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Solvatochromism as a Probe of the Microenvironment in Dendritic Polyethers: Transition from an Extended to a Globular Structure

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The influence of small changes in the polarity of the medium on the absorption spectra of solvatochromic molecules has found broad application. Solvatochromic probes have been used to study the polarity of pure and mixed solvents,[1] micelle/solution interfaces,[2] microemulsion and phospholipid bilayers,[3] and the retention behavior in reverse-phase liquid chromatography.[4] However, the application of solvatochromism to the study of polymeric materials has been limited.[5] The preparation of dendritic macromolecules has been studied extensively,[6,7] but their microstructure and overall shape have remained controversial.[8] This study utilizes the attachment of a solvatochromic probe to the "focal point" or "core" of a polyether dendrimer to establish the nature of the probe microenvironment in dendritic molecules of varying sizes.

The choice of chromophore was governed by synthetic considerations and the magnitude of the solvatochromic effect. One of the most widely studied[9] solvatochromic molecules is 4-(*N*,*N*-dimethylamino)-1-nitrobenzene (**1**), which has a solvatochromic absorption range of 65 nm. The presence of a reactive benzylic group at the focal point of the polyether dendrimers facilitated the incorporation of this chromophore through alkylation of the commercially available 4-(*N*-methylamino)-1-nitrobenzene (**2**). However, under standard conditions in a variety of solvents[10] and in the presence of different bases,[11] reaction of **2** with the fifth generation bromide [G-5]-Br **3** was found to give very low yields of the desired alkylated product **4**, contaminated by side products. To overcome this, the anion of **2** was formed by reaction with sodium hydride. Reaction of the anion with **3** in tetrahydrofuran heated at reflux was found to proceed smoothly to give the desired product **4** in 81% yield (Scheme I). Purification of **4** was by flash chromatography due to significant R_f difference between **3** and **4**. For the lower generation bromides, generations 0–4, the reaction could be performed at room temperature with the yield of purified product being above 90%, decreasing to 81% for generation 5 and to 72% for generation 6. Purification was by flash chromatography in all cases.

The purity and structure of all products were determined by standard spectroscopic and chromatographic techniques as described previously.[12] The unique resonances of the *N*-methylamino-*p*-nitrobenzene chromophore in both the ^{1}H and ^{13}C NMR spectra were observed and quantified.

The dendritic molecules from generations 0–6 which contain the solvatochromic chromophore at the focal point were then investigated by UV–vis analysis in a variety of solvents ranging in polarity from CCl_4 to dimethyl sulfoxide (DMSO). The absorption maxima for the solvatochromic chromophore are listed in Table I. As expected, the model compound 4-(*N*-benzyl-*N*-methylamino)-1-nitrobenzene (G = 0) (**5**) behaves similarly to 4-*N*,*N*-dimethylamino-1-nitrobenzene[9] and gives a variation in its UV absorption maximum from 366 nm in CCl_4 to 404 nm in DMSO. As the molecular weight and size of the dendritic macromolecule increases, the absorption maximum in CCl_4 undergoes a bathochromic shift to a value of 383 nm for [G-6]-N(Me)-Ph-NO_2 (**6**). A plot of λ_{max} *vs* generation number[13] (Figure 1) shows a noticeable discontinuity on going from generation 3 to generation 4. These observations confirm that the influence of the repeating units of the dendrimer on the microenvironment of the chromophore becomes more pronounced as the size of the dendrimer increases. In effect, the chromophore becomes less and less influenced by the CCl_4 solvent, and the increased polarity of the medium in its immediate vicinity is due to the higher concentration of aromatic polyether moieties that form a shell around it. We believe that the discontinuity in λ_{max} observed in the progression from third to fourth generation dendrimers corresponds to the onset of the transition from extended to globular structure as the steric requirements of the dendritic branches increase. The same pattern of discontinuous solvatochromic behavior is also observed for other relatively nonpolar solvents such as toluene and dichloromethane but not for very polar solvents such as DMSO. This finding correlates well with that of a previous study on the same polyether dendrimers without the chromophore at their focal points. In this earlier study, the variation of intrinsic viscosity with generation number[14] was shown to undergo a transition at the fourth generation. While the intrinsic viscosity of low-generation dendrimers increases with molecular weight, a behavior that is commonly observed for linear polymers, a decrease in viscosity is observed for higher generation dendrimers as a globular shape prevails due to increased steric constraints. An analogous transition has been observed for a family of carboxylate-terminated starburst dendrimers[15] for which photoinduced electron-transfer measurements demonstrate that a structural change occurs between generations 3 and 4. This type of shape transition has also been predicted on the basis of theoretical calculations and molecular modeling.[16]

When the difference in λ_{max} between generation 6 and generation 0 ($\Delta\lambda_{max}$) was evaluated, a decrease in $\Delta\lambda_{max}$ was observed with an increase in the solvent polarity. This is illustrated in Figure 2 where $\Delta\lambda_{max}$ is plotted *vs* the solvent polarizability parameter[17] π^*. A relatively straight line is obtained which intersects the *x*-axis at a value of π^* near 0.95. Since the environment of the chromophore may be considered to be a binary mixture of the dendrimer and a solvent, increasing the dendrimer size results in an enhancement of the effect of its building blocks on the chromophore, especially as the globular shape is achieved.

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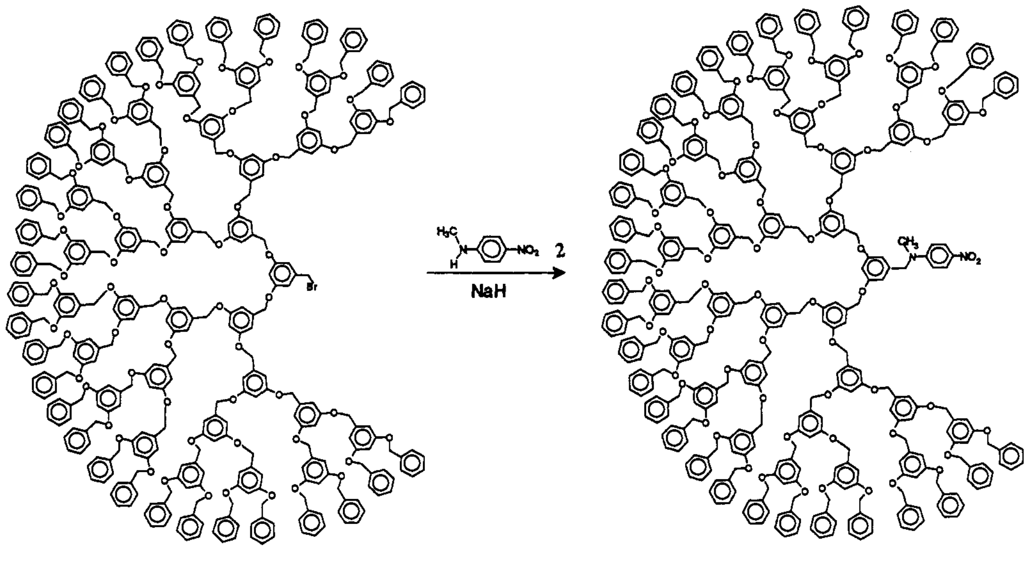
Scheme I



[G-5]-Br 3

[G-5]-N(Me)-Ph-NO$_2$ 4

Table I. λ_{max} (nm) Data for Dendritic Molecules Containing the Solvatochromic Unit at the Focal Point in Various Solvents

	generation number [G-X]-N(Me)-Ph·NO$_2$						
solvent	0	1	2	3	4	5	6
CCl$_4$	366	367	369.5	372	378.5	381	383
toluene	374.5	375	377.5	379.5	384	385.5	387
benzene	379	380	381	382	386	387.5	388.5
acetone	387.5	388	388.5	389	391.5	392.5	392.5
CH$_2$Cl$_2$	388.5	389.5	389.5	390	391.5	391.5	392.5
DMF	395.5	395.5	396	396	398.5	399	399
DMSO	403	402.5	403	402.5	403	403	404

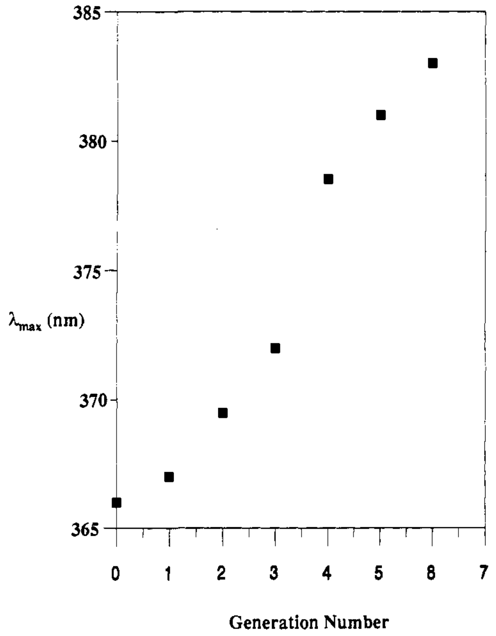


Figure 1. Plot of λ_{max} (nm) *vs* generation number with CCl$_4$ as solvent.

At the x-intercept, $\Delta\lambda_{max} = 0$, there is little difference between the medium effect of the dendrimer and the solvent. Therefore the value at the intercept is a measure of the π^* of the local microenvironment. A value of 0.95 implies that the local polarizability parameter of the dendrimer near the chromophore is very high, comparable to that of highly polar solvents such as DMF. However, it is well known[5] that polymers always appear to be more polar than small molecules of analogous structure.

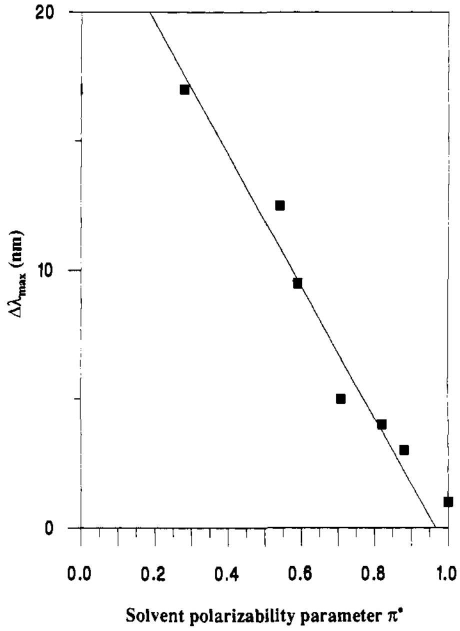


Figure 2. Plot of $\Delta\lambda_{max}$ (nm) *vs* solvent polarizability parameter π^*.

In conclusion, we have demonstrated the preparation of a series of dendritic molecules of defined molecular weight and size containing a solvatochromic chromophore at their focal point. For solvents of low polarity, a dramatic change in the absorption maximum was observed on going from generation 3 to generation 4; this correlates with a transition in shape of the dendritic macromolecule from an extended to a more globular structure. Examination of the variation in absorption maximum with changes in solvent polarity showed that the microenvironment near the chromophore had a high polarity especially as the dendrimer adopted a globular shape at generation 4 and above. We are currently extending the concept of clefts with defined polarity to dendritic macromolecules, for example with the synthesis of dendritic catalysts where the catalytic group is placed at the focal point. The use of a covalently bound solvatochromic probe to investigate the microenvironment of both linear polymer chains and 3-dimensional network polymers is also being actively studied.

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