3282 J. Am. Chem. Soc. 1995, 117, 3282−3283

Synthesis and Reactivity of Unusual Phosphorus Dendrimers. A Useful Divergent Growth Approach Up to the Seventh Generation

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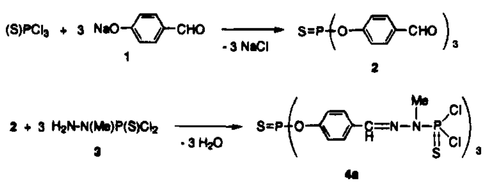
Received September 9, 1994

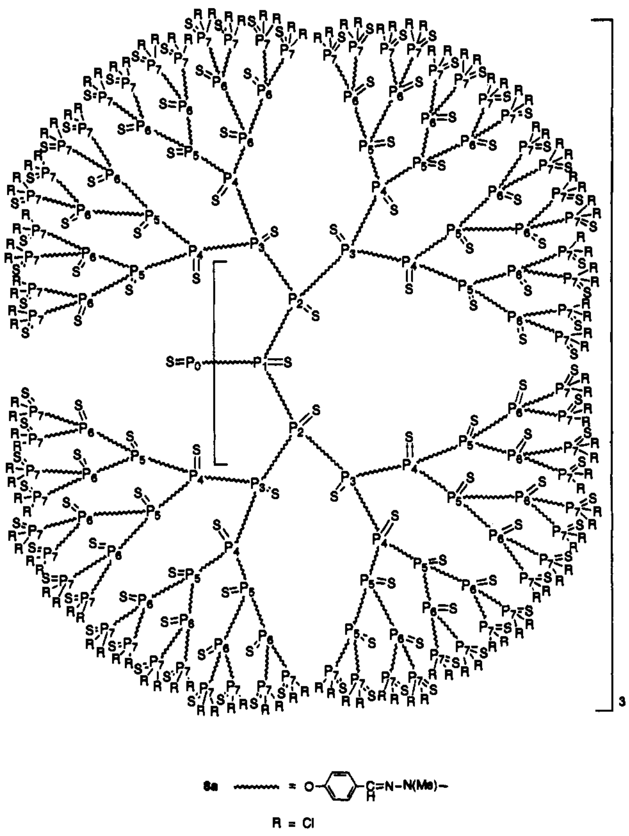
Considerable interest has focused on the preparation as well as the physical and chemical properties of dendrimers, the most highly branched three-dimensional structures known.[1] Among these multifunctionalized polymers, a few incorporate main group elements.[2] Neutral phosphorus-containing dendrimers prepared by our divergent growth method[3] up to the fourth generation possess 46 pentavalent phosphorus atoms and 48 terminal functions [aldehydic groups or phosphorus−chlorine bonds (MW 11 268 or 15 381)]. This background led us to explore the scope and limitation of this process and to study the effect of the molecular architecture of these species on the chemical reactivity of the chain ends.

We now report the synthesis of phosphorus dendrimers elaborated to the fifth, sixth, and seventh generations possessing up to 384 functional groups (MW 94 146). A preliminary study of the chemical properties of dendrimers of the first, second, third, and fourth generations allows incorporation of new terminal functions such as α,β unsaturated ketones, alcohols, allylic groups, or crown ethers.

Our first goal was to determine at which point steric congestion or loss of solubility prevents further growth of the dendrimer. Dendrimers were obtained by careful stepwise growth of successive phosphorus-containing layers. The synthesis of each generation required two steps: addition of the sodium salt of 4−hydroxybenzaldehyde (**1**) to halogenated phosphane sulfide, followed by treatment of the resulting polyaldehyde with dichloro(methylhydrazino)phosphate sulfide (**3**) (Scheme 1). The construction of each generation was followed by ^{31}P NMR. This supports hypotheses on dendrimer branch cell hierarchy.[4] Until the fourth generation, no overlapping of ^{31}P chemical shifts were observed. Partial overlapping occurred for dendrimers of the fifth (compounds **6a,b**), sixth (compounds **7a,b**), and seventh (compound **8a**) generations. Nevertheless, a significant deshielding effect for the terminal P_n phosphorus atoms was always observed when moving from P_n-Cl groups to $P_n-OC_6H_4CHO$ groups ($\Delta\delta \approx 2.5$ ppm). Remarkably, the resonance of the phosphorus atom of the core was detected up to the sixth generation.[5] Note that the use of an excess of sodium salt **1** or an excess of **3** in each step (easily eliminated during workup) prevented partial substitution. None of the ^1H and ^{13}C NMR spectra of compounds **6a**, **7a**, and **8a** exhibited any signal that could be attributed to unreacted carbonyl functions. All these observations are consistent with full substitution of chain ends.[6]

Scheme 1





Dendrimers **6a,b** and **7a,b** are stable, not sensitive to hydrolysis, and highly soluble in a variety of organic solvents (e.g., chloroform and THF). Therefore, our approach allowed the preparation of the first functionalized dendrimer containing 382 phosphorus atoms!

Having in hand a large number of dendrimers, we focused our attention on the reactivity of such systems. For example, the dendrimer of the fourth generation **5b** (terminal aldehyde functions) was reacted with three different reagents: acetyl methylene triphenylphosphorane (**9**), piperazine (**10**), or 4-aminobenzo-15 crown-5 (**11**). The Wittig reaction with **9** easily took place, leading to the arborol **12** possessing 48 terminal α,β unsaturated ketones. Schiff base formation occurred with piperazine, affording the corresponding arborol **13** with terminal alcohol functions, while treatment of **5b** with the crown ether **11** gave rise to the dendrimer **14** possessing 48 crown ether

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[2] (a) Rebrov, E. A.; Muzafarov, A. M.; Papkov, V. S.; Zhdanov, A. A. *Dokl. Akad. Nauk SSSR* **1989**, *309*, 376. (b) Rengan, K.; Engel, R. *J. Chem. Soc., Chem. Commun.* **1990**, 1084. (c) Uchida, H.; Kabe, Y.; Yoshino, K.; Kawamata, A.; Tsumuraya, T.; Masamune, S. *J. Am. Chem. Soc.* **1990**, *112*, 7077. (d) Mathias, L. J.; Carothers, T. W. *J. Am. Chem. Soc.* **1991**, *113*, 4043. (e) Rengan, K.; Engel, R. *J. Chem. Soc., Perkin Trans. 1* **1991**, 987. (f) Roovers, J.; Toporowski, P. M.; Zhou, L. L. *Polym. Prepr. Am. Chem. Soc. Div. Polym. Chem.* **1992**, *33*, 182. (g) van der Made, A. W.; van Leeuwen, P. W. N. M. *J. Chem. Soc., Chem. Commun.* **1993**, 1400. (h) Engel, R.; Rengan, K.; Chan, C. S. *Phosphorus, Sulfur Silicon* **1993**, *77*, 221. (i) Zhou, L. L.; Roovers, J. *Macromolecules* **1993**, *26*, 963. (j) Roovers, J.; Zhou, L. L.; Toporowski, P. M.; van der Zwan, M.; Iatrou, H.; Hadsichristidis, N. *Macromolecules* **1993**, *26*, 4324. (k) Hudson, R. H. E.; Damha, M. J. *J. Am. Chem. Soc.* **1993**, *115*, 2119. (l) Seyferth, D.; Son, D. Y. *Organometallics* **1994**, *13*, 2682.

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[5] The resonance of the phosphorus atom of the core being detected up to the sixth generation, even *one* uncompleted substitution or condensation reaction should be detected without any doubt by ^{31}P NMR.

[6] For the seventh generation, even under the best conditions, structure defects cannot be totally ruled out[10] in the limit of NMR precision (3%).

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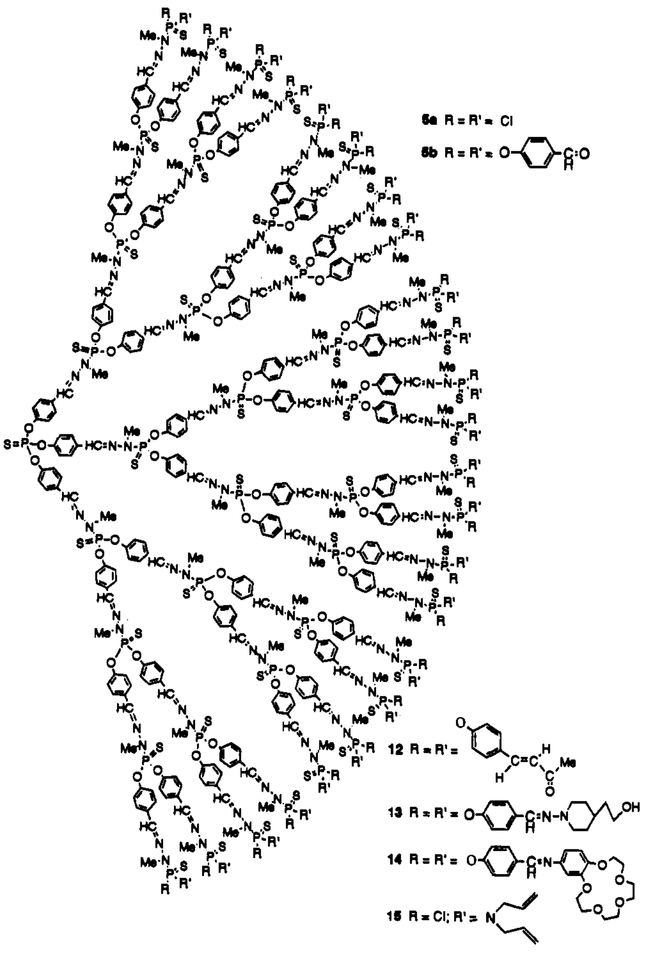
units at the periphery. Remarkably, terminal crown ethers in **14** acted as shields against hydrolysis of imine functions: no hydrolysis was observed after stirring a THF/water (80/20) solution of **14** for 48 h at room temperature. It can be noted that dendrimers of the first, second, and third generations reacted similarly with **9** and **10**; no difference of reactivity was observed.[7] These preliminary reactions illustrate how useful these phosphorus-containing dendrimers are for the preparation of highly unusual three-dimensional structures with a variety of terminal groups.



In order to learn more about the scope of the reactivity of the corresponding P—Cl dendrimer **5a**, we reacted this derivative (1 equiv) with a large excess of bisallylamine (72 equiv) in the presence of triethylamine (72 equiv). The reaction proceeded smoothly at room temperature for 1 week, exclusively affording dendrimer **15** through the monosubstitution of the PCl_2 moieties![8] To our knowledge, only one type of dendrimer with two different functions at the chain ends has been reported.[9]

In conclusion, the usefulness of a quantitative method of formation of neutral phosphorus-containing dendrimers up to the seventh generation was fully demonstrated. Chain end functionality remained highly reactive and allowed the preparation of dendrimers possessing α,β unsaturated ketones, crown ethers, or both P—Cl bonds and allyl groups at the periphery. These preliminary results augur well for a general application of this chemistry in the still unknown different tri- or tetrafunctionalization of dendrimers.

Acknowledgment. Thanks are due to the CNRS for financial support.

Supplementary Material Available: Full experimental details, spectral data, and elemental analyses for products **6a,b**, **7a,b**, **8a**, **12**, **13**, **14**, and **15** (5 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA942992C

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(8) Such a monosubstitution was observed with dendrimers of the first, second, and third generations.

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