Colloid Polym Sci (2005) 284: 58–65
DOI 10.1007/s00396-005-1340-3

ORIGINAL CONTRIBUTION

Mandeep Singh Bakshi
Rohit Sood
Radha Ranganathan
Paul Shin

ESR and NMR studies of poly (amidoamine) dendrimers with ionic surfactants in different media

Received: 28 October 2004
Accepted: 6 December 2004
Published online: 23 July 2005
© Springer-Verlag 2005

M. S. Bakshi (✉) · R. Sood
Department of Chemistry,
Guru Nanak Dev University,
Amritsar 143005 Punjab, India
E-mail: ms_bakshi@yahoo.com

R. Ranganathan
Department of Physics and Astronomy,
California State University,
Northridge CA, USA

P. Shin
Department of Chemistry,
California State University,
Northridge CA, USA

Abstract The electron paramagnetic resonance (EPR) study has been carried out for the micellar solutions of various ionic surfactant solutions as well as various generations of aqueous dendrimer both in their respective presence as well as their absence at 25°C and in different media. From these measurements, the rotation correlation time (τ_B) have been calculated for all the ionic surfactant + PAMAM + water system. A variation in the $\tau_B$value remains mostly constant for the dodecyltrimethyammonium bromide (DTAB) and tetradecyltrimethylammonium bromide (TTAB) + PAMAM + water ternary mixtures. The $\tau_B$value shows an increase with the increase in the amount of PAMAM for SDS in basic medium and for 12-2-12 in acidic medium. It has been concluded from these results that SDS undergo complexation with all generations of PAMAM in basic medium and 12-2-12 in acidic medium and produce stronger hydrophobic environment. The nuclear magnetic resonance study (NMR) allowed us to evaluate the spin–spin relaxation (T_1) times of SDS in the presence of all generations of PAMAM. The T_1 values for all the tail protons of SDS showed a slight decrease with the increase in the constant amount of PAMAM suggesting the adsorption of PAMAM molecules on the micelle surface.

Keywords Ionic surfactants · Poly (amido amine) dendrimer · Rotational correlation time · EPR measurements · pH dependence

Introduction

The class of poly (amidoamine) dendrimers belongs to a novel category of polymers with entirely different solution properties from that of conventional linear polymers [1–5]. The solution properties of former drastically change with the change in generation of dendrimer [6]. We have recently synthesized a series of poly (amido amine) dendrimers and studied their solution properties and their interactions with surfactants [7–9], (M.S. Bakshi, R. Sood, G. Kaur communicated). For this purpose, various physicochemical techniques have been employed to elucidate the self-aggregation behavior in PAMAM as well as their mode of interaction with ionic surfactants [10, 11]. It has been observed that the increase in the number of generations leads to a significant shift in the hydrophilic nature of PAMAM, and higher generations mostly act as central hydrophobic domains [6]. In this study, we have employed electron spin resonance (ESR) technique to evaluate the microenvironment of solubilized PAMAM as well as that in the presence of aqueous surfactant solutions. The results have been compared with those obtained from NMR studies. In pure water, the surface groups of PAMAM are generally in protonated form, therefore, show less interactions with cationic surfactants in comparison to anionic surfactants. Hence, in the present study, the measurements have also been carried out in acidic and basic media apart from that in neutral phase. An appropriate spin probe like 16-doxy stearic ester (16-DSE) helps us to evaluate the nature of microenvironment in which it is solubilized. Since this probe is equipped with C-18 stearic acid tail, which provides it sufficient hydrophobicity, hence, it is solubilized predominantly in the hydrophobic environment. Few studies have been reported in the literature regarding the ESR behavior of poly(amido amine) dendrimers in the absence as well as in the presence of surfactants [12]. Tomalia et al. [13] studied the intermolecular dendrimer interactions between poly (amidoamine) dendrimers (SBDs) of different generations ($G = 2$, 4, and 6) in aqueous solutions by EPR and fluorescence depolarization. The interactions between poly (amidoamine) starburst dendrimers (SBDs) and vesicles consisting of dimyristoylphosphatidylcholine (DMPC) and its salt (DMPA-Na) in various relative ratios were studied by EPR and transmission electron microscopy (TEM) [14–22].

In order to explore the potential of ESR in evaluating the microenvironment of aggregated assembly, we herein report the ESR results of 16-DSE in aqueous PAMAM of various generations, i.e., 0–4.5 G in the absence as well as in the presence of a variety of surfactants such as sodium dodecylsulfate (SDS), dodecyltrimethylammonium bromide (DTAB), tetradecyltrimethylammonium bromide (TTAB), and di(dodecyldimethylammonium bromide) (12-2-12). The purpose of selecting these surfactants is simply to evaluate the dependence of the nature of interactions on both monomeric (anionic and cationic) and dimeric head groups as well as on the difference in their hydrophobicities.

Experimental

EPR measurements

The spectra were taken at X-band with a bruker ESP-300 spectrometer. A macro within Bruker's software tuned the bridge, obtained a spectrum, and wrote it to the hard disk, repeating the process five times in a row for each sample [23, 24]. Mother solutions of the surfactants prepared at concentrations 10×cmc containing the spine probe 16-doxylstearic acid methyl ester (16-DSE) with a surfactant-to-probe ratio 500:1 were prepared in Milli Q water. Solutions with various combinations of surfactant and dendrimer were prepared from the mother solution. Computer fits of the EPR spectra yield the line positions and line heights to high precision. Rotational correlation times are computed from the following well-known formulas

$$C_{\text{uncorrected}} = \frac{1}{2}\Delta H^0_{\text{pp0}}\left\{\sqrt{\frac{V_{\text{pp0}}}{V_{\text{pp+1}}}} + \sqrt{\frac{V_{\text{pp0}}}{V_{\text{pp}-1}}} - 2\right\}, \tag{1}$$

$$B_{\text{uncorrected}} = \frac{1}{2}\Delta H^0_{\text{pp0}}\left\{\sqrt{\frac{V_{\text{pp0}}}{V_{\text{pp+1}}}} - \sqrt{\frac{V_{\text{pp0}}}{V_{\text{pp}-1}}}\right\}, \tag{2}$$

where Δ H^0 pp_0 is the overall line width of the $M_1 = 0$ line and $VppM_1$ is the peak-to-peak height of the line M_1 line, where $M_1 = 1$, 0, −1 labels the low-, center-, and high-fields lines, respectively. The subscript "uncorrected" means that the coefficients have not yet been corrected for inhomogeneous broadening, which is carried out using equations 28–30 of ref. [25]. From corrected coefficients, rotational correlation times may be computed from

$$\tau_B = -1.27 \times 10^{-9} B_{\text{corrected}}, \tag{3}$$

$$\tau_c = -1.16 \times 10^{-9} C_{\text{corrected}}, \tag{4}$$

where τ_B, τ_c are given in seconds, and $B_{\text{corrected}}$, $C_{\text{corrected}}$, in gauss. The derivation of Eqs. 3 and 4 require that the rotational averaging of the g- and hyperfine-tensors be isotropic, which would require that $\tau_B = \tau_c$, and that τ_B, τ_c be < 3 ns. See ref. [26] and the references therein for a careful discussion of the validity of these expressions and for details of their derivation.

NMR measurements

^{1}H NMR spectra were run on Bruker AC400E instrument. NMR measurements were carried out in D_2O and all chemical shifts were measured relative to sodium 4,4-dimethyl-4-silapentane-1-sulfonate (DSS), which acted as an internal standard. Inversion recovery pulse sequence was used for the calculation of T_1 (spin–spin) relaxation time measurements at 25°C. Thirty accumulations were acquired generally. D_2O, 99.9%, purchased from Aldrich, was used as solvent instead of water in order to weaken the water signal. Meanwhile, the presaturation method was used to further suppress the proton signal of the solvent.

Results

The rotational correlation time (τ_B) values of 16-DSE for surfactant + 0.5G/4.5 G systems have been plotted in Fig. 1 with respect to the increase in [0.5 G/4.5 G] at constant [surfactant] at pH = 4, 7, and 10. Similar plots have also been observed in the presence of other PAMAM (not shown). All the figures, i.e., from Fig. 1a–f show almost identical variation of τ_B for corresponding systems. The τ_B value in the absence of surfactant, i.e., in pure aqueous 0.5 G or 4.5 G remains relatively very small and identical to each other at different pH. In the presence of surfactant, the τ_B value for SDS and DTAB

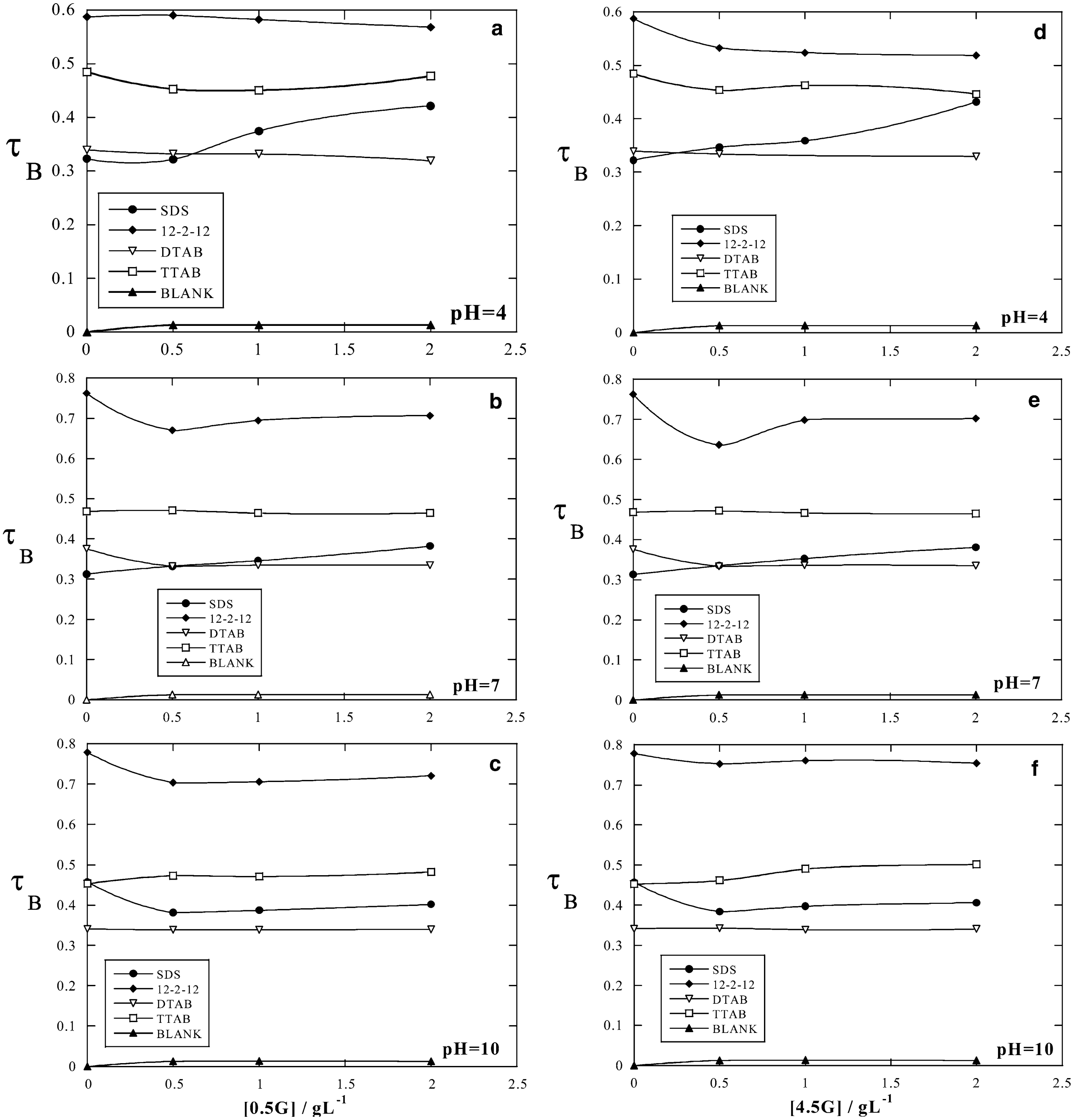


Fig. 1 Plots 1a, 1b, and 1c shows the variation of rotation correlation time (τ_B) versus concentration of 0.5G PAMAM at pH = 4, 7, and 10, respectively, where as plots 1d, 1e, and 1f shows the variation of rotation correlation time (τ_B) versus concentration of 4.5 G PAMAM at pH = 4, 7, and 10, respectively

with identical hydrophobic tail are quite close to each other at pH = 7 (Fig. 1b–e), but differ from each other at pH = 4 or 10 (Fig. 1a, c, d, f). A close inspection of Fig. 1 indicates that all plots of τ_B show almost constant value particularly in the case of DTAB/TTAB, while a small decrease in the τ_B value is observed at various [0.5 G/4.5 G], especially in the acidic and basic media. An almost constant value of τ_B for DTAB/TTAB demonstrates that 16-DSE is always located in the micellar phase and there is no significant change in the hydrophobic environment of DTAB/TTAB micelles even in the presence of different amounts of 0.5 G/

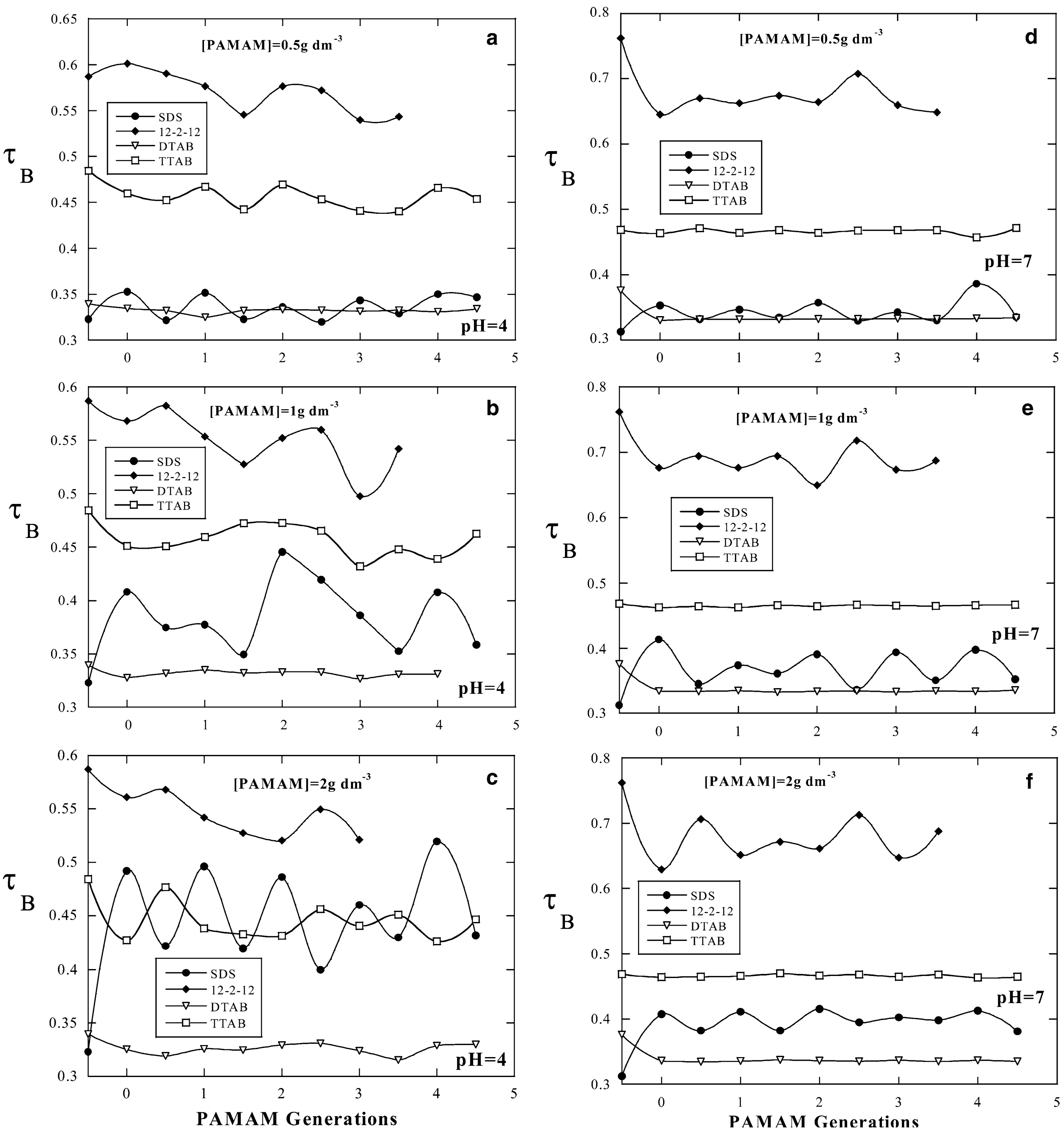


Fig. 2 Plots 2a, 2b, and 2c shows the variation of rotation correlation time (τ_B) versus PAMAM generations at different fixed [PAMAM] = 0.5, 1, and 2 gdm^{-3}, respectively, at pH = 4, whereas, plots 2d, 2e, and 2f shows the variation of rotation correlation time (τ_B) versus PAMAM generations at different fixed [PAMAM] = 0.5, 1, and 2 gdm^{-3}, respectively, at pH = 7

4.5 G. On the other hand, a slight increase in the τ_B value in SDS especially in acidic medium (Fig. 1a, d) from that in the absence of PAMAM can be related to the solubilization of 16-DSE in more hydrophobic environment resulting in the increase in τ_B value. On the contrary, a small decrease in τ_B value of SDS in the basic medium (Fig. 1e, f) can be attributed to the solubilization of 16-DSE in more hydrophilic environment. This

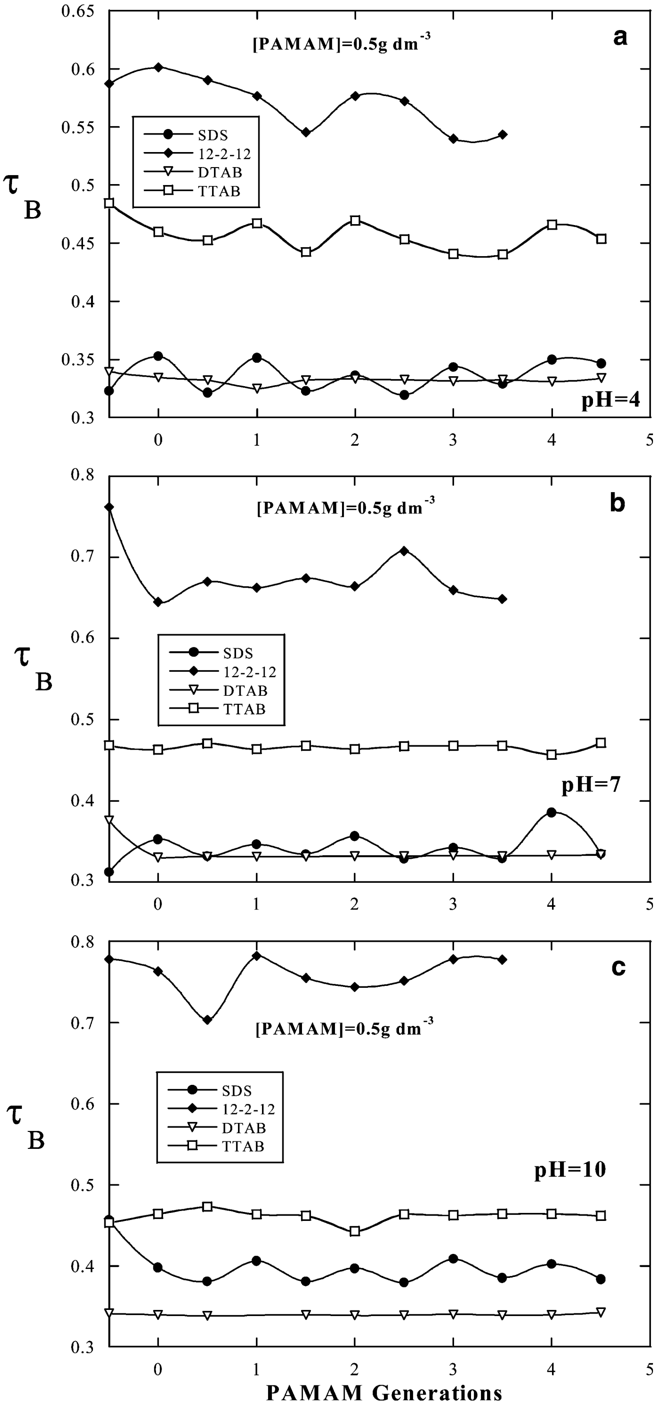


Fig. 3 Plots 3a, 3b, and 3c shows the variation of rotation correlation time (τ_B) versus PAMAM generations at fixed [PAMAM] = 0.5 gdm^{-3} at pH = 4, 7, and 10, respectively

kind of variation of τ_B and its dependence on pH is not very much clear for 12-2-12, where the presence of both 0.5 G/4.5 G always results in a small decrease in τ_B over the concentration range of PAMAM studied.

Figure 2 shows the τ_B for various systems both at fixed [surfactant] and [PAMAM] versus the number of PAMAM generations. The τ_B values remain mostly constant with the increase in number of generations for TTAB/DTAB + PAMAM at different fixed [PAMAM]. These values are also predominantly remain constant for 12-2-12 + PAMAM systems, but sometime show dependence on the number of generations. In the case of SDS + PAMAM, there is a large change in the τ_B value when we increase the fixed [PAMAM] from Fig. 2a–c with the increase in [PAMAM] = 0.5–2 gdm^{-3}. The τ_B value for SDS + PAMAM system starts increasing over all the generations and show large difference at [PAMAM] = 2 gdm^{-3} (Fig. 2c) where the τ_B is much higher for amine terminated generations while much smaller for the ester terminated generations. Similar results have also been shown by Fig. 2d–f at pH = 7, but the variation in the τ_B value for SDS + PAMAM at various generations are less significant. A constant τ_B value of DTAB/TTAB certainly points to the previous conclusion demonstrating a little interaction of all generations with DTAB/TTAB in different media. A significant increase in the τ_B value for SDS in the presence of various generations can be attributed to the solubilization of 16-DSE probe in more hydrophobic environment, which is obviously expected due to the protonation of all generations of PAMAM in acidic media, thereby, triggering their interactions with anionic head groups of SDS. An effect of pH on the τ_B value can clearly be observed in Fig. 3 for all surfactants. A comparison of various plots of Fig. 3a–c demonstrates that there is no pH effect on the τ_B value for DTAB/TTAB while τ_B value systematically increases for 12-2-12 from acidic to basic through neutral media. As we do not expect the protonation of dendritic molecules in the basic media, therefore, electronegative amine and ester terminated surface groups of PAMAM would interact cationic dimeric 12-2-12 head groups favorably in basic media. However, no change in the τ_B for DTAB/TTAB suggest relatively much weaker interactions with dendritic surface groups in the basic media due to their monomeric nature. Furthermore, in the basic medium (Fig. 3c), the anionic head groups of SDS are not expected to interact with the dendritic surface groups due to their electronegative character with the result of which τ_B value decreases in aqueous PAMAM in comparison to that in the absence of PAMAM.

NMR Behavior

Figure 4 shows representative NMR spectra of SDS. The proton resonances have been shown for the proton labeled in Fig. 4. The spin–spin relaxation time (T_1) has been calculated for all the protons and has been plotted in Fig. 5 in the presence of 0, 0.5, 4, and 4.5 G. The

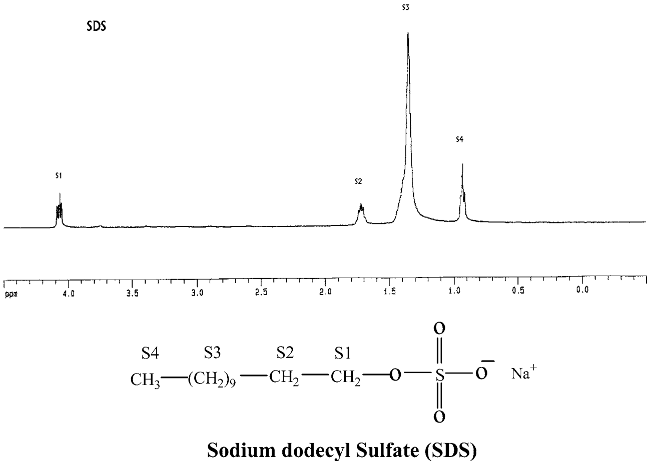
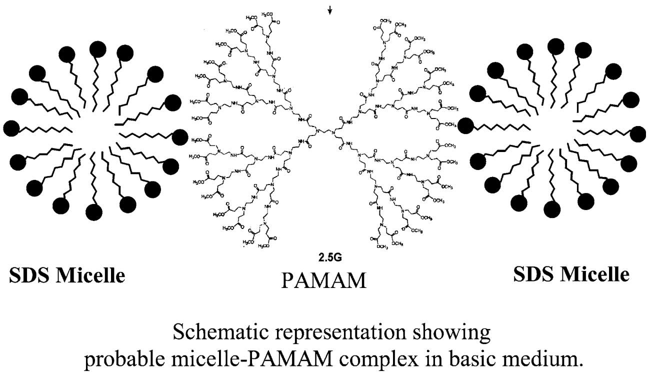


Fig. 4 Figure showing NMR spectra of SDS labeling various peaks for which relaxation times have been evaluated

variation of the T_1 is also identical in the presence of other generations (not shown). All the protons of Fig. 5 shows that the T_1 value for each proton decreases slightly with the increase in the amount of each generation. A decrease in the T_1 value can be explained on the basis of a compact micellar arrangement, which restrict the motion of these protons with shorter relaxation times. It is also difficult to differentiate the variation in T_1 value from one proton to another indicating the fact that all protons experience almost identical change in the environment in the micellar presence of aqueous PAMAM.

Discussion

The above results have been explained on the basis of electrostatic interactions between the various ionic surfactant head groups and PAMAM surface groups. The effect of pH has been opted to clearly evaluate the nature of electrostatic interactions. Figures 1, 2, and 3 clearly indicate that DTAB/TTAB have relatively much weaker interactions with various generations of PAMAM even in the presence of basic media where no protonation of amine and ester terminated PAMAM surface groups is expected. It seems that the electropositive character is not strong enough so that clear electrostatic interactions with electronegative surface groups are achieved. This can further be attributed to the screening of electropositive character of cationic head groups by alkyl groups, thereby, reducing its chances to interact with dendritic surface groups. On the other hand, the dimeric cationic head groups seems to be much effective in interacting with the PAMAM surface groups with the result of which the τ_B value increases for 12-2-12 in basic medium (Fig. 3c). Thus among the cationic surfactants dimeric head group seems to have greater probability to interact with the PAMAM surface groups in comparison to that of monomeric surface groups. The interactions seem to be much stronger in the case of SDS, which show an increase in τ_B value in acidic medium for all generations and this effect increases with the increase in amount of PAMAM (Fig. 2a–c). Therefore, comparatively, it is clear from these results that cationic surfactant especially 12-2-12 interact with all generations of PAMAM in basic medium while SDS interacts with all generations when they are protonated in acidic media. Furthermore, it was not possible to support these results in different media from the variation of spin–spin relaxation time. But the variation of T_1 in Fig. 5, for all the tail protons of SDS indicates a short relaxation time in aqueous PAMAM in comparison to that in pure D_2O. A short relaxation time clearly indicates a restriction in the molecular motion of these protons, which seems to be due to the strengthening of the hydrophobic environment in view of electrostatic interactions with dendritic surface groups. The origin of which can be attributed to the reduction in the anionic head group repulsions upon interactions with protonated surface groups of dendritic macromolecules thus generating additional hydrophobicity as shown in Scheme 1.



Scheme 1 Schematic representation showing probable micelle-PAMAM complex in basix medium

Conclusions

The EPR measurements have been carried out for various ionic surfactant + PAMAM + water ternary mixtures. It has been concluded that cationic surfactant with dimeric character interacts with all generations of PAMAM in comparison to cationic surfactant of monomeric nature and these interactions are much stronger in basic medium. On the other hand, anionic surfactant, SDS interacts with

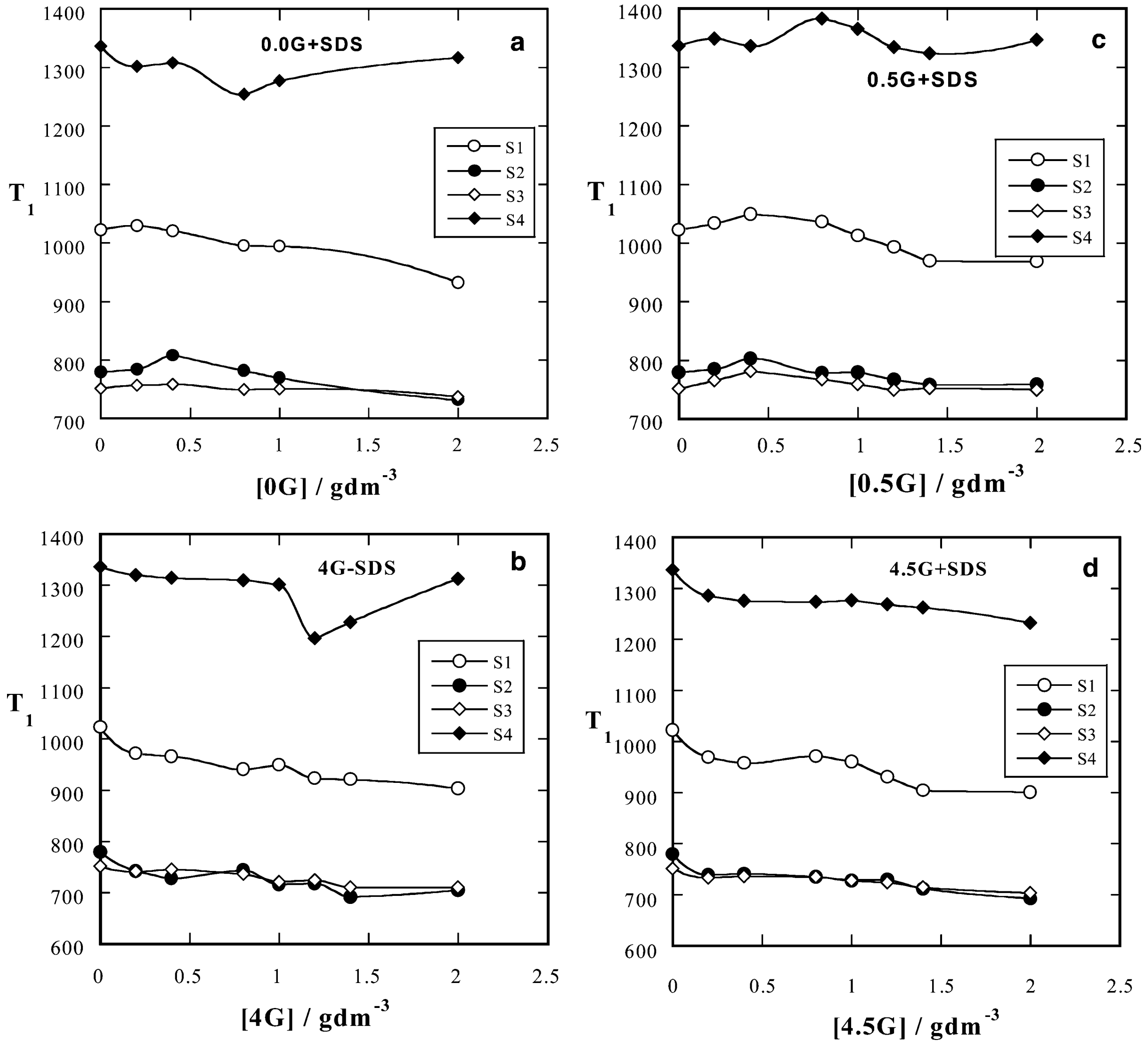


Fig. 5 Plots 5a and 5b shows the variation of spin-spin relaxation time (T_1) versus concentration of 0 G and 4 G for the different tail protons of SDS. Plots 5c and 5d shows the variation of spin–spin relaxation time (T_1) versus concentration of 0.5 G and 4.5 G for the different tail protons of SDS

all generations of PAMAM and interactions are much stronger in acidic media.

Acknowledgments Financial assistance from CSIR under a research project [Ref. No. 01(1777)/02/EMR-II] is thankfully acknowledged. R. Sood thanks the CSIR, New Delhi, for a Junior Research Fellowship. Support for this project from the NIH/NIGMS SCORE program under contract S06 GM48680, the CSUN Research and Grants Committee, the College of Science and Mathematics is acknowledged.

References

1. Ottaviani MF, Turro NJ, Jockusch S, Tomalia DA (1996) Colloids Surf 115:9
2. Ottaviani MF, Andechaga P, Turro NJ, Tomalia DA (1997) J Phys Chem 101:6057
3. Tomalia DA, Naylor AM, Goddard WA (1990) Angew Chem Int Ed Engl 29:138
4. Esumi K, Kuwabara K, Chiba T, Kubayashi F, Mizutani H, Torigoe K (2002) Colloids Surf 197:141
5. Esumi K, Saika R, Miyazaki M, Torigoe K (2000) Colloids Surf 166:115
6. Caminati G, Turro NJ, Tomalia DA (1990) J Am Chem Soc 112:8515
7. Bakshi MS, Sood R (2004) Colloid Surf 233:203
8. Bakshi MS, Sood R (2004) J Colloid Interface Sci 277:221
9. Bakshi MS, Kaura A, Mahajan RK, Yoshimura T, Esumi K (2004) Colloid Surf 246:39
10. Bakshi MS, Kaura A (2004) Colloid Surf 244:45
11. Bakshi MS, Kaura A, Miller JD, Paruchuri VK (2004) J Colloid Interface Sci 278:472

12. Jockusch S, Turro NJ, Ottaviani MF, Tomalia DA
13. Ottaviani MF, Matteini P, Brustolon B, Turro NJ, Jockusch S, Tomalia DA (1998) J Phys Chem 102:6029
14. Ottaviani MF, Daddi R, Brustolon M, Turro NJ, Tomalia DA (1999) Langmuir 15:1973
15. Tomalia DA, Hall M, Hedstrand DM (1987) J Am Chem Soc 109:1601
16. Tomalia DA, Naylor AM, Goddard WA III (1990) Angew Chem Int Ed Engl 29:138
17. Tomalia DA, Durst HD (1993) In: Weber E (ed) Topics in current chemistry, vol 165. Springer, Berlin Heidelberg New York, p 193
18. Ottaviani MF, Favuzza P, Sacchi B, Turro NJ, Jockusch S, Tomalia DA (2002) Langmuir 18:2347
19. Duncan R (1996) Proc Natl Acad Sci USA 93:4897
20. Bielinska AU, kukowska-Latallo JF, Johnson J, Tomalia DA, Baker JR (1996) Nucleic Acids Res 24:2176
21. kukowska-Latallo JF, Bielinska AU, Johnson J, Spindler R, Tomalia DA, Baker JR Jr (1996) Proc Natl Acad Sci USA 93:4897
22. Kim Y, Zimmerman SC (1988) Curr Opin Chem Biol 2:733
23. Bales BL, Ranganathan R, Griffiths PC (2001) J Phys Chem B 105:7465
24. Bales BL, Zana R (2002) J Phys Chem B 106:1926
25. Bales BL (1989) Inhomogeneously Broadened Spin-Label Spectra. In: Berliner LJ, reuben J (eds) Biological magnetic resonance, vol 8. Plenum Publishing Corporation, New York, p 77
26. Schreier S, Polnaszek CF, Smith ICP (1978) Biochim Biophys Acta 515:375