Effect of Solvent Quality on the Molecular Dimensions of PAMAM Dendrimers

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ABSTRACT: The average dimensions of poly(amido amine) (PAMAM) dendrimers of generations G5 and G8 are studied by small-angle neutron scattering (SANS) as a function of solvents of differing quality, the composition of mixtures of a good solvent and a nonsolvent, and temperature. The radius of gyration, $R_{\rm g}$, of the G8 dendrimer decreases for the series of solvents D(CD₂)_mOD (with m = 0, 1, 2, 4) by approximately 10% from m = 0 to m = 4 with decreasing solvent quality. The average segment density in solution is calculated for G5 and G8. The size of PAMAM dendrimers, as reflected by $R_{\rm g}$, is not influenced by the composition of mixtures of methyl alcohol/acetone in the full range of solubility of the dendrimers. In the temperature range -10 °C $\leq T \leq 50$ °C, the dimensions of the G8 and G5 dendrimer are constant, within \approx 5% of each other.

Introduction

Dendrimers are highly branched macromolecules that consist of a central core, regularly branched building blocks, and a large number of terminal groups.¹ Dendritic structures can be formed through either a divergent or a convergent approach, both of which lead to a similar topology. A wide variety of synthetic methods have led to a multitude of chemical structures available in dendrimers.

Poly(amido amine) (PAMAM) dendrimers were among the first successfully synthesized dendritic structures.² Starting with ammonia as a trifunctional core, the addition of methyl acrylate followed by amidation with ethylenediamine (EDA) leads to a zero-generation (G0) dendrimer. The repetition of these two steps results in higher generations. With every new generation, the dendrimer doubles the number of terminal groups and also approximately doubles the molecular weight. The mass of a dendrimer increases as 2^{G} while the volume available for the units only increases as G^3 . The local density, which is a ratio of mass to volume, diverges with generation. Therefore, a maximum generation exists, beyond which a perfect growth of the dendrimer can no longer be achieved.3 This so-called "starburst limit" was predicted theoretically, and was later observed experimentally for different families of dendrimers.1

Dendrimers can obtain high molecular masses, placing them in the class of true macromolecules. Also, the chemical repeat units of dendrimers can resemble monomers of linear polymers. But apart from these obvious similarities, dendritic structures appear to be distinctly different from linear polymers. Features that are unique to dendrimers are the high branching density, the regular structure with practically no defects, and the high number of terminal units. In many ways, dendrimers are more closely related to star polymers with a high number of arms than to linear polymers.⁴ Being spherical and having a narrow size distribution, higher generation PAMAM dendrimers exhibit a welldefined geometry.^{5–8} The internal segment density is significantly higher than the density of linear polymers. Also, the radial segment distribution in the interior of a dendrimer appears to differ from the one of linear chains. The uniformity and spherical shape of dendrimers are unique in the size range of dendrimers, which typically have a diameter in the range 1-15 nm. This makes them excellent candidates for the use as size calibration standards. Particles in this size range can be used as a cross-reference for techniques such as small-angle X-ray and neutron scattering (SAXS and SANS), size exclusion chromatography and transmission electron microscopy, and reflectivity.

However, there are indications in the literature that the size of dendrimers is largely influenced by the solvent quality. A molecular dynamics study by Murat and Grest resulted in an increasing internal segment density of dendrimers when the dendrimer–solvent interactions are less favorable, which leads to a considerable decrease of the average dimensions of the simulated structures.⁹ On the basis of a holographic relaxation spectroscopy study, Stechemesser and Eimer concluded that the radius of higher generation PAMAM dendrimers would be extremely sensitive to solvent conditions.¹⁰ The effect of solvent quality on the dimensions of linear chains has been studied for many years, and chain dimensions can change a large amount, especially at high molecular mass.¹¹

We report the results of a SANS study with G5 and G8 PAMAM dendrimers in different solvents and in mixtures of methyl alcohol and acetone, which are good solvents and nonsolvents for PAMAM dendrimers, respectively. The average dendrimer dimensions are determined from the scattering data to measure the effects of solvent quality and solvent composition. After summarizing the experimental procedures, we report the effect of solvent on the size of G8 dendrimers in dilute solution for the series of solvents $D(CD_2)_mOD$ (with m = 0, 1, 2, 4). R_g measurements for dilute solutions of G5 and G8 dendrimers in solvent mixtures

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at temperatures in the range -10 °C $\leq T \leq 50$ °C are then given.

Experimental Section

Dendrimer Solutions. Poly(amido amine) (PAMAM) dendrimers, synthesized according to reported methods, were received from Dendritech (Midland, MI).^{2,12,13} The generation 5 (G5) dendrimer was shipped as an aqueous solution and the generation 8 (G8) dendrimer as a solution in methyl alcohol; both solutions contained a mass fraction of $x \approx 0.20$ dendrimer (x in g/g). Appropriate amounts of the solution of G5 were transferred to glass containers, and the solvent was thoroughly evaporated in a vacuum. The dried dendrimer was weighed and dissolved with the amount of solvent required to give a known mass fraction of dendrimer, x. The G8 dendrimer was diluted with four equal volumes of deionized water (NANOpure Series 550, conductivity $\leq 18 \text{ M}\Omega \text{ cm}^{-1}$; Barnstead, IA) and freeze-dried. The fluffy white material was dissolved in deionized water and extensively dialyzed in a molecular porous membrane tubing (SPECTRA/POR, MWCO = 3500; Spectrum Medical Ind., CA) against deionized water to eliminate traces of salts and other impurities. The dialyzed solution was freezedried, and the resulting material was kept in an inert atmosphere to avoid the adsorption of moisture by the hygroscopic dendrimers. The G8 dendrimers were dissolved in the required amount and type of solvent just prior to the SANS experiment.

All deuterated solvents were used as received from the Aldrich Chemical Corp. The molar dendrimer concentration of the solutions is calculated based on the solvent density, ρ , as given by the manufacturer, (ρ (DOD) = 1.107 g cm⁻³; ρ (D(CD₂)OD) = 0.888 g cm⁻³; ρ (D(CD₂)₂OD) = 0.888 g cm⁻³; ρ (D(CD₂)₄OD) = 0.920 g cm⁻³; ρ (CD₃COCD₃) = 0.872 g cm⁻³).¹⁴ For the experiments with solvent mixtures, the solvents were mixed and weighed, resulting in a known composition of the solvent. This was then used to dissolve the dry dendrimer. In all cases, the dendrimer solution was stirred thoroughly for 1 h to ensure complete dissolution and transferred to quartz cells for the SANS experiments.

Small-Angle Neutron Scattering. The SANS experiments were performed at the 8 m facility at the National Institute of Standards and Technology Center for Cold Neutron Research (Gaithersburg, MD).^{15,16} During the experiments, the temperature was controlled by a circulating bath that has a nominal temperature stability of $\Delta T = \pm 0.1$ °C. When required, the sample chamber was sealed and flushed with a constant stream of nitrogen, to avoid the condensation of moisture on the windows and the scattering cells. A sample to detector distance of 360 cm was maintained throughout the study, operating at a wavelength $\lambda = 9$ Å, with a wavelength spread of $\Delta \lambda / \lambda = 0.25$. The number of counts was corrected for detector efficiency, background scattering, and empty cell for each pixel of the two-dimensional detector plane. Absolute scattering intensities were calculated by use of a H₂O standard and the experimental transmission values. Circular averaging the twodimensional data sets of the absolute intensities results in the values of the absolute scattering intensity as a function of the scattering vector q (with $q = (4\pi/\lambda) \sin(\theta/2)$, θ being the scattering angle). The data processing was carried out on a μ VAX 4000 computer with the software provided by the Center for Neutron Research at NIST.¹⁷ Based on the hydrogen content of the materials, an estimate for the incoherent scattering was subtracted from the values of the absolute solution scattering intensity, to give the final form of the experimental data, which is the absolute intensity of the coherent scattering, I, as a function of q.

Results and Discussion

Pure Solvents. SANS experiments were performed with solutions of generation 8 (G8) PAMAM dendrimer in D₂O, methyl- d_4 , ethyl- d_6 , and *n*-butyl- d_{10} alcohol at a temperature of T = 20.0 °C. A series of four different concentrations of G8 in water were measured, to study



Figure 1. Values of the apparent radius of gyration, $R_{\rm g.app}$, of G8 dendrimer in D₂O, as calculated from SANS, plotted versus the molar dendrimer concentration, *c*. The solid line corresponds to the result of a weighted linear least-squares fit to the data, represented by the open circles, and the filled symbol is the result of this linear extrapolation.

the effect of concentration on the experimental value for the radius of gyration of the dendrimer, covering the range of molar concentration of dendrimer, *c*, of 0.233 $\times 10^{-5}$ mol dm⁻³ $\leq c \leq 6.00 \times 10^{-5}$ mol dm⁻³. Here, the molar dendrimer concentration, *c*, was calculated using the dendrimer theoretical molecular mass of 233 383 g mol⁻¹ and the density of the solvent. To evaluate the effect of solvent quality on the dendrimer size, the scattering functions of solutions of G8 PAMAM dendrimer in the solvent D(CD₂)_{*m*}OD with the chain parameter *m* = 0, 1, 2, 4 were measured for a constant dendrimer mass fraction of *x* = 0.005. The solvent quality is for this series of solvents a decreasing function of the length of the carbon chain.

The values of $R_{\rm g}$ are calculated from the scattering intensities by using the Guinier approximation in the functional form

$$\ln(I) = \ln(I_0) - \frac{R_g^2}{3} q^2$$
(1)

where I_0 and R_g are the fit parameters.¹⁸ Weighted linear least-squares fits are applied to plots of $\ln(J)$ versus q^2 (weighting the data by the experimental standard deviation of the intensity). The validity of the Guinier approximation in the analysis of scattering data of dendrimer solutions has been discussed in previous reports and has shown to yield accurate numbers for the radius of gyration of a dendrimer when fit over the q range used here.^{6–8}

In Figure 1, the values of the apparent radius of gyration, $R_{g,app}$, as determined from a fit of eq 1 to the plot of $\ln(I)$ vs q^2 , are plotted as a function of the molar concentration of dendrimer. The radii of gyration are apparent, $R_{g,app}$, since the values are fit at nonzero concentrations. The data show a weak dependence of the calculated radius on the concentration, but the magnitude is similar in size to the experimental standard uncertainty. (The experimental uncertainties of $R_{g,app}$ are calculated from the standard deviations of the Guinier fit.)

We note here that the variation of $R_{g,app}$ in this range of concentration does not reflect a change in the size of the dendrimer. Instead, it is due to the presence of the



Figure 2. Guinier plot of the scattering intensity of solutions of G8 in the solvents: water; methyl, ethyl, and *n*-butyl alcohol, i.e., the series $D(CD_2)_mOD$ with m = 0, 1, 2, 4. The solid lines represent the result of weighted linear least-squares fits. The mass fraction of the solutions is x = 0.5%. The data are offset for clarity by a constant value. The parameter of the plot is the length of the carbon chain: $(\diamondsuit) m = 0$, water; $(\bigtriangleup) m = 1$, methyl alcohol; $(\Box) m = 2$, ethyl alcohol; $(\bigcirc) m = 4$, *n*-butyl alcohol.

structure factor, which causes a depression of the scattered intensity in the low-q region, even in dilute dendrimer solutions. The low-q scattering is depressed at finite concentrations. This is a typical observation for dendrimer solutions and reflects the tendency of the dendrimers to avoid interpenetration.¹⁹ The depression of the intensity at low q has an influence on the value of $R_{\rm g,app}$ as determined from a Guinier fit, since eq 1 is based solely on the single particle scattering.

The weak dependence of the fitted value of $R_{g,app}$ on the concentration, as shown in Figure 1, shows that intermolecular effects do not significantly affect the experimental value for $R_{g,app}$ in this range of concentration. Therefore, the studies of dendrimer size variations in different solvents were done at a constant low concentration.

Guinier plots of SANS for the G8 dendrimer in different solvents are shown in Figure 2. The solid lines represent the results of weighted linear least-squares fits. (Data are weighted by the experimental standard deviations, which are smaller than the symbols in Figure 3, are not plotted, and are typically less than 1% of the value.) The values for the radius of gyration are calculated from the slope of the fits according to eq 1. For clarity, we will omit the notation of $R_{g,app}$ as apparent in the remaining part of this section and write R_g instead. As one can see from the approximately parallel data sets, the radius of gyration of the PAMAM dendrimers does not change significantly in this range of solvents.

The effect of solvent quality on R_g is shown in Figure 3 in a plot of the experimental radius of gyration versus the length of the methylene chain, m, in the series of solvents $D(CD_2)_mOD$ (with m = 0, 1, 2, 4). The values for R_g are also included in Table 1. For this series of solvents, the solvent quality decreases with increasing m, due to the decrease of the polarity of the solvent. A weak decrease of R_g with decreasing solvent quality is found. This shows a correlation between the dendrimer size and the solvent quality, but the absolute value of the change of R_g with m is small.



Figure 3. Apparent radius of gyration of G8 PAMAM dendrimer, $R_{\rm g}$, as a function of the length of the hydrocarbon chain, *m*. The value for m = 0 (the solvent D₂O) represents the extrapolated value from Figure 1; for m = 1, 2, and 4 the values are calculated from SANS of solutions of the mass fraction x = 0.005 ($c \approx 2 \times 10^{-5}$ mol dm⁻³). The error bars are a standard deviation of the fits to eq 1.

 Table 1. Characteristic Values of PAMAM Dendrimers in Different Solvents^a

generation	solvent	$R_{ m g}$ /Å	R+/Å	$R_{\rm h}/{\rm \AA^{10}}$	$\phi_{ m di}$
8	DOD	43.8 ± 0.1	56.5 ± 0.1	71.4	0.42 ± 0.04
8	$D(CD_2)OD$	42.0 ± 0.2	54.2 ± 0.2	57.9	0.47 ± 0.05
8	$D(CD_2)_2OD$	40.6 ± 0.1	52.4 ± 0.1		0.53 ± 0.06
8	$D(CD_2)_4OD$	39.5 ± 0.1	51.0 ± 0.1	44.9	0.57 ± 0.06
8	bulk	$\textbf{32.8} \pm \textbf{1.2}$	42.3 ± 1.5		1
5^b	$0 \leq x_{\rm s} \leq 0.4$	22.1 ± 0.2	28.5 ± 0.3		0.40 ± 0.03
5^c	$0 \leq x_{\rm s} \leq 0.4$	22.9 ± 0.2	29.6 ± 0.3		0.36 ± 0.03
5	bulk	16.4 ± 0.6	$21.1{\pm}~0.8$		1

^{*a*} Values of the $R_{\rm g}$ of PAMAM dendrimers: G8 in the solvent series D(CD₂)_{*m*}OD, with m = 0, 1, 2, 4, and G5 in methyl alcohol/acetone mixtures of the composition $x_{\rm s}$ ($x_{\rm s}$ in *m*(methyl alcohol)/*m*(acetone) in g/g). Also given in the table are the values for the radius of the dendrimers in solution, R^+ , the average volume fraction of the dendrimer interior occupied by dendrimer units, $\phi_{\rm di}$. Also listed are sizes calculated from bulk density and $R_{\rm h}$ values from literature.¹⁰ Uncertainty calculation is described in the text. ^{*b*} At 20 °C. ^{*c*} At 50 °C

An estimate for the segment density inside the dendrimers, ϕ_{di} , can be given by assuming a uniform segment distribution inside the volume occupied by dendrimer segments. This is a reasonable assumption for higher generation PAMAM dendrimers, according to the results of a recent X-ray study⁸ which shows that the dendrimers are spherical and have a narrow size distribution. Even if a nonuniform segment distribution was present, the calculation can be made giving the average amount of solvent inside the dendrimer. Assuming a uniform sphere, the radius of the dendrimer, R^+ , is related to the radius of gyration of the dendrimer, R_{g} , via

$$R^+ = R_o / (3/5)^{1/2} \tag{2}$$

The average volume fraction, ϕ_{di} , of the interior of the dendrimer that contains dendrimer units is then calculated from the relationship

$$\phi_{\rm di} = \frac{M_{\rm t}}{(4\pi/3)\rho N_{\rm A} R^{+3}} \tag{3}$$

where $N_{\rm A}$ is Avogadro's constant and ρ is the dendrimer bulk density.



Figure 4. Guinier plot of the SANS for solutions of G8 PAMAM dendrimers in methyl alcohol/acetone mixtures in the range of solvent composition $0 \le x_s \le 0.5$ as indicated in the figure. The value of the temperature is kept constant at 20 °C. The data sets for different x_s are offset by an appropriate value for visual clarity.

The calculated values for the average segment density of the G8 dendrimers in the solvents $D(CD_2)_mOD$ (with m = 0, 1, 2, 4) are given in Table 1. (The uncertainties of ϕ_{di} are calculated on the basis of the standard deviation of $R_{\rm g}$ as given by the Guinier fits.) The values of ϕ_{di} , as calculated from SANS, reveal a significant influence of the solvent quality on the segment density of the PAMAM dendrimers, which varies for the solvents studied in the range $0.42 \le \phi_{di} \le 0.57$, as shown in Table 1. This change is greater than small changes of the radius of gyration, R_{g} , as shown in Figure 4 and Table 1 because it involves the cube of the R_{g} . We use the average of the value of ρ for the generations G3– G5, 1.22 \pm 0.122 g cm⁻³, for the value ρ for the G8 dendrimer (assuming a relative standard uncertainty of 10% in ρ).²⁰ This gives a value for the radius of the hypothetical dendrimer of bulk density of 42.3 ± 1.5 Å. The changes in the average segment density of the dendrimers with changes of the solvent quality reflect a change in the volume inside the dendrimers that is accessible to the solvent molecules.

In the literature, values for the segment density of ammonia core PAMAM dendrimers are reported, which are calculated from the results of viscosity measurements.^{12,21} The authors report for the G8 dendrimer a value of $\rho_{visc}(G8) \approx 0.55$ g cm⁻³, giving $\phi_{di} = 0.45$. The PAMAM dendrimers that were used for the viscosity experiments were built on a trifunctional core, whereas the present study uses dendrimers with a tetrafunctional core. Table 1 shows that ϕ_{di} of the G8 dendrimer is in reasonable agreement with the value for the average segment density of the G8 dendrimer in D₂O and methyl alcohol reported here.

Stechemesser and Eimer studied the effect of solvent quality on the self-diffusion coefficient of tetrafunctional PAMAM dendrimers in the range of generation G2–G10 by holographic relaxation spectroscopy (HRS).¹⁰ Applying the Stokes–Einstein equation, the authors compute values for the hydrodynamic radii, R_h . They observe a pronounced effect on the value of R_h for the generation G8 dendrimer in the solvents H₂O, methyl alcohol, and butyl alcohol. The reported values range from $R_h = 71.4$ Å in H₂O to $R_h = 44.9$ Å in butyl alcohol and are discussed in terms of the radius of the dendrimers. A comparison with the values reported for R^+

in this SANS study shows significant differences of the dendrimer dimensions as a function of solvent quality. A closer look at the values reported by Stechemesser and Eimer reveals that the value reported for the solvent H₂O is much larger than the results given by this SANS study and viscosity measurements and leads to the extremely small segment density $\phi_{di} = 0.40$. Segment densities refer to volume fractions of the interior. At the other limit, the value of $R_{\rm h} = 44.9$ Å reported for butyl alcohol turns out to be very close to the value for the radius of a hypothetical G8 dendrimer of bulk density, 42.3 ± 1.5 Å, which was calculated earlier in this section, and leads to a segment density of $\phi_{di} = 0.84$. Both limits for the size of the G8 dendrimer as calculated from the HRS study are well out of the range of the SANS results and viscosity measurements. A possible reason for this discrepancy is that the hydrodynamic radii, when calculated from the HRS measurements under the assumption of the validity of the Stokes-Einstein relationship, do not give an accurate value for the actual size of the dendrimer. The large number of hydrophilic terminal units of a PAMAM dendrimer may lead to an atmosphere of solvent molecules of a considerable thickness that surrounds the dendrimer. In this case the hydrodynamic radii, as calculated from self-diffusion coefficients, would be larger than the molecule, as is observed in the HRS study.

Murat and Grest performed a molecular dynamics study for dendrimers that have a trifunctional core and seven spacer units between the branching points, which was chosen to correspond to the molecular structure of PAMAM dendrimers.⁹ The authors observe a very pronounced influence of the solvent quality on the average dimensions of the dendrimers and report a change of the radial monomer density, $\phi(r)$, of a G8 dendrimer in the range $0.65 \le \phi(r) \le 0.1$. Our study finds a relatively small change in ϕ_{di} for a G8 PAMAM dendrimer. The dendrimers simulated by Murat and Grest consist of equal segments throughout the dendrimer and branch points that are similar to the terminal units. However, PAMAM dendrimers have a far more complex chemical structure. The terminal primary amines are chemically different from the branch units and the building blocks in the interior. Hence, the simulation predicts the trend for the influence of solvent quality on dendrimer dimensions in general, but does not give quantitatively correct results for PAMAM dendrimers.

Mixed Solvents. PAMAM dendrimers do not dissolve in acetone, but they readily dissolve in methyl alcohol/ acetone mixtures over a wide range of composition. Solvents of different composition, expressed as mass fraction *x*_s (*m*(methyl alcohol)/(*m*(acetone)) in g/g), were prepared and added to a weighed amount of dried G5 or G8 dendrimer. The mixtures were then stirred, and the solubility was determined by visual inspection. It was found that the PAMAM dendrimers are soluble in the range $0 \le x_s \le 0.50$, with the exception of a solubility gap for G8 around the solvent composition $x_s \approx 0.30$. A turbid dispersion of G8 with the solvent composition x_s = 0.30 and a dendrimer content of $x \approx 0.01$ turned clear at a temperature $T \approx -5$ °C. For both generations, a similar temperature-induced turbidity was observed in the close vicinity of the solubility limit around $x_s \approx 0.52$. This behavior may reflect the importance of H-bonding for the solubility of PAMAM dendrimers.



Figure 5. Values of the apparent radius of gyration, R_g , for G8 PAMAM dendrimers in methyl alcohol/acetone mixtures within the range of solvent composition $0 \le x_s \le 0.5$ as a function of the temperature, *T*. The error bars are a standard deviation of the fits to eq 1.

SANS experiments were performed with solutions of G5 and G8 PAMAM dendrimers in solvents composed by different mass fractions of methyl alcohol and acetone. In the case of the G8 dendrimer, a series of the solvent compositions $x_s = 0.0, 0.10, 0.20, 0.25, 0.35, 0.40$, and 0.50 were studied that contained a dendrimer mass fraction in the range $0.005 \le x \le 0.01$. All solutions that contained G8 PAMAM dendrimer were measured at temperatures, *T*, in the range $-10 \text{ °C} \le T \le 50 \text{ °C}$. With the G5 PAMAM dendrimer, a series of solutions with the solvent compositions $x_s = 0, 0.10, 0.20, 0.30, \text{ and } 0.40 \text{ and a molar dendrimer concentration of } c = 2.6 \text{ mol dm}^{-3}, \text{ based on the theoretical molecular mass}, 28 826 \text{ g mol}^{-1}, were measured at the temperatures <math>T = 20 \text{ °C}$.

Figure 4 shows the SANS data of the G8 dendrimer for solvent compositions in the range $0 \le x_s \le 0.50$ at a constant temperature of T = 20 °C. The data are plotted in a Guinier plot, each data set being offset by an appropriate value for clarity. Weighted least-squares fits to the data are shown as solid lines in the figure. The slope of the lines is related to the radius of gyration of the dendrimers according to eq 1. As can be seen from Figure 4, the slope varies little over the whole range of solvent composition, indicating that the radius of the dendrimers is not significantly affected by the fraction of acetone in the solvent. The same result is found over the whole range of temperature studied, i.e., in the range -10 °C $\le T \le 50$ °C.

The values of the apparent radius of gyration resulting from the Guinier fits are shown in Figure 5 as a function of the temperature for the dilute solutions of the G8 PAMAM dendrimer for all solvent compositions studied. It follows from Figure 5 that the temperature has no significant influence on the average dimensions of the G8 dendrimers. Also, the value of R_{α} is apparently not strongly affected by the solvent composition. Only the data taken in the solvent of the composition $x_s =$ 0.50 show some consistent decrease of $R_{\rm g}$, relative to the other solvent compositions. This may indicate the onset of a shrinkage of the dendrimers in the vicinity of the solubility gap, which is around $x_{\rm s} \approx 0.52$. However, the difference from the value of R_g for $x_s =$ 0.50 is less than 5% of the mean value of $R_{\rm g}$ for the other solvent compositions.



Figure 6. Plot of the apparent radius of gyration of G5 PAMAM dendrimers, R_{g} , versus the composition of the solvent, x_{s} (x_{s} , mass fraction of acetone in methyl alcohol/acetone mixtures). The values are shown for two different temperatures; the solid lines represent weighted average of R_{g} : (\bigcirc) T = 20 °C; (\square) T = 50 °C. The error bars are a standard deviation of the fits to eq 1.

The low-concentration solutions of the G5 dendrimer show a behavior that is similar to the G8 dendrimer over the range of solvent composition $0.0 \le x_s \le 0.40$. In Figure 6, the apparent radii of gyration, R_g , is plotted as a function of the solvent composition. The values of R_g were calculated from Guinier fits in a similar fashion as was the G8 dendrimer fits. We find that the size of the G5 dendrimer is not affected by the solvent composition in the range $0.0 \le x_s \le 0.4$, which is in agreement with the data for G8. The values of R_g are larger for the higher temperature, T = 50 °C, than at T = 20 °C, but the absolute value of the decrease R_g is small and does not exceed 5% of the R_g value.

As we did with the G8 dendrimer in the solvent series $D(CD_2)_mOD$, we want to elucidate the dimensions of the G5 PAMAM dendrimer in terms of the average segment density. Following the procedure described in previously, we use eqs 2 and 3 to calculate the average segment density of a G5 PAMAM dendrimer in methyl alcohol/acetone mixtures. The average value of $\phi_{di}(G5)$ for all different solvent compositions at T = 20 °C is shown in Table 1. The ϕ_{di} value is significantly smaller than the values for the G8 dendrimer. This is consistent with the general dependence of the segment density of PAMAM dendrimers on the generation, as reported on the basis of viscosity measurements, which show a minimum in the segment density for intermediate generation numbers.²¹ For the tetrafunctional dendrimers considered here, the difference between ϕ_{di} of G5 and G8 is smaller than given by the viscosity results for the trifunctional dendrimers.

Conclusions

The average dimensions of G8 PAMAM dendrimers, as studied by SANS, show a small, but significant, dependence on the solvent quality. For the series of solvents $D(CD_2)_mOD$ with m = 0, 1, 2, 4, the radius of gyration is reduced by $\approx 10\%$ when changing the solvent from m = 0 to m = 4. This relatively small variation of R_g leads to an increase of the average segment density of the G8 dendrimer from $\phi_{di} = 0.42$ to ϕ_{di} (G8, m = 4) = 0.57. Our results do not show a large size change as does a HRS study of the self-diffusion coefficient of PAMAM dendrimers in different solvents. Also, the

absolute value of the variation of R_g as measured by SANS is much smaller than predicted by the computer simulations performed by Murat and Grest. We attribute this difference to the more complex structure of PAMAM dendrimers compared to the simulated homogeneous structures.

The generations G5 and G8 of PAMAM dendrimers were studied in solvents composed of methyl alcohol and acetone within the range of solubility. No significant change of the average dimensions of G5 and G8 PAMAM dendrimer is found in solvent mixtures $0 \le x_s \le 0.5$. The average segment density of the G5 dendrimer is smaller than the value for the G8 dendrimer. Temperature also has only a small effect on the dendrimer size.

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References and Notes

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