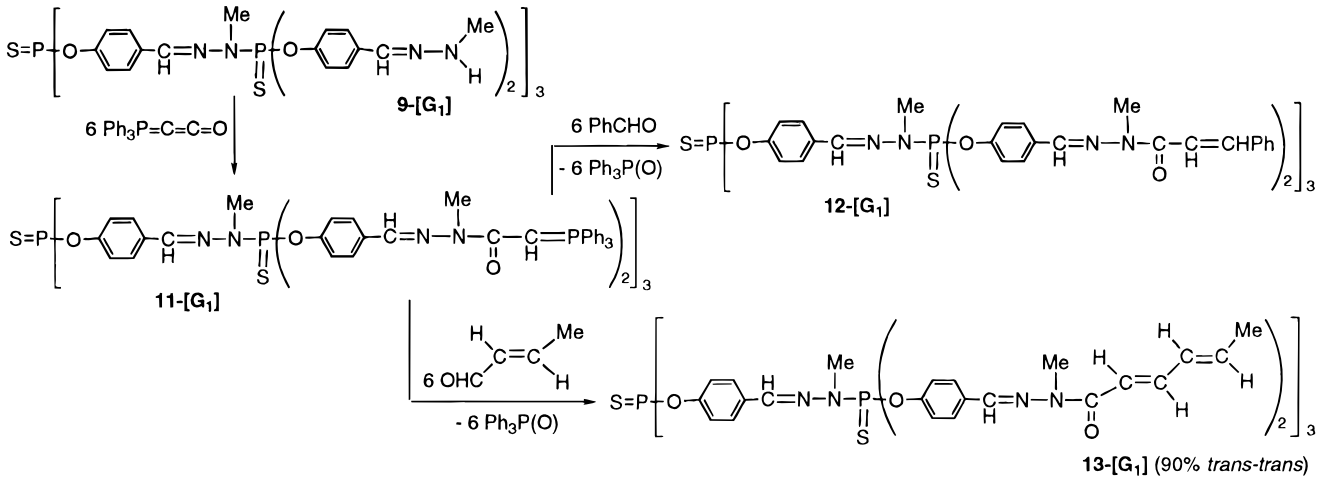


to find other strategies to graft phosphorus derivatives on the dendrimer.

We tried first another condensation reaction, with aldehyde groups on the dendrimer and NH_2 groups on the phosphorus derivative to be grafted, such as $H_2NN(Me)P(O)(OEt)_2$ **7**. This compound, obtained by reaction of methylhydrazine with $ClP(O)(OEt)_2$, reacts easily with the first generation of the dendrimer **1-[G$_1$]** (6 CHO end groups) but also with the fifth generation **1-[G$_5$]** (96 CHO end groups) (Scheme 3, Figure 1). In both cases, the quantitative formation of the hydrazonophosphate-terminated dendrimer **8-[G$_n$]** is monitored by ^{31}P NMR. Indeed, we observed the total disappearance of the signal corresponding to **7** ($\delta^{31}P$ = 8.7 ppm) on behalf of the appearance of a new signal ($\delta^{31}P = 2.8$ ppm) corresponding to the P=O groups of **8-[G$_n$]**. Furthermore, the signal of the phosphorus atoms on the external layer of the dendrimer (P_1 for **[G$_1$]**, P_5 for **[G$_5$]**) is slightly deshielded on going from **1-[G$_n$]** to **8-[G$_n$]** ($\Delta\delta = 2.2$ ppm). The total disappearance of signals corresponding to CHO and NH_2 groups in ^1H NMR confirms the quantitative formation of dendrimers **8-[G$_n$]** as crude product. It is worth noting that the fifth generation of the dendrimer **8-[G$_5$]**, which possesses 96 hydrazonophosphate groups, remains perfectly soluble in several organic solvents such as THF, chloroform, dichloromethane, etc.

Obviously, many types of phosphorus derivatives can be grafted on the surface of the dendrimers in this way, provided the formation of the phosphorohydrazide $H_2NNMeP(X)R_2$ could be accomplished. This is the case with most P^{IV} derivatives (X = O, S, N...) but is extremely difficult and even impossible with P^{III} derivatives. In-

Scheme 5



deed, the higher reactivity of tricoordinated phosphorus precludes the specificity of the reaction on the NHMe group of methylhydrazine, which is observed with tetracoordinated phosphorus. However, another strategy can be applied, for instance, to graft hydrazinophosphites, in two steps. The first step is the condensation of **1-[G$_n$]** with methylhydrazine, which affords dendrimers **9-[G$_n$]**.[2b−d] The second step consists of grafting $(EtO)_2$-PCl in the presence of NEt_3, which yields the hydrazonophosphite-terminated dendrimers **10-[G$_n$]** (Scheme 4, Figure 1). These reactions have been applied to generation 1 (**10-[G$_1$]**: 6 N−P(OEt)$_2$ end groups) and generation 5 (**10-[G$_5$]**: 96 N−P(OEt)$_2$ end groups) in the same conditions. Both compounds are particularly characterized by the appearance of a new singlet in ^{31}P NMR (δ^{31}P = 139 ppm, NP(OEt)$_2$) and by the shielding of the terminal NMe groups in ^{13}C NMR on going from **9-[G$_n$]** (δ^{13}C = 34.0 ppm, −NMeH) to **10-[G$_n$]** (δ^{13}C = 28.4 ppm, −NMeP^{III}).

All the experiments described above allow to bind phosphorus groups to the dendrimer by means of O or N linkages; we have thus isolated dendrimers with phosphate (OP(O)[OR]$_2$), phosphinite (OPR$_2$), aminophosphate (NP(O)[OR]$_2$), or aminophosphite (NP[OR]$_2$) end groups. In previous papers, we already described the use of carbon−phosphorus bonds to graft phosphines (CH_2-PR$_2$).[2c,f,g] It appeared interesting to extend this work to the grafting of other types of phosphorus derivatives with C−P bonds, particularly ylides and phosphonates because of their numerous applications in different fields.

Dendrimers **9-[G$_n$]** may be used as the starting material for the grafting of ylides. Indeed, it is known that triphenylphosphoranylidene ethenone $Ph_3P{=}C{=}C{=}O$ undergoes the addition of compounds with acidic hydrogens, such as alcohols, thiols, or amines, to the C=C bond.[3] Application of this type of addition to dendrimer **9-[G$_1$]** affords the ylide-terminated dendrimer **11-[G$_1$]** (Scheme 5). This compound is characterized in particular by the presence of the signal of the ylide moieties in ^{31}P NMR (δ^{31}P = 18.3 ppm), whereas ^{13}C NMR displays the presence of amido groups (δ^{13}C = 170.3 ppm, d, $^2J_{CP}$ = 26.8 Hz) and a slight deshielding of the signal corresponding to the NMe end groups (δ^{13}C = 26.8 ppm). In view of the widespread use of ylides in organic chemistry, it would have been interesting to synthesize higher generations of dendrimers with ylide end groups; thus, we tried to obtain the same type of compound from the second generation **9-[G$_2$]**. Unfortunately, the corresponding ylide-terminated dendrimer **11-[G$_2$]** was found to be insoluble in water and in a variety of organic solvents.

However, we decided to test the reactivity of the first generation **11-[G$_1$]** in the Wittig reaction, toward benzaldehyde and crotonaldehyde. Benzaldehyde reacts at room temperature to afford compound **12-[G$_1$]** in quantitative yield as crude product (Scheme 5). The reaction is monitored by ^{31}P NMR, which indicates the total disappearance of the ylide signal on behalf of the appearance of the signal corresponding to $Ph_3P(O)$ (δ^{31}P = 24 ppm). After removal of the triphenylphosphine oxide, ^{1}H NMR indicates a slight deshielding of the signal corresponding to the CH_3NCO groups, but the signals of the CH=CH linkages are overlapped by the aromatic signals and did not allow us to determine the geometry of the ethylenic linkage. However, ^{13}C NMR indicates the formation of both cis and trans isomers; indeed, each carbon atom of the $CH_3NC(O)CH{=}CH-$ linkages gives two close singlets, approximately in a 1:3 ratio, whereas for all the other parts of the dendrimer **12-[G$_1$]**, each carbon gives a single set of signals. According to the known tendency of stabilized ylides to give predominantly trans isomers in the Wittig reaction,[4] we tentatively assign the largest signals to the trans isomer.

This assignment is corroborated by the study of the reaction of crotonaldehyde (trans isomer) with **12-[G$_1$]** (Scheme 5). In this case also, ^{13}C NMR displays the formation of two isomers, characterized by the presence of two signals for each carbon atom of the $CH_3NC(O)$-$CH{=}CHCH{=}CHMe$ linkages in an approximate 1:9 ratio. The attribution of these signals to the cis-trans and trans-trans isomers, respectively, is unambiguous in this case owing to ^{1}H two-dimensional NMR experiments. Indeed, two doublets in a 1:9 ratio are observed for the H$_d$ protons of the $CH_d{=}CH_cCH_b{=}CH_aMe$ linkages: δ ^{1}H = 6.80 (d, $^3J_{HdHc}$ = 10.0 Hz), and 7.12 (d, $^3J_{HdHc}$ = 15.0 Hz) ppm. The value of the coupling constants allows us to attribute unambiguously the former signals to the minor cis-trans isomer and the latter to the major trans-trans isomer.

The last type of phosphorus derivatives we tried to graft on dendrimers is phosphonates. In all cases, the

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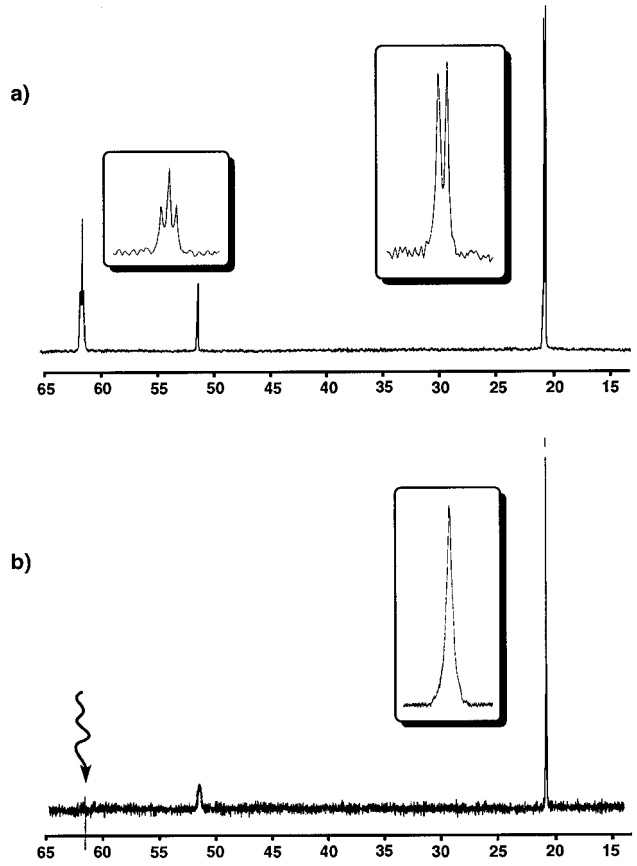


Figure 2. (a) $^{31}P\{^{1}H\}$NMR spectra of dendrimer **14-[G$_1$]**. (b) $^{31}P\{^{1}H\}$NMR spectra of dendrimer **14-[G$_1$]** with selective irradiation of the signal at $\delta = 62$ ppm.

method of synthesis we used consists of the addition of P−H bonds on polar double bonds of the dendrimer. In our first attempts, we tried to graft phosphonate groups by addition of diethyl phosphite to the aldehyde functions of dendrimer **1-[G$_1$]** in several conditions, using THF as solvent. It is well known that this type of reaction is catalyzed by bases;[5] thus, we used either CsF, NEt_3, or DBU as catalysts, heating for several days at 65 °C. In all cases, we observed only a partial reaction, even after heating for 2 weeks (when CsF is used), or a degradation (when DBU is used). On the other hand, when a large excess of diethyl phosphite is used without solvent, and in the presence of CsF as catalyst under heating, the reaction with **1-[G$_1$]** goes to completion. However, the resulting α-hydroxy methylphosphonate-terminated dendrimer **14-[G$_1$]** is difficult to purify in these conditions, both from CsF and from the large excess of diethyl phosphite.

We also tried to use NEt_3 as catalyst (20−40%) without solvent, the dendrimer **1-[G$_1$]** being dissolved in the mixture $Et_3N/(EtO)_2P(O)H$. In these conditions, the reaction proceeds rapidly and quantitatively at room temperature, and the resulting phosphonate-terminated dendrimer **14-[G$_1$]** is more easily purified (Scheme 6). However, the ^{31}P NMR spectrum of compound **14-[G$_1$]** appears surprisingly complex. Indeed, beside the singlet corresponding to the phosphorus of the core (δ $^{31}P = 51.8$ ppm, P_0), we observed two signals centered at $\delta = 21.3$ ppm, corresponding to $P(O)(OEt)_2$, and three signals centered at $\delta = 62.0$ ppm, corresponding to the phosphorus of the first generation P_1 (Figure 2a). At first glance, these signals could be due to the formation of three diastereoisomers (one racemic and two meso forms) for each branch of the dendrimer, as the addition of PH groups to aldehydes creates chiral carbon centers (Figure 3). However, the relative intensity for each set of signals (1:2:1 for $\delta = 62.0$ ppm and 1:1 for $\delta = 21.3$ ppm) and the line separation seems to be in agreement with the presence of a triplet and a doublet, with a coupling constant of 3.9 Hz, which should correspond to the coupling of $P_1(S)$ with P(O) through seven bonds! This surprising result prompted us to verify this hypothesis by selective phosphorus-decoupling NMR experiments. The selective irradiation of the signal at $\delta = 62.0$ ppm clearly induces the transformation of the signal at $\delta =$ 21.3 ppm from a doublet to a singlet (Figure 2b). Furthermore, the selective irradiation of the signal at δ = 21.3 ppm also transforms the signal at $\delta = 62.0$ ppm to a singlet. These experiments confirm the existence of the $^{7}J_{PP}$ coupling constant in compound **14-[G$_1$]**. Very few coupling constants through so many bonds have been reported in the literature, most of them concerning through-space couplings,[6] which are unlikely for compound **14-[G$_1$]** for steric reasons. However, a phosphorus−phosphorus coupling constant over seven bonds has already been measured for a compound whose structure is closely related to that of **14-[G$_1$]**: the analysis of the outer ^{13}C satellites in the ^{31}P NMR spectrum of $(EtO)_2P(O)CH_2C_6H_4CH_2P(O)(OEt)_2$ gave $^{7}J_{PP} = 7.8$ Hz, a value attributed to a large Π-electron contribution.[7] The value directly obtained in the case of **14-[G$_1$]** ($^{7}J_{PP} = 3.9$ Hz) compares well with these data.

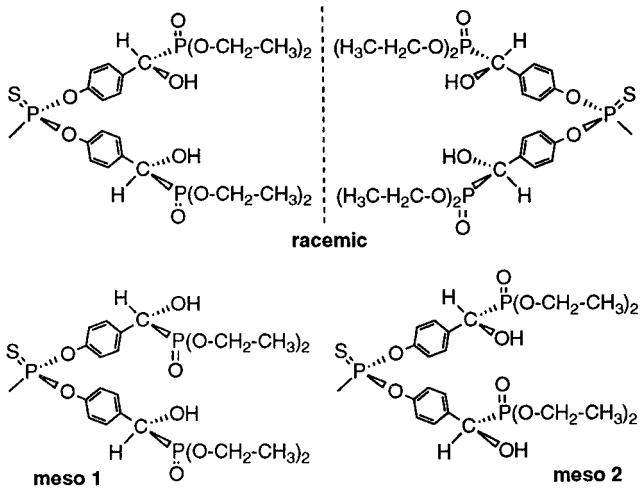
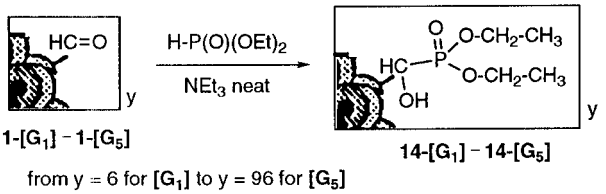


Figure 3. Racemic and meso forms for each branch of dendrimers **14-[G$_n$]**.

Scheme 6

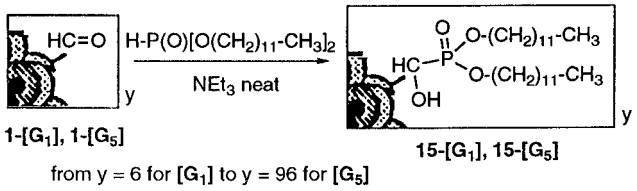


(5) See, for instance, Abramov, V. S. *Zh. Obsch. Khim.* **1957**, *27*, 169; (*Chem. Abstr.* **1957**, *51*, 12878e).

(6) (a) Szalontai, G.; Bakos, J.; Toth, I.; Heil, B. *Magn. Reson. Chem.* **1987**, *25*, 761. (b) Pastor, S. D.; Hyun, J. L.; Odorisio, P. A.; Rodebaugh, R. K. *J. Am. Chem. Soc.* **1988**, *110*, 6547. (c) Pastor, S. D.; Shum, S. P.; DeBellis, A. D.; Burke, L. P.; Rodebaugh, R. K.; Clarke, F. H.; Rihs, G. *Inorg. Chem.* **1996**, *35*, 949 and references cited therein.

(7) Ernst, L. *J. Chem. Soc., Chem. Commun.* **1977**, 375. (b) Ernst, L. *Org. Magn. Reson.* **1977**, *1*, 35.

Scheme 7



The grafting of phosphonate groups can be extended to higher generations without any problem of solubility. We have carried out this reaction under the same conditions for all the generations from 1 to 5 and, thus, isolated dendrimers **14-[G_1]**−**14-[G_5]**, with up to 96 phosphonate end groups (Scheme 6). In all cases, we observed a doublet in the ^{31}P NMR spectra at $\delta = 21$ ppm ($3.8 < {}^7J_{PP} < 4.5$ Hz) for the P(O)$(OEt)_2$ groups, whereas the signal at $\delta = 62$ ppm becomes a broad singlet for generations higher than 2, presumably due to the formation of an increasing number of stereoisomers. The full transformation of the aldehyde groups in alcohol for all compounds is characterized in ^{1}H NMR by the total disappearance of the singlet of the aldehyde groups on behalf of the appearance of a doublet at *ca.* 5 ppm corresponding to the C**H*OH groups. The presence of chiral carbon atoms also complicates the ^{1}H and ^{13}C NMR spectra for all generations, as this renders the CH_2CH_3 groups diastereotopic. This is clearly seen in ^{13}C NMR spectra by the presence of two distinct doublets at *ca* 63−65 ppm corresponding to the OCH_2CH_3 groups.

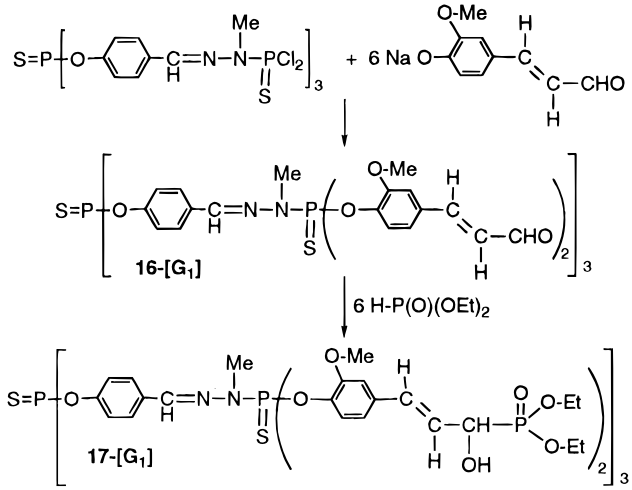
The facility of the synthesis of dendrimers **14-[G_1]**−**14-[G_5]** incited us to try to extend this reaction to other phosphonates and to other end groups on the dendrimers. For instance, the long chain phosphonate HP(O)[O$(CH_2)_{11}$-$CH_3]_2$ also reacts with dendrimers **1-[G_1]** and **1-[G_5]** to afford dendrimers **15-[G_1]** and **15-[G_5]** (Scheme 7). These compounds possess the same spectral characteristics already noted for dendrimers **14-[G_1]**−**14-[G_5]**, in particular, a $^7J_{PP} = 3.8$ Hz is clearly observed on the ^{31}P NMR spectrum of **15-[G_1]**. The presence of several long-chain hydrocarbons modifies the solubility of the dendrimer: for instance, compound **15-[G_1]** is soluble in pentane, whereas none of the dendrimers we already synthesized is.

We also tried the addition of phosphonates on a dendrimer with α,β-unsaturated aldehydes as end groups, **16-[G_1]**. This compound is obtained in THF at 40 °C by reacting 6 equiv of the sodium salt of 4-hydroxy-3-methoxycinnamaldehyde with (S)P[OC_6H_4CH=NN(Me)P-(S)$Cl_2]_3$ (Scheme 8). Addition of HP(O)$(OEt)_2$ on **16-[G_1]** affords dendrimer **17-[G_1]**, which possesses six unsaturated alcohol−phosphonate end groups. In this case, no phosphorus−phosphorus coupling constant through nine bonds is observed on the ^{31}P NMR spectrum of **17-[G_1]**. ^{1}H NMR shows the total disappearance of the CHO groups on behalf of the appearance of a doublet of doublet at $\delta = 4.6$ ppm ($^2J_{HP} = 13.4$ Hz, $^3J_{HH} = 5.0$ Hz) corresponding to C**H*OH. As expected, no reaction occurred on the CH=CH bonds.

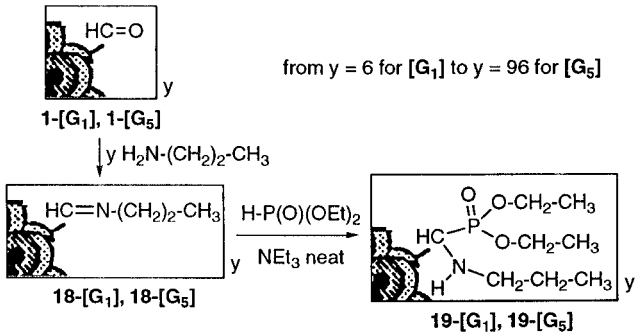
IR spectra of compounds **14-[G_1]**−**14-[G_5]**, **15-[G_1]**, **15-[G_5]**, and **17-[G_1]** exhibit classical $\nu_{OH} \cong 3270$ cm^{-1}, demonstrating the presence of a hydrogen bond between hydroxyl and phosphoryl groups.

Finally, we also tried to add phosphonates to imine terminal functions, as it is known that this type of reaction proceeds approximately under the same conditions as the addition to aldehydes.[8] For this purpose, we synthesized first the imine-terminated dendrimers **18-[G_1]** and **18-[G_5]**, easily obtained by condensation of propylamine with dendrimers **1-[G_1]** and **1-[G_5]**, respectively (Scheme 9). Addition of HP(O)$(OEt)_2$ on dendrimers **18-[G_1]** and **18-[G_5]** at room temperature affords dendrimers **19-[G_1]** and **19-[G_5]**, respectively. In this case also, the phosphorus−phosphorus coupling constant through seven bonds ($^7J_{PP} = 4.5$ Hz) is clearly observed on the ^{31}P NMR spectra of both generations. The reaction has gone to completion, as demonstrated by the total disappearance of the imine functions ($\delta = 8.20$ ppm) in ^{1}H NMR. The addition to the imine bonds is chemoselective; no reaction occurs on the hydrazone functions of the skeleton of the dendrimer, either in this experiment or in all the previous cases.

Scheme 8



Scheme 9



Conclusion

We have experimented with several strategies to graft tri- and tetracoordinated phosphorus derivatives on dendrimers of generation one−five, depending on the solubility of the resulting dendrimer. It can be inferred from all these experiments that the solubility of the dendrimers depends essentially on the type of substituents grafted on the surface. Indeed, azinephosphate, azinephosphinite, and ylide linkages on the periphery dramatically reduce the solubility of dendrimers possessing more than six end groups. On the other hand, the grafting of long-chain hydrocarbons increases the solubility of the dendrimer in organic solvents. However, it can

(8) See, for instance: (a) Fields, E. K. *J. Am. Chem. Soc.* **1952**, *74*, 1528. (b) Caccamese, S.; Failla, S.; Finocchiaro, P.; Hägele, G.; Principato, G. *J. Chem. Res., Synop.* **1992**, 242.

be pointed out that each end group seems to behave independently as far as the reactivity is concerned. Moreover, the reactivity of the ylide-terminated dendrimer with aldehydes follows the rules elaborated for classical Wittig reactions in organic chemistry.

The phosphonate-terminated dendrimers appears to be very interesting, as all of them remain soluble in common organic solvents, even for high generations. Furthermore, the addition reaction we used allows several variations, both in the nature of the phosphonate to be grafted and in the nature of the polar double bond on the surface of the dendrimer. It is also worth noting that this reaction creates additional functions on the surface on the dendrimer, besides the phosphonate groups: alcohols or secondary amines groups, whose reactivity should be interesting to investigate. Furthermore, these compounds possess a rare and unexpected long-range phosphorus−phosphorus coupling constant through seven bonds for the $(S)POC_6H_4CHRP(O)(OR')_2$ linkages (R = OH, NHPr; R′ = Et, $(CH_2)_{11}CH_3$).

To summarize, this work clearly demonstrates for the first time that it is possible to anchor to the surface of dendritic molecules a large variety of phosphorus groups (phosphates, phosphites, hydrazonophosphates, hydrazonophosphites, phosphorus ylides, and phosphonates (from 6 to 96 units), each of them having potentially a great interest in different fields. Indeed, biologically important phosphates are known (nucleotides, phospholipides, nucleosides, polyphosphates, phosphate sugars);[9,10] phosphite monomers are used in some catalytic processes (acrylonitrile dimerization) and in the well-known Arbusov rearrangement,[11] while phosphorus ylides play a key role in Wittig reactions.[11] Moreover, phosphonate monomers have found wide applications in general organic synthesis[12−14] (Horner−Wadsworth−Emmons condensation, Diels−Alder reactions, Michael additions, etc.), and they can be used as versatile intermediates for the preparation of a number of heterocycles.[14]

Work is in progress to study the properties of these new terminated dendrimers in some of the areas reported above and to extend the scope of reactions developed in this paper to other types of phosphorus derivatives.

Experimental Section

General Methods. All manipulations were carried out with standard high vacuum or dry argon atmosphere techniques. ^1H, $^{31}P\{^1H\}$, and $^{13}C\{^1H\}$ NMR spectra were recorded on Bruker AC 200 or WM 250 or AMX 400 spectrometers, using $CDCl_3$ as solvent, except where noted. ^{31}P NMR chemical shifts are reported in ppm relative to 85% H_3PO_4. Coupling constants (*J*) are reported in Hz.

Synthesis of Compound 3. To a solution of 4-hydroxybenzaldehyde sodium salt (0.500 g, 3.47 mmol) in THF (10 mL) was added $(EtO)_2P(O)Cl$ (0.500 mL, 3.47 mmol). The resulting mixture was stirred for 1 h at room temperature and then filtered to give an oil that was used without further purification.

3: colorless oil; 70% yield (0.627 g); ^{31}P NMR δ −7.0; ^1H NMR δ 1.04 (t, J = 7.0, 6H), 3.92 (q, J = 7.0, 2H), 3.96 (q, J = 7.0, 2H), 7.08 (dd, J = 8.5, 2H), 7.58 (dd, J = 8.5, 2H), 9.65 (s, 1H); ^{13}C NMR δ 15.6 (d, J = 6), 64.6 (d, J = 6), 120.2 (d, J = 5), 131.3, 132.9, 155.0 (d, J = 7), 190.4.

Synthesis of Phosphate-Terminated Dendrimer 4-[G_1]. To a solution of 0.200 g of dendrimer **2-[G_1]** (0.133 mmol) in THF (10 mL) was added phosphate **3** (0.206 g, 0.798 mmol). The resulting mixture was stirred overnight at room temperature and then evaporated to dryness to give a yellow powder. This powder was washed with pentane/ether (1/1).

4-[G_1]: yellow powder; 72% yield (0.282 g); ^{31}P NMR δ −6.7, 52.0, 61.2; ^1H NMR δ 1.33 (m, 36H), 3.36 (d, J = 9.8, 9H), 4.19 (m, 24H), 7.26−7.78 (m, 63H), 8.56 (br s, 12H); ^{13}C NMR δ 15.9 (d, J = 6), 32.8 (d, J = 16), 64.6 (d, J = 6), 120.2 (d, J = 5), 121.3, 121.7 (d, J = 4), 128.3, 129.8, 129.9, 130.6, 131.2, 138.4 (d, J = 14), 150.5 (d, J = 9), 152.5 (d, J = 9), 152.7 (d, J = 9), 160.5, 160.8. Anal. Calcd for $C_{132}H_{144}N_{18}O_{33}P_{10}S_4$: C, 53.77; H, 4.92; N, 8.55. Found: C, 53.63; H, 4.89; N, 8.47.

Synthesis of Compound 5. To a solution of 4-hydroxybenzaldehyde (0.250 g, 2.047 mmol) in THF (10 mL) were added triethylamine (0.285 mL, 2.047 mmol) and then diphenylchlorophosphine (0.367 mL, 2.047 mmol). The resulting mixture was stirred for 1 h at room temperature and then filtered and evaporated to dryness to give a pale yellow paste. This compound was used without further purification.

5: yellow paste; 83% yield (0.520 g); ^{31}P NMR δ 112.3; ^1H NMR δ 7.0−7.8 (m, 14H), 9.87 (s, 1H); ^{13}C NMR δ 118.8 (d, J = 13), 128.5 (d, J = 7), 130.0, 130.5 (d, J = 23), 131.7, 132.1, 139.5 (d, J = 17), 155.5 (d, J = 9), 190.8.

Synthesis of Phosphinite-Terminated Dendrimer 6-[G_1]. To a solution of dendrimer **2-[G_1]** (0.177 g, 0.117 mmol) in dichloromethane (10 mL) was added a solution of compound **5** (0.215 g, 0.702 mmol) in CH_2Cl_2 (4 mL) in the presence of molecular sieves (4 Å). The resulting mixture was stirred overnight at room temperature and then filtered and evaporated to dryness to give a yellow powder very sensitive to oxidation.

6-[G_1]: yellow powder; 64% yield (0.242 g); ^{31}P NMR δ 52.5, 61.6, 111.5; ^1H NMR δ 3.30 (d, J = 10.5, 9H), 7.20−7.80 (m, 123H), 8.60 (br s, 12H); ^{13}C NMR δ 32.9 (d, J = 12), 118.8 (d, J = 11), 120.9, 121.6, 128.4, (d, J = 7), 128.7, 129.8, 130.0 (d, J = 13), 130.6, 131.5, 131.7, 138.4 (d, J = 14), 140.0 (d, J = 17), 151.2 (d, J = 8), 152.4 (m), 161.00. Anal. Calcd for $C_{180}H_{144}N_{18}O_{15}P_{10}S_4$: C, 66.78; H, 4.48; N, 7.79. Found: C, 66.51; H, 4.36; N, 7.65.

Synthesis of Compound 7. To a solution of 0.31 mL (5.83 mmol) of methylhydrazine in THF (10 mL) was slowly added a solution of 0.42 mL (2.92 mmol) of chloro diethyl phosphite in THF (10 mL) at −90 °C. This mixture was allowed to slowly warm to room temperature. After filtration, the solvent was eliminated under vacuum to give a pale-yellow oil. This compound was used without further purification.

7: yellow oil; 70% yield (0.372 g); ^{31}P NMR δ 8.7; ^1H NMR δ 0.97 (t, J = 7.0, 6H), 2.57 (d, J = 8.8, 3H), 3.67 (q, J = 7.0, 2H), 3.77 (q, J = 7.0, 2H), 3.98 (br s, 2H); ^{13}C NMR δ 15.8 (d, J = 6), 40.3 (d, J = 11), 62.4 (d, J = 6).

General Procedure for the Synthesis of Aminophosphate-Terminated Dendrimers 8-[G_1] and 8-[G_5]. To a solution of 0.250 g of **1-[G_n]** (***n*** = 1, 0.176 mmol; ***n*** = 5, 0.008 mmol) in THF (10 mL) was added an excess of $(EtO)_2P(O)$-$NMeNH_2$ (***n*** = 1, 0.385 g, 2.11 mmol; ***n*** = 5, 0.280 g, 1.54 mmol) in the presence of molecular sieves (4 Å). The resulting mixture was stirred for 2 days at room temperature and then evaporated to dryness to give an oil. Addition of pentane precipitated the oil to give a white powder. Pentane was eliminated via cannula, and the powder was dried under vacuum. This powder was then washed with ether.

8-[G_1]: white powder; 65% yield (0.275 g); ^{31}P NMR δ 2.8, 52.7, 62.6; ^1H NMR δ 1.3 (br t, J = 7.3, 36H), 3.2 (d, J = 7.3, 18H), 3.4 (d, J = 10.4, 9H), 4.0 (m, 24H), 7.1−7.8 (m, 45H); ^{13}C NMR δ 15.9 (d, J = 7), 31.9 (d, J = 10), 32.9 (d, J = 13), 63.4 (d, J = 6), 121.5 (d, J = 5), 127.6, 128.3, 132.6, 136.7, (d, J = 15), 138.3 (d, J = 14), 150.7 (d, J = 8), 151.0 (d, J = 9). Anal. Calcd for $C_{96}H_{132}N_{18}O_{27}P_{10}S_4$: C, 47.88; H, 5.52; N, 10.47. Found: C, 47.79; H, 5.46,; N, 10.24.

8-[G_5]: white powder; 15% yield (0.056 g); ^{31}P NMR δ 2.7, 62.6 (br s); ^1H NMR δ 1.25 (br s, 576 H), 3.18 (d, J = 6.4, 288H), 3.33 (d, J = 10, 279 H), 4.05 (m, 384H), 7.14−7.65 (m, 945H);

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^{13}C NMR δ 16.0 (d, J = 7), 32.0 (d, J = 10), 32.9 (d, J = 14), 63.4 (d, J = 6), 121.5 (d, J = 3), 127.6, 128.1, 132.0, 132.5, 136.8 (d, J = 15), 138−140 (m), 150.7 (d, J = 7), 151.2 (m). Anal. Calcd for $C_{1896}H_{2472}N_{378}O_{477}P_{190}S_{94}$: C, 48.36, H, 5.29; N, 11.24. Found: C, 48.17; H, 5.14; N, 11.07.

General Procedure for the Synthesis of Aminophosphite-Terminated Dendrimers 10-[G$_1$] and 10-[G$_5$]. To a solution of 0.120 g of dendrimer **9-[G$_n$]** (n = 1, 0.075 mmol; n = 5, 0.0035 mmol) in THF (10 mL) were added chlorodiethylphosphine (n = 1, 130 μL, 0.90 mmol; n = 5, 98 μL, 0.677 mmol) and triethylamine (n = 1, 126 μL, 0.90 mmol; n = 5, 100 μL, 0.677 mmol). The resulting mixture was stirred for 2 h at room temperature and then filtered and evaporated to dryness to give a white powder, very sensitive to oxidation.

10-[G$_1$]: white powder; 40% yield (0.070 g); ^{31}P NMR δ 52.5, 62.8, 139.2; ^{1}H NMR δ 1.22 (t, J = 7.0, 36H), 2.93 (d, J = 1.0, 18H), 3.33 (d, J = 10.4, 9H), 3.71−3.85 (m, 24H), 7.15−7.77 (m, 45H); ^{13}C NMR δ 16.7 (d, J = 6), 28.4, 32.9 (d, J = 13), 59.7 (d, J = 17), 121.4 (d, J = 4), 126.9, 128.3, 132.5, 132.6, 133.3 (d, J = 28), 138.2 (d, J = 12), 149.9 (d, J = 7), 150.9 (d, J = 8). Anal. Calcd for $C_{96}H_{132}N_{18}O_{21}P_{10}S_4$: C, 49.87; H, 5.75; N, 10.90. Found: C, 49.73; H, 5.71; N, 10.72.

10-[G$_5$]: white powder; 64% yield (0.102 g); ^{31}P NMR δ 62.6, 62.7, 138.6; ^{1}H NMR δ 1.15−1.27 (m, 576H), 2.85 (d, J = 1.87, 288H), 3.25 (d, J = 11.6, 279H), 3.70−3.86 (m, 384H), 7.11−7.60 (m, 945H); ^{13}C NMR δ 16.7 (d, J = 5), 28.4, 32.9 (d, J = 12), 59.6 (d, J = 17), 121.3 (d, J = 3), 121.6 (d, J = 6), 126.9, 128.0, 132.0, 132.6, 133.2 (d, J = 28), 138.3−140.0 (m), 149.9 (d, J = 7), 151.1 (d, J = 9). Anal. Calcd for $C_{1896}H_{2472}N_{378}O_{381}P_{190}S_{94}$: C, 49.99; H, 5.47; N, 11.62. Found: C, 49.76; H, 5.32; N, 11.51.

Synthesis of Ylide-Terminated Dendrimer 11-[G$_1$]. To a solution of (triphenylphosphoranylidene)ethenone (0.120 g, 0.397 mmol) in THF (7 mL) was added **9-[G$_1$]** (0.105 g, 0.066 mmol) in THF (5 mL) at room temperature. The resulting mixture was stirred for 24 h at room temperature and then evaporated to dryness. The resulting powder was washed with 3 × 10 mL of THF/ether/pentane (1/2/2).

11-[G$_1$]: yellow powder; 78% yield (0.175 g); ^{31}P NMR δ 18.3, 52.8, 62.6; ^{1}H NMR δ 3.3 (s, 18H), 3.3 (d, J = 11.5, 9H), 4.2 (br d, J = 25, 6H), 7.1−7.7 (m, 135H); ^{13}C NMR δ 26.8, 32.4 (d, J = 13), 32.5 (d, J = 127), 120.9 (d, J = 4), 126.7, 127.5, 128.0 (d, J = 12), 129.7 (d, J = 13), 131.1, 132.4 (d, J = 10), 133.3, 134.3, 137.5 (d, J = 14), 149.6 (d, J = 7), 150.4 (d, J = 8), 170.3 (d, J = 12); IR (KBr) 1663 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_{192}H_{168}N_{18}O_{15}P_{10}S_4$: C, 67.71; H, 4.97; N, 7.40. Found: C, 67.62; H, 4.87; N, 7.01.

Reaction of Dendrimer 11-[G$_1$] with Aldehydes. To a solution of 0.211 mg (0.062 mmol) of dendrimer **11-[G$_1$]** in THF (10 mL) was added benzaldehyde (0.040 mL, 0.37 mmol) or crotonaldehyde (0.031 mL, 0.37 mmol). The resulting mixture was stirred overnight at room temperature (benzaldehyde) or for 1 week at 40 °C (crotonaldehyde). The solvent was evaporated under vacuum to give a yellow powder that was washed with 3 × 10 mL of THF/ether/pentane (1/2/2).

12-[G$_1$]: pale yellow powder; 66% yield (0.097 g); ^{31}P NMR δ 52.9, 62.2; ^{1}H NMR δ 3.32 (d, J = 14.1, 9H), 3.42 (s, 18H), 7.2−7.8 (m, 87H); ^{13}C NMR δ 27.3, 27.6, 32.4 (d, J = 12), 116.8, 117.0, 121.3 (d, J = 6), 121.7 (d, J = 6), 127.9, 128.1, 128.3, 128.4, 128.6, 131.9, 132.0, 137.5 (d, J = 12), 137.6, 139.2, 142.2, 142.5, 151.0 (d, J = 9), 151.3 (d, J = 7), 166.3, 167.0. IR (KBr) 1663 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_{126}H_{114}N_{18}O_{15}P_4S_4$: C, 63.79; H, 4.84; N, 10.63. Found: C, 63.52; H, 4.71; N, 10.49.

13-[G$_1$]: pale yellow powder; 63% yield (0.08 g); ^{31}P NMR δ 52.9, 62.2; ^{1}H NMR (400 MHz, ^{2}D) δ 1.80−1.90 (m, 12H, CH=CHCH_3), 3.30−3.40 (m, 27H, P_1NCH_3, C(O)NCH_3), 6.05 (m, (6 × 0.1)H, *cis*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 6.13 (dq, $^3J_{HaHb}$ = 15.1, $^3J_{HaCH3}$ = 6.6 (6 × 0.9)H, *trans*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 6.31 (m, (6 × 0.9)H, *trans*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 6.54 (m, (6 × 0.1)H, *cis*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 6.80 (d, $^3J_{HdHc}$ = 10.0, (6 × 0.1)H, *cis*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 7.12 (d, $^3J_{HdHc}$ = 15.0, (6 × 0.9)H, *trans*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 7.37 (dd, $^3J_{HcHd}$ = 15.0, $^3J_{HcH}$ = 10.1, (6 × 0.9)H, *trans*,*trans*-CH$_d$=CH$_c$CH$_b$=CH$_a$Me), 7.20−7.80 (m, 45H, CH=N, C_6H_4 and *cis*,*trans*-CH$_d$=CH$_c$-CH$_b$=CH$_a$Me); ^{13}C NMR δ 18.5, 27.4, 27.9, 32.9 (d, J = 13), 114.7, 117.8, 121.4 (d, J = 4), 121.6 (d, J = 5), 128.0, 128.3, 130.3, 130.4, 132.2, 137.1, 137.2 (d, J = 11), 138.2, 138.3, 142.7, 143.6, 151.0 (d, J = 7), 151.2 (d, J = 9), 166.6, 167.5; IR (KBr) 1663 cm^{-1} ($\nu_{C=O}$). Anal. Calcd for $C_{108}H_{114}N_{18}O_{15}P_4S_4$: C, 60.15; H, 5.33; N, 11.69. Found: C, 59.97; H, 5.27; N, 11.60.

General Procedure for the Synthesis of Phosphonate-Terminated Dendrimers 14-[G$_1$]−14-[G$_5$]. To 0.200 g of dendrimer **1-[G$_n$]** (n = 1, 0.140 mmol; n = 2, 0.058 mmol; n = 3, 0.027 mmol; n = 4, 0.013 mmol; n = 5, 0.0064 mmol) were added triethylamine (n = 1, 30 μL; n = 2, 50 μL; n = 3, 50 μL; n = 4, 140 μL; n = 5, 140 μL) and diethyl phosphite (the quantity necessary to dissolve **1-[G$_n$]:** n = 1, 0.6 mL, n = 2, 1.0 mL; n = 3, 1.0 mL; n = 4, 2.9 mL; n = 5, 2.9 mL). The mixture was stirred overnight at room temperature and then evaporated under vacuum to give an oil. Addition of ether/pentane precipitated this oil. The resulting powder was washed with acetonitrile.

14-[G$_1$]: white powder; 27% yield (0.085 g); ^{31}P NMR δ 21.3 (d, $^7J_{PP}$ = 3.9, P(O)), 51.8 (s, P_0), 62.0 (t, $^7J_{PP}$ = 3.9, P_1); ^{1}H NMR δ 1.20 (m, 36H), 3.30 (d, J = 10.3, 9H), 3.92 (m, 24H), 4.90 (s, 6H), 4.93 (d, J = 11.5, 6H), 7.15−7.73 (m, 39H); ^{13}C NMR δ 16.2 (d, J = 4), 32.7 (d, J = 13), 63.0 (d, J = 10), 63.2 (d, J = 8), 69.8 (d, J = 160), 121.0, 121.3, 128.2, 132.5, 133.8, 138.2 (d, J = 12), 150.0 (d, J = 7), 150.9 (d, J = 6); IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{90}H_{120}N_6O_{33}P_{10}S_4$: C, 48.00; H, 5.37; N, 3.73. Found: C, 47.81; H, 5.28; N, 3.61.

14-[G$_2$]: white powder; 19% yield (0.079 g); ^{31}P NMR (CH_2Cl_2) δ 20.8 (d, J = 4.0), 51.7, 61.4, 61.8 (t, J = 4.0); ^{1}H NMR (CD_3OD) δ 1.23 (m, 72H), 3.32 (d, J = 10.3, 27H), 3.98 (m, 48H), 5.04 (d, J = 13.0, 12H), 7.23−7.76 (m, 93H); ^{13}C NMR (CD_3OD) δ 17.3 (d, J = 3), 34.1 (d, J = 13), 64.7 (d, J = 7), 65.0 (d, J = 7), 71.0 (d, J = 165), 122.6, 123.3, 129.7, 130.2 (d, J = 4), 134.0, 136.3, 141.2 (d, J = 12), 151.3, 152.0 (d, J = 4); IR (KBr) 3272 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{204}H_{264}N_{18}O_{69}P_{22}S_{10}$: C, 48.32; H, 5.25; N, 4.97. Found: C, 48.27; H, 5.19; N, 4.85.

14-[G$_3$]: white powder; 18% yield (0.052 g); ^{31}P NMR (CH_2Cl_2) δ 21.2 (d, J = 3.8), 52.3, 62.2 (br s); ^{1}H NMR (CD_3OD) δ 1.21 (m, 144H), 3.22 (m, 63H), 4.00 (m, 96H), 5.03 (d, J = 12.6, 24H), 7.23−7.67 (m, 201H); ^{13}C NMR (CD_3OD) δ 17.3, 34.2 (d, J = 10), 64.7 (d, J = 8), 65.0 (d, J = 7), 71.0 (d, J = 166), 122.6, 123.2, 130.3 (m), 134.1, 136.3, 140.5 (m), 151.0, 152.1 (d, J = 4); IR (KBr) 3271 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{432}H_{552}N_{42}O_{141}P_{46}S_{22}$: C, 48.40; H, 5.19; N, 5.49. Found: C, 48.23; H, 5.11; N, 5.37.

14-[G$_4$]: white powder; 18% yield (0.052 g); ^{31}P NMR (CH_2Cl_2) δ 21.2 (d, J = 4.3), 62.2 (br s); ^{1}H NMR (CD_3OD): δ 1.21 (m, 288H), 3.26 (m, 135H), 4.00 (m, 192H), 5.03 (d, J = 12.7, 48H), 7.25−7.67 (m, 417H); ^{13}C NMR (CD_3OD) δ 17.3, 34.0 (m), 64.7 (d, J = 7), 65.0 (d, J = 7), 71.0 (d, J = 166), 122.6, 130.2, 133.7−134.0 (m), 136.3, 140.0−141.5 (m), 152.1 (d, J = 5); IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{888}H_{1128}N_{90}O_{285}P_{94}S_{46}$: C, 48.46; H, 5.16; N, 5.73. Found: C, 48.23; H, 5.03; N, 5.61.

14-[G$_5$]: white powder; 22% yield (0.059 g); ^{31}P NMR (CH_2Cl_2) δ 21.3 (d, J = 4.5), 62.4 (br s); ^{1}H NMR (CD_3OD) δ 1.20 (m, 576H), 3.25 (m, 279H), 4.05 (m, 384H), 5.03 (d, J = 13.2, 96H), 7.23−7.67 (m, 849H); ^{13}C NMR (CD_3OD) δ 17.3, 34.0 (m), 64.7 (d, J = 7), 65.0 (d, J = 7), 71.0 (d, J = 166), 122.6, 130.2, 133.8−134.1 (m), 136.3, 140.0−141.0 (m), 151.0, 152.1; IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{1800}H_{2280}N_{186}O_{573}P_{190}S_{94}$: C, 48.48; H, 5.15; N, 5.84. Found: C, 48.51; H, 5.09; N, 5.78.

General Procedure for the Synthesis of Phosphonate-Terminated Dendrimers 15-[G$_1$] and 15-[G$_5$]. To 0.200 g of dendrimer **1-[G$_n$]** (n = 1, 0.140 mmol; n = 5, 0.0064 mmol) were added dilauryl phosphite (n = 1, 0.775 mL, 1.68 mmol; n = 5, 0.682 mL, 1.5 mmol) and then triethylamine (n = 1, 20 μL; n = 5, 100 μL). The resulting mixture was stirred for 3 days at room temperature (for **15-[G$_1$]**) or for 5 days at room temperature then for 2 days at 45 °C (for **15-[G$_5$]**). Evaporation under vacuum gave an oil that was washed several times with acetonitrile to give a white powder.

15-[G$_1$]: white powder; 16% yield (0.089 g); ^{31}P NMR δ 21.2 (d, J = 3.8), 51.8, 62.2 (t, ^7J = 3.8); ^{1}H NMR δ 0.85 (t, J = 5.0, 36H), 1.22 (br s, 216 H), 1.40−1.55 (m, 24H), 3.30 (d, J = 9.8,

9H), 3.80−3.95 (m, 24H), 4.60 (br s, 6H), 4.95 (d, J = 6.5, 6H), 7.16−7.74 (m, 39H); ^{13}C NMR δ 13.9, 22.5, 25.2, 28.9, 29.2, 29.4, 29.5, 30.3, 30.4, 31.7, 32.9 (d, J = 12), 66.9 (d, J = 8), 67.2 (d, J = 7), 70.0 (d, J = 159), 121.0, 121.4, 128.2, 132.5, 133.7, 137.9, 150.0, 151.0 (d, J = 9); IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{210}H_{360}N_6O_{33}P_{10}S_4$: C, 64.10; H, 9.22; N, 2.14. Found: C, 64.25; H, 9.34; N, 2.07.

15-[G$_5$]: white powder; 27% yield (0.123 g); ^{31}P NMR δ 21.3, 62.6 (m); ^{1}H NMR δ 0.84 (br s, 576H), 1.21 (br s, 3456H), 1.50 (br s, 384H), 2.87 (br s, 96H), 3.27 (br s, 279H), 3.90 (br s, 384H), 4.95 (br s, 96H), 7.17−7.65 (m, 849H); ^{13}C NMR δ 13.9, 22.5, 25.2, 28.9, 29.2, 29.5, 30.3, 31.7, 32.5 (m), 66.5 (d, J = 7), 67.1 (d, J = 7), 71.3, 121.0, 121.7, 128.1, 132.0, 133.9, 137.6−139.4 (m), 149.9 (d, J = 7), 151.2 (d, J = 7); IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{3720}H_{6120}N_{186}O_{573}P_{190}S_{94}$: C, 62.47; H, 8.62; N, 3.64. Found: C, 62.73; H, 8.80; N, 3.52.

Synthesis of Dendrimer 16-[G$_1$]. To 0.300 g (0.33 mmol) of (S)P[OC$_6$H$_4$CH=NN(Me)P(S)Cl$_2$]$_3$[2] in THF (30 mL) was added 0.420 g (2.27 mmol) of 4-hydroxy-3-methoxycinnamaldehyde sodium salt. The resulting mixture was stirred for 5 days at 40 °C and then centrifuged. The solution was evaporated to dryness to give a powder that was washed twice with pentane/ether (1/1).

16-[G$_1$]: yellow powder; 48% yield (0.278 g); ^{31}P NMR δ 52.7, 62.0; ^{1}H NMR δ 3.40 (d, J = 9.9, 9H), 3.73 (s, 18H), 6.51 (dd, J = 16.0, 7.0, 6H), 7.00−7.34 (m, 33H), 7.55 (d, J = 16.0, 6H), 9.54 (d, J = 7.0, 6H); ^{13}C NMR δ 32.5 (d, J = 12), 55.9, 111.7, 121.1, 121.5, 122.3, 128.2, 131.7, 132.6, 137.9 (d, J = 15), 142.3 (d, J = 8), 150.6 (d, J = 8), 151.3 (d, J = 6), 151.9, 193.4; IR (KBr) 1677 cm^{-1} (ν_{CHO}). Anal. Calcd for $C_{84}H_{78}N_6O_{21}P_4S_4$: C, 57.33; H, 4.47; N, 4.78. Found: C, 57.18; H, 5.48; N, 4.71.

Synthesis of Phosphonate-Terminated Dendrimer 17-[G$_1$]. To 0.280 g (0.160 mmol) of dendrimer **16-[G$_1$]** were added triethylamine (30 μL) and diethyl phosphite (the quantity necessary to dissolve **16-[G$_1$]**: 0.5 mL). The mixture was stirred overnight at room temperature and then evaporated under vacuum to give an oil that was washed with acetonitrile to give a powder.

17-[G$_1$]: yellow powder; 18% yield (0.074 g); ^{31}P NMR δ 21.3, 52.3, 62.1; ^{1}H NMR δ 1.28 (m, 36H), 2.62 (br s, 6H), 3.40 (d, J = 10.0, 9H), 3.75 (s, 18H), 4.13 (m, 24H), 4.61 (dd, J = 13.4, 5.0, 6H), 6.21 (d, J = 15.7, 6H), 6.67 (dd, J = 15.7, 5.0, 6H), 6.86−7.67 (m, 33H, C$_6$H$_4$); ^{13}C NMR δ 16.5 (d, J = 6), 32.7 (d, J = 12), 56.0, 63.2 (d, J = 6), 69.3 (d, J = 162), 110.7, 119.1, 121.3, 122.2, 124.1, 128.3, 133.0, 134.3, 137.4 (d, J = 16), 139.9, 150.8 (d, J = 8), 151.2, (d, J = 6); IR (KBr) 3270 cm^{-1} (ν_{OH}). Anal. Calcd for $C_{108}H_{144}N_6O_{39}P_{10}S_4$: C, 50.12; H, 5.61; N, 3.25. Found: C, 50.01; H, 5.49; N. 3.21.

General Procedure for the Synthesis of Imine-Terminated Dendrimers 18-[G$_1$] and 18-[G$_5$]. To a solution of 0.250 g of **1-[G$_n$]** (***n*** = 1, 0.176 mmol; ***n*** = 5, 0.008 mmol) in THF (10 mL) was added propylamine (***n*** = 1, 0.180 mL, 2.112 mmol; ***n*** = 5, 0.130 mL, 1.530 mmol) in the presence of molecular sieves (4 Å). The mixture was stirred at room temperature for 24 h and then filtered and evaporated to dryness. The resulting powder was washed with ether.

18-[G$_1$]: white powder; 61% yield (0.179 g); ^{31}P NMR δ 52.4, 61.9; ^{1}H NMR δ 0.90 (t, J = 6.7, 18H), 1.67 (m, 12H), 3.35 (d, J = 10, 9H), 3.51 (m, 12H), 7.26−7.70 (m, 39H), 8.20 (s, 6H); ^{13}C NMR δ 11.7, 23.8, 32.9 (d, J = 14), 63.2, 121.4, (d, J = 4), 128.3, 129.2, 132.4, 133.5, 138.4 (d, J = 14), 151.0 (d, J = 7), 152.0 (d, J = 9), 159.3; IR (KBr) 1647 cm^{-1} ($\nu_{C=N}$). Anal. Calcd for $C_{84}H_{96}N_{12}O_9P_4S_4$: C, 60.42; H, 5.79; N, 10.06. Found: C, 60.31; H, 5.67; N, 9.95.

18-[G$_5$]: white powder; 46% yield (0.130 g); ^{31}P NMR δ 61.9, 62.5; ^{1}H NMR δ 0.86 (br s, 288H), 1.61 (br s, 192H), 3.28 (br s, 279H), 3.47 (br s, 192H), 7.21−7.65 (m, 849H), 8.15 (s, 96H); ^{13}C NMR δ 11.7, 23.8, 32.8 (m), 63.2, 121.4 (d, J = 4), 121.7, 128.1, 129.1, 131.9, 133.5, 138−139 (m), 151.2 (d, J = 5), 151.9 (d, J = 6), 159.3; IR (KBr) 1647 cm^{-1} ($\nu_{C=N}$). Anal. Calcd for $C_{1704}H_{1896}N_{282}O_{189}P_{94}S_{94}$: C, 58.01; H, 5.42; N, 11.20. Found: C, 57.88; H, 5.33; N, 11.06.

General Procedure for the Synthesis of Phosphonate-Terminated Dendrimers 19-[G$_1$] and 19-[G$_5$]. To 0.130 g of dendrimer **18-[G$_n$]** (***n*** = 1, 0.078 mmol; ***n*** = 5, 0.0037 mmol) was added diethyl phosphite (the quantity necessary to dissolve **18-[G$_n$]**: ***n*** = 1, 0.6 mL; ***n*** = 5, 2.0 mL) and then triethylamine (***n*** = 1, 30 μL; ***n*** = 5, 150 μL). This mixture was stirred overnight at room temperature and then evaporated to dryness. Dendrimer **19-[G$_1$]** was purified by extraction with pentane/toluene. Dendrimer **19-[G$_5$]** was purified by washings with pentane, ether, and then acetonitrile.

19-[G$_1$]: white powder; 11% yield (0.022 g); ^{31}P NMR δ 23.5 (d, J= 4.5), 52.6, 62.5 (t, J = 4.5); ^{1}H NMR δ 0.83 (t, J = 7.3, 18H), 1.08 (t, J = 7.0, 18H), 1.21 (t, J = 7.0, 18H), 1.40 (m, 12H), 2.11 (s, 6H), 2.41 (m, 12H), 3.34 (d, J = 10.4, 9H), 3.70−4.08 (m, 30H), 7.15−7.77 (m, 39H); ^{13}C NMR δ 11.5, 16.1 (d, J = 7), 16.2 (d, J = 6), 22.7, 32.8, (d, J = 13), 49.7 (d, J = 16), 60.2 (d, J = 153), 62.6 (d, J = 7), 62.8 (d, J = 8), 121.1 (d, J = 3), 121.4, 128.2, 129.4 (d, J = 6), 132.5, 133.0 (d, J = 4), 138.2 (d, J = 15), 149.9 (d, J = 7), 150.9 (d, J = 8); IR (KBr) 3300 cm^{-1} (ν_{NH}). Anal. Calcd for $C_{108}H_{162}N_{12}O_{27}P_{10}S_4$: C, 51.92; H, 6.53; N, 6.73. Found: C, 51.80; H, 6.50; N, 6.62.

19-[G$_5$]: white powder; 24% yield (0.043 g); ^{31}P NMR δ 22.9 (d, J = 4.5), 62.1; ^{1}H NMR δ 0.77 (br s, 288H), 1.03 (br s, 288H), 1.18 (br s, 288H), 1.45 (br s, 192H), 2.3−2.4 (m, 288H), 3.30 (br s, 279H), 3.85−4.00 (m, 480H), 7.15−7.65 (m, 849H); ^{13}C NMR δ 11.4, 16.0 (d, J = 5), 16.2 (d, J = 5), 21.2−22.0 (m), 32.6−33.0 (m), 49.3−49.5 (m), 59.5 (d, J = 160), 62.9 (m), 121.2−121.6 (m), 128.0, 129.7, 131.5−131.9 (m), 138.1−139.1 (m), 150.1−150.3 (m), 151.1; IR (KBr) 3300 cm^{-1} (ν_{NH}). Anal. Calcd for $C_{2088}H_{2952}N_{282}O_{477}P_{190}S_{94}$: C, 51.67; H, 6.13; N, 8.14. Found: C, 51.32; H, 6.05; N, 8.06.

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