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Permanent and Reversible Gels: Transport of Guests and Guest-Host Interactions

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SUMMARY: We describe the application of electron spin resonance imaging (ESRI) for measuring *macroscopic* diffusion coefficients of paramagnetic guests in polymeric systems. The ESRI method is based on encoding spatial information in the ESR spectra via magnetic field gradients, and on simulating the time evolution of the spectra in order to extract the diffusion coefficient, *D*. This paper presents one dimensional (1D) ESRI experiments planned to study (a) the dependence of the diffusion coefficients of probes on the presence of permanent crosslinks in gels, and (b) the effect of the probe site on the transport rates in self-assembled polymers. These effects were investigated, respectively, in two types of gels: chemically crosslinked (permanent) hydrogels, and reversible gels formed by self-assembly of polymeric surfactants.

Introduction

Diffusion processes in polymer solutions and in swollen polymer networks ("gels") are of considerable importance for an understanding of polymer dynamics, and for numerous applications such as separation processes, drug delivery systems, transport across biological membranes, and prosthetic devices. The transport data reflect the interactions between polymer, solvent and guests, and the relaxation phenomena in the presence of temporary entanglements (in polymer solutions), and obstacles such as permanent crosslinks (in swollen networks). Two types of methods for measuring diffusion coefficients, *D*, have been described in the literature: tracer methods, which measure *macroscopic* transport on the length scale of millimeters and on the time scale of minutes or more, and *microscopic* methods, which measure the self-diffusion coefficients on the time and length scales typical for molecular motion.[1-5)]

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Imaging based on ESR, ESRI, provides information on the spatial distribution of paramagnetic diffusants and has been used for measuring diffusion coefficients.⁶⁾ In our laboratory 1D and 2D (spatial-spectral) ESRI based on nitroxide spin probes and paramagnetic Mo^V have been applied for the determination of the spatial distribution and the diffusion coefficients of paramagnetic species in ion-containing polymers, polymer solutions, crosslinked polymers swollen by solvents, and self-assembled polymers.[7-9)] The method is based on encoding spatial information in the ESR spectra via magnetic field gradients, and on simulating the time evolution of the spectra in order to extract the diffusion coefficient, D. This summary illustrates the application of 1D ESRI to the measurement of transport in two types of gels: permanently crosslinked networks swollen by water ("hydrogels"), and reversible gels formed by self-assembly of polymeric surfactants. Our objectives were to study the effect of the permanent crosslinks in hydrogels on the diffusion coefficients of tracers, and the transport rates of guests in polymeric amphiphiles that self-assemble in water solutions, leading to the formation of thermoreversible gels.

Determination of the Diffusion Coefficients by 1D ESRI

ESR Imaging and Data Acquisition. The ESR imaging system in our laboratory consists of the Bruker 200D ESR spectrometer equipped with two Lewis Coils (George Associates, Berkeley, USA, type 503D), and two regulated DC power supplies (Kikusui Electronic Corp., Japan, model PAE 35-30). The coils supply a maximum linear field gradient of ≈320 G/cm in the direction parallel to the external magnetic field (z axis), or ≈250 G/cm in the vertical direction (along the long axis, x, of the microwave cavity), with a control voltage of 20 Amperes applied to each power supply. Additional details have been published.[7-9)]

Simulation of 1D ESR Images. The D values for a paramagnetic guest can be determined from one pair of ESR spectra, measured respectively with and without field gradient. In the presence of a gradient G_x (G/cm) along the x axis, the ESR spectrum ("projection") $I_C(H)$ is given by the convolution integral, equation 1,

$$I_C(H) = \int_{-\infty}^{\infty} f_0(H-H^*)\ p(H^*)\ dH^* \qquad (1)$$

where $f_0(H)$ is the spectrum, H is the homogeneous stationary magnetic field, $H^*=x \cdot G_x$ is the local magnetic field (at x) due to the gradient G_x, and $p(H^*)$ is the distribution of the paramagnetic centers along the direction of the gradient. The spatial distribution of the spin probe $C(x)$ can be calculated from $p(H^*)$ if the gradient is known.

In a diffusion experiment, the concentration profiles as a function time, $C(x,t)$, can be calculated from a solution of Fick's law that is appropriate for the specific sample configuration.[10)] The distribution function $p(H^*)$ for a gradient G_x and at time t in the diffusion process was calculated with D and h as parameters, convoluted according to equation 1 with the ESR lineshape $f_0(H-H^*)$, and compared with the experimental lineshape; the best visual fit[8)] or a least square fit[9)] were used to extract the diffusion coefficient. No correction for the sensitivity profile of the ESR cavity was needed, if only the initial stages of the diffusion process were used to deduce the diffusion coefficients (in the case of a long polymer layer), or if the polymer layer was <5 mm in length.

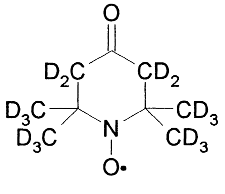
Diffusion Coefficients in Permanent Gels

In a recent study by 2D ESRI we detected a significant difference between the diffusion coefficients of a small paramagnetic tracer (MW 186) in a permanent polystyrene network swollen by toluene and in toluene solutions containing the same concentration of linear polystyrene.[7c)] This finding encouraged us to focus on the effect of permanent chemical crosslinks in gels on the diffusion coefficients of tracers.

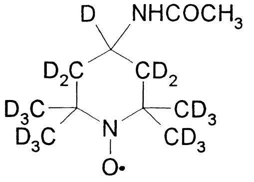
The diffusion coefficients of various tracers were measured by 1D ESRI in lightly crosslinked poly(1-vinylpyrrolidone) gel swollen at equilibrium with water, and in the corresponding aqueous solutions of the polymer. The formulae of the tracers are shown in Chart 1.[9)] For ESR measurements, aqueous solutions of linear PVP were polymerized in glass capillaries with i.d. ≈ 1 mm. The gel layer (3 to 5 mm) was topped with 0.4 μL of 10^{-2}M aqueous solution of the paramagnetic tracer, sealed by parafilm, and positioned vertically in the cavity of the ESR spectrometer, with the capillary axis parallel to the gradient direction. ESR spectra were measured at suitable time intervals in the presence and in the absence of the gradient. The effect of the gradient magnitude on the quality of the data was checked by using different gradients, 46.6 G/cm or 94.5

G/cm for most of the samples.

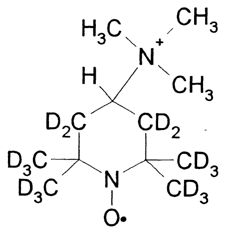
A typical experimental and simulated projection, together with corresponding concentration profile of the paramagnetic tracer in the sample are shown in Fig. 1. Analysis of the data indicated that the most precise data are obtained once a measurable concentration of the tracer has reached the end of the sample. In such cases the sample length can be determined with high accuracy using the positions of the high-field features in the projection, as seen in Fig. 1.



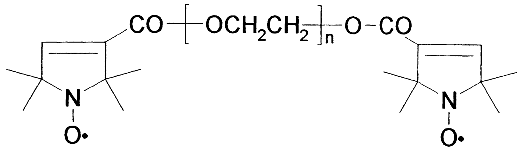
PDT (1)



AATEMPO (2)



CAT1 (3)



SLPEO:

(a): MW=1500 (4a)

(b): MW=1500 (4b)

Chart 1

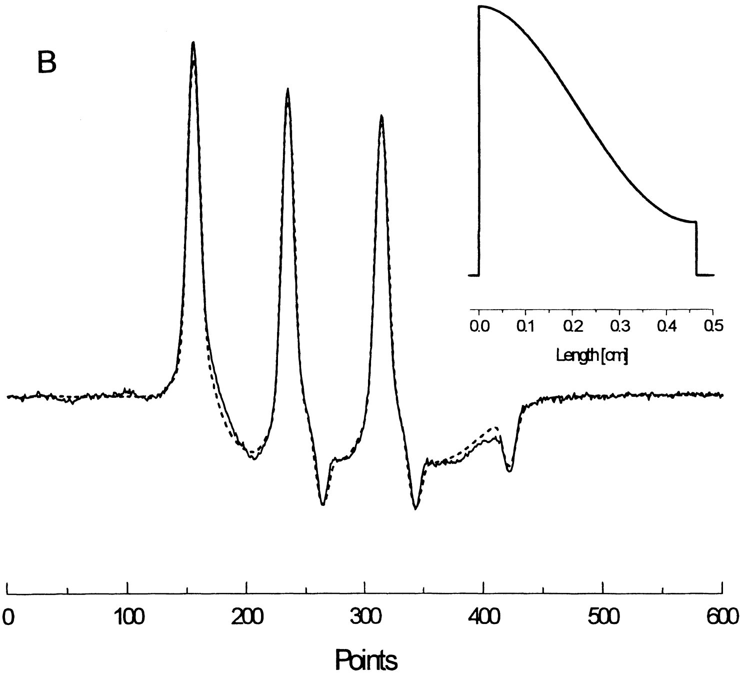


Fig. 1: Experimental (full line) ESR spectrum at time t=27,480 s after diffusion onset for tracer **4b** in the 12 % w/w PVP solution, measured with magnetic field gradient G = 46.6 G/cm, 9 scans, magnetic field sweep 120 G, and modulation amplitude 1.5 G. The simulated projection (dotted line) was calculated with D=0.83×10^{-6}cm^{2}s^{-1}, h= 0.049cm, and l=0.464 cm. The external magnetic field increases from left to right. The parameters were chosen by a nonlinear least squares fit. The inset presents the concentration profile of the tracer in the sample, with the top of the sample on the left.

The macroscopic diffusion coefficients were determined by ESRI at 300 K for the five paramagnetic tracers in the lightly crosslinked PVP gel containing in equilibrium 88 % w/w of water, in the concentrated aqueous solution of linear PVP containing the same polymer volume fraction, and in a solution of linear PVP containing 24 % w/w polymer. As expected, slower diffusion was observed for the solution containing the higher PVP concentration. No significant difference was detected between the diffusion coefficients of the four small tracers in the lightly crosslinked gel and in the solution of linear PVP containing the same polymer volume fraction (12%). A significant difference was found between diffusion coefficients in the lightly crosslinked gel and in the corresponding solution for the largest paramagnetic tracer, PEO with MW≈3000. The data clearly indicate that even a small concentrations of permanent crosslinks in the PVP gel can reduce the rate of transport of a bulky paramagnetic tracer to the value corresponding to a higher concentration (two-fold) of linear PVP in solution, where no fixed obstacles (permanent crosslinks) are present.[11)]

Diffusion in Reversible Gels

The triblock copolymers poly(ethylene oxide)-*b*-poly(propylene oxide)-*b*-poly(ethylene oxide), $EO_mPO_nEO_m$, (commercial name Pluronics) have been extensively studied in the last few years, because of their interesting polymorphic structures and gel formation in aqueous solutions, and their numerous applications in drug release systems, detergents, cosmetics, treatment of burns, and water purification.[12)]

We have initiated a study of the Pluronic copolymers based on the ESR spectra of spin probes that are known to intercalate in, and report on, various regions of the self-assembled system. The main objectives of these studies are to obtain *local* information on the hydration of the hydrophobic and hydrophilic domains, on the degree of order in the aggregates, and on the transport of various guests in the system. Most of our studies have focused on $EO_{13}PO_{30}EO_{13}$ (commercial name L64, Chart 2), whose phase diagram in aqueous solutions has been deduced by ^{2}H NMR, polarizing microscopy, and ocular inspection.[13)] In the vicinity of 300 K, the main phases detected with increasing polymer content are L_1 (micellar), H (hexagonal), L_α (lamellar), and L_2 (reverse micellar). Using probes of various hydrophobicity we were able to follow changes in the hydration of the EO blocks at various distances from the hydrophobic core in the L64 aggregates on a scale of ≤ 2 nm, and to infer from these changes the mechanism of phase transitions.[14)]

The viscosity, η, of L64 aqueous solutions at 300 K as a function of polymer content has two maxima: a strong maximum, $\eta \approx 1430$ P, for a polymer content of 50 % w/w (hexagonal phase), and a second maximum, $\eta \approx 289$ P, for a polymer content of 70 % w/w (L_α phase).[15)] The viscosity of neat L64 is 7.6 P. The high viscosities are evidence for the formation of gel systems, due to the connectivity established by one chain that is part of two aggregates, for instance when each EO block in a chain is in *different* cylinders in the hexagonal phase.

We have measured the diffusion coefficients of small nitroxides PDT (Chart 1), CAT1 (the protiated analog of DCAT1, Chart 1), and 5DSE as guests in aqueous solutions of $EO_{13}PO_{30}EO_{13}$ (Pluronic L64), Chart 2. The ESR spectra have indicated that the three probes have different locations: in the water phase (CAT1), in the hydrophobic domains (5DSE)8) and at the interface between the aggregates and the solvent (PDT).14) The variation of the diffusion coefficients for the three probes is plotted as a function of the polymer concentration in Fig. 2.

Pluronic L64

$$\mathbf{HO[-CH_2CH_2O-]_{13}[-CH(CH_3)CH_2O-]_{30}[-CH_2CH_2O-]_{13}H}$$

$$\mathbf{(EO_{13}PO_{30}EO_{13},\ L64)}$$

Spin Probe 5DSE

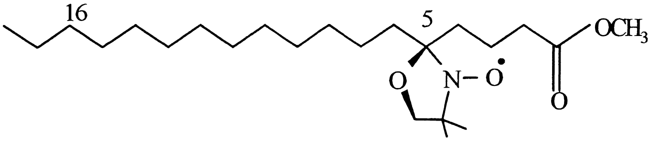


Chart 2

The dependence of D_{CAT1} on polymer content follows the expression $D=D_0\exp(-aw_2)$, where D_0 is the diffusion coefficient of the probe in neat water, and w_2 is the weight fraction of the polymer. The straight line in Fig. 2 shows the excellent agreement between this expression and the experimental results for CAT1. This behavior is consistent with the expression suggested by Phillies for the diffusion of probes:16) $D=D_0\exp(-\alpha c^{\nu})$, where c is polymer concentration, and α and ν are constants.Moreover, we have used a similar expression for simulating the dependence of the diffusion coefficient of pure solvents and solvent mixtures in crosslinked polyisoprene swollen by the solvents.[4] Data for CAT1 therefore suggest a behavior typical of a solvent. From these considerations it is clear that the major factor that controls the transport rate of the guests is their location: The range of D values measured in this study for tracers with similar MWs varied in the range $1.0 \cdot 10^{-5} cm^2 s^{-1} - 1.0 \cdot 10^{-7} cm^2 s^{-1}$, depending on tracer site.

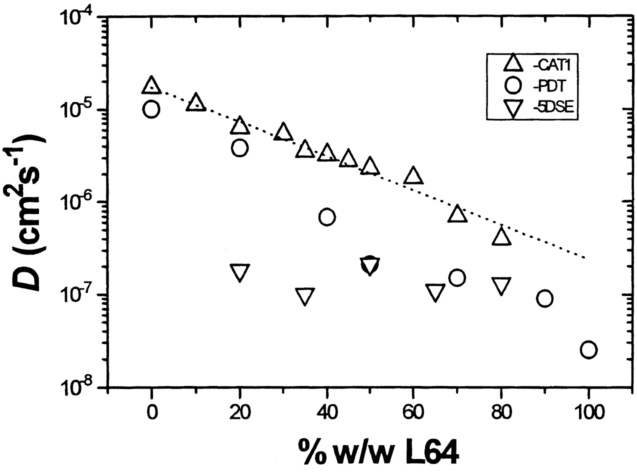


Fig.2: Variation of the diffusion coefficient, D, at 300 K for CAT1, PDT, and 5DSE with L64 concentration.

Conclusions

ESR Imaging (ESRI) is an important method for measuring *macroscopic* diffusion coefficients in hydrogels and self-assembled polymeric surfactants, and is applicable even to guests that are in low concentrations (10^{-3}-10^{-5} M), for instance drugs and other additives. The diffusion coefficients of guests in hydrogels are sensitive to the presence of permanent crosslinks (as compared to temporary entanglements): D can be reduced by a factor of ≈ 2 for large diffusants (MW 3000), even in a water-rich hydrogel (88 % w/w water). The diffusion coefficients of small guests with similar molecular weights in self-assembled polymeric surfactants can vary by two orders of magnitude, depending on the guest location.

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References and Notes

1. S. Pickup, F.D. Blum, *Macromolecules* **22**, 3961 (1989)
2. B. Lindman, U. Olson, O. Söderman, in: *Dynamics of Solutions and Fluid Mixtures by NMR*, J.J. Delpuech (Ed.), J. Wiley, New York, 1995, Chapter 8, p 345
3. H. Yasunaga, I. Ando, *Polymer Gels and Networks* **1**, 83 (1993). S. Matsukawa, I. Ando, *Macromolecules* **29**, 7136 (1996) and *Macromolecules* **30**, 8310 (1997). C. Zao, S. Matsukawa, H. Kurosu, I. Ando, *Macromolecules* **31**, 3139 (1998)
4. S. Schlick, Z. Gao, S. Matsukawa, I. Ando, E. Fead, G. Rossi, *Macromolecules* **31**, 8124 (1998), and references therein
5. F.P. Duval, P. Porion, H. Van Damme, *J. Phys. Chem. B* **103**, 5730 (1999)
6. J.K. Moscicki, Y.K. Shin, J.H. Freed, in: *EPR Imaging and in Vivo EPR*; G.R. Eaton, S.S. Eaton, K. Ohno (Eds.), CRC Press, Inc., Boca Raton, 1991, Chapter 19, p 189. D. Xu, E. Hall, C.K. Ober, J.K. Moscicki, J.H. Freed, *J. Phys. Chem.* **100**, 15856 (1996)
7. (a) S. Schlick, J. Pilar, S.-C. Kweon, J. Vacik, Z. Gao, J. Labsky, *Macromolecules* **28**, 5780 (1995). (b) K. Kruczala, Z. Gao, S. Schlick, *J. Phys. Chem.* **1996**, *100*, 11427. (c) Z. Gao, J. Pilar, S. Schlick, *J. Phys. Chem.* **100**, 8430 (1996). (d) S. Schlick, P. Eagle, K. Kruczala, J. Pilar, in: *Spatially Resolved Magnetic Resonance: Methods, Materials, Medicine, Biology, Rheology, Ecology, Hardware*; P. Blümler, B. Blümich, R. Botto, E. Fukushima (Eds.), Wiley-VCH, Weinheim, 1998, Chapter 17, p 221
8. E.N. Degtyarev, S. Schlick, *Langmuir* **15**, 5040 (1999)
9. J. Pilar, J. Labsky, A. Marek, C. Konak, S. Schlick, *Macromolecules* **32**, 8230 (1999)
10. J. Crank, *The Mathematics of Diffusion*, Clarendon Press, Oxford, U.K., 1993.
11. The hydrodynamic correlation length, ξ_h, measured by dynamic light scattering (DLS) was 2.82 ± 0.05 nm in the equilibrium-swollen PVP gel containing 88 wt% of water, and 2.88±0.05 nm in concentrated aqueous solution containing the same polymer volume fraction (Φ=0.096 for 12 wt% of PVP in water). This result indicates that in the lightly crosslinked gel the hydrodynamic correlation length is virtually the same as in corresponding solution and that the presence of permanent crosslinks, which makes the only difference between gel and solution matrices, plays only a negligible role. Together with transport data, the DLS results suggest that the permanent entanglements in the gel are more effective in reducing the transport rates for the largest probe, compared to the entanglements present in the polymer solution
12. *Plutonic and Tetronic Surfactants*, Technical Brochure, BASF Corp., Parsipanny, NJ, 1989
13. K. Zhang, A. Khan, *Macromolecule* **28**, 3807 (1995). P. Alexandridis, D. Zhou, A. Khan, *Langmuir* **12**, 2690 (1996)
14. (a) K. Malka, S. Schlick, *Macromolecule* **30**, 456 (1997). (b) A. Caragheorgheopol, S. Schlick, *Macromolecule* **31**, 7736 (1998). (c) L. Zhou, S. Schlick, *Polymer* **41**, 4679 (2000)
15. K. Malka, S. Schlick, unpublished results
16. G.D.J. Phillies, *J. Phys. Chem.* **93**, 5029 (1989)