Communications to the Editor

Fluorine–Proton Chemical Shift Correlation in Poly(*p*-fluorostyrene)

Nuclear magnetic resonance spectroscopy is an indispensible tool for characterization of the structural and dynamical properties of a polymer.[1-5] Carbon-13 NMR observations in particular are able to reveal details of polymer stereoregularity and have been used in many studies of polystyrene.[6-8] Fluorine chemical shifts are extremely sensitive to molecular environment, and fluorine-19 NMR has found application in providing stereochemical details of the structures of several fluorinated vinyl polymers.[9] It is, therefore, surprising that the fluorine spectrum of poly(*p*-fluorostyrene) at magnetic fields less than 4 T is a single, rather broad resonance giving no evidence of stereochemistry. Detailed interpretations of fluorine spin–lattice relaxation and proton–fluorine nuclear Overhauser effects on this resonance have been carried out without regard to the possibility that the observed signal may represent a variety of stereochemical isomers that have sufficiently similar chemical shifts that they are not resolved under these conditions.[10,11]

Figure 1 shows the fluorine-19 spectrum of a sample of atactic poly(*p*-fluorostyrene) at 282 MHz. It is clear that the single resonance observed at lower frequencies[10,11] is a composite of several resonances. (There may be an appreciable broadening of lines due to chemical shift anisotropy at high frequencies.[12]) The proton NMR spectrum (Figure 2) and carbon spectrum (Figure 3) of this polymer at high fields show some fine structure in the aromatic portions, which likely also indicate in some way stereochemical details of the polymer structure.

Two-dimensional NMR techniques provide means for effectively resolving complex NMR spectra and are now being applied to polymeric systems in spite of the potential limitations imposed by rapid transverse relaxation in such molecules.[13,14] We show in this paper that a two-dimensional experiment which correlates fluorine and proton chemical shifts provides significantly more information about the magnetic environments available to the fluorophenyl ring in poly(*p*-fluorostyrene) than is apparent in the directly observed proton, carbon, or fluorine spectra.

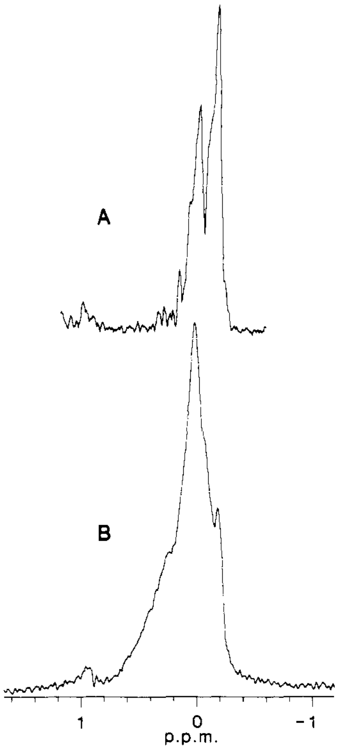

Figure 1. Fluorine NMR spectra of poly(*p*-fluorostyrene) at 282 MHz. The spectrum obtained by direct observation (B) is compared to the projection of the shift correlation map in Figure 5 to the fluorine shift axis (A).

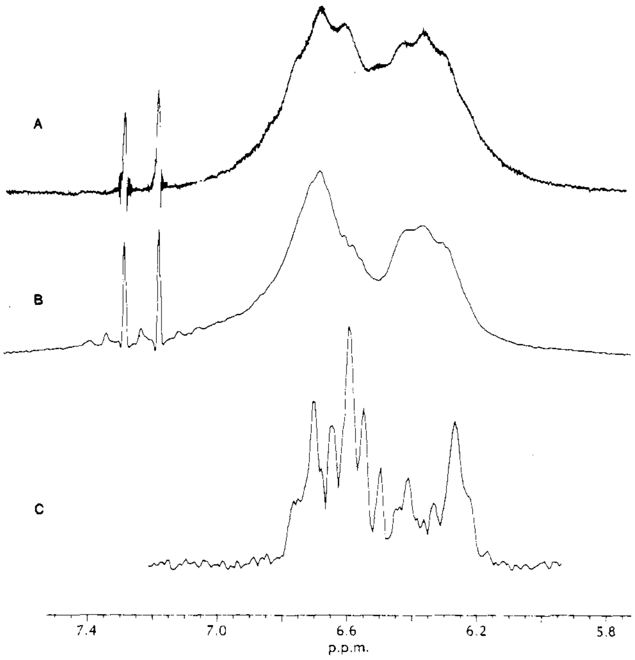

Figure 2. Proton NMR spectra of poly(*p*-fluorostyrene) obtained at 100 MHz (A) and 300 MHz (B) compared to the projection of the shift correlation map (Figure 5) to the proton shift axis (C). Chemical shifts are given relative to Me_4Si by setting the bulk $CHCl_3$ signal to 7.24 ppm.

Experimental Section. *p*-Fluorostyrene was synthesized by a Wittig reaction. In a 100-mL round-bottom flask equipped with a condenser, drying tube, an addition funnel, and a rubber septum were placed 20 mL of diethyl ether and 6.2 mL of *n*-butyllithium solution (1.6 M in hexane, Aldrich). Methyltriphenylphosphonium bromide (4 g, Aldrich) was added and the mixture stirred magnetically for 3 h. Hydroquinone (0.05 g) was then added to the mixture and the solution bubbled for 1 h with dry nitrogen using a stainless steel needle inserted through the septum. *p*-Fluorobenzaldehyde (1.4 g, Aldrich) in 20 mL of ether was added through the addition funnel and the mixture heated to reflux overnight. The reaction mixture was filtered through a sintered glass, and the precipitate was washed with ether, water, and finally ether. The washings and the filtrate was combined, the organic phase was separated, and the water phase was extracted three times with ether. The combined ether layers were dried over anhydrous sodium sulfate, and the solvent was removed by rotary evaporation. Distillation of the residue in vacuo gave the desired product in 65% yield; all spectral data, including the proton and fluorine NMR spectra, were in accord with the structure. The monomer was stored in the freezing compartment of a refrigerator until use.

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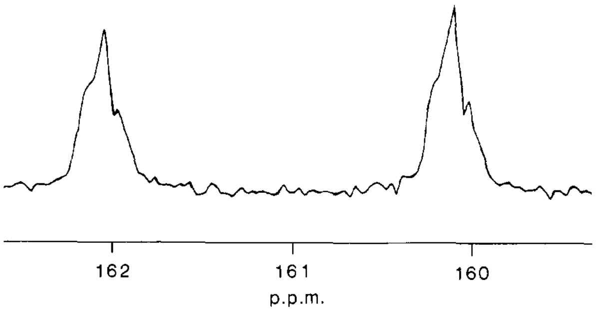

Figure 3. Carbon-13 NMR spectrum of the C–F carbon of poly(*p*-fluorostyrene) obtained at 126 MHz. The central signal from the solvent ($CDCl_3$) was set to 77 ppm.

Poly(*p*-fluorostyrene) was prepared by placing 2 mL of CCl_4, 5 mg of azobisisobutyronitrile (Aldrich), and 100 mg of the monomer in a 10-mL tube stoppered with a serum cap. By means of stainless steel needles the reaction mixture was bubbled 15 min with dry nitrogen and then heated to 60 °C for 20 h. The polymer was precipitated by pouring the reaction mixture into ethanol. After reprecipitation, the solid polymer was dried and stored in a vacuum desiccator. The polymer was not further characterized. However, the polymerization and isolation conditions are similar to those used by Matsuo and Stockmayer,[16] and, based on the results of these authors, it is expected that an atactic polymer of M_w = 50 000–150 000 has been produced.

Polymer samples for NMR spectroscopy were prepared by placing a 5% by weight solution of the polymer in $CDCl_3$ (Aldrich) in a 5- or 10-mm NMR tube, bubbling the solution with dry nitrogen, and then sealing the tube with a torch. Most spectral data were collected on a Nicolet NT-300 instrument with a fluorine resonance frequency of 282.3 MHz. Spectra at 94.1 MHz were obtained with a Varian Associates XL-100 while proton and carbon spectra at 500 and 125 MHz, respectively, were obtained at the NSF Regional Instrumentation facility at the California Institute of Technology. The signal from the residual proton on the $CDCl_3$ provided a proton chemical shift reference (7.24 ppm) while the resonance of the solvent provided a chemical shift reference for carbon-13 spectra (77 ppm). Spin–lattice relaxation times were estimated by use of an inversion–recovery sequence that incorporated a compensating 180° pulse.[17] Proton transverse relaxation times were estimated by the 90–t–180° spin echo method.[18] Two-dimensional shift correlation experiments used the pulse sequence discussed by Bax;[13] the proton pulses generated by the decoupler were calibrated by using pulse sequence B described by Pegg et al.[19] and a test sample composed of α-fluorocinnamic acid (Aldrich) dissolved in $CDCl_3$. All spectra shown in the text were obtained at a sample temperature of 25 °C.

Fluorine free induction decays for the shift correlations were represented by 2K data points and results for 400–512 values of the delay t in the sequence shown in eq 1 were accumulated. Forty to eighty FIDs were accumulated for each t value with a delay between acquisitions equal to at least 5 times the observed proton T_1. During the data workup, the fluorine FIDs were multiplied by a double-exponential apodization function (DM = 10 in the Nicolet software). After transposition of the data matrix, FIDs in the proton dimension were zero-filled to 2K points and multiplied by the double-exponential apodization function (DM = 5) before Fourier transformation. Usually, the digital resolution along the fluorine shift axis was 1.95 Hz/point while in the proton dimension the resolution was 3.32 Hz/point.

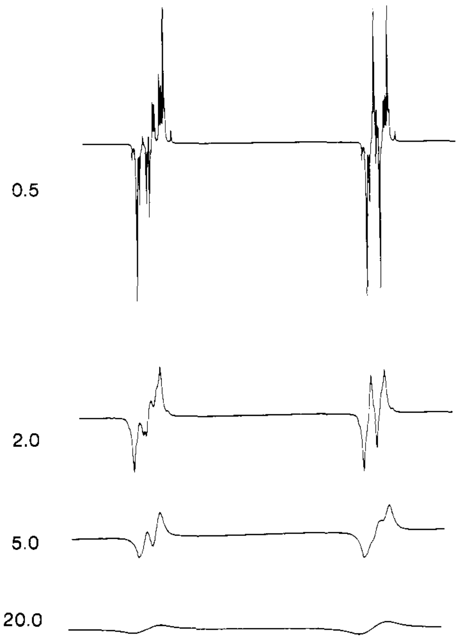

Figure 4. Theoretical "slices" in the proton dimension through a proton–fluorine chemical shift correlation map of a *p*-fluorophenyl ring obtained by a pulse sequence that retains the effects of spin coupling in both dimensions.[13] All plots use the same vertical scale but differ in the proton line width, indicated on the left. The exact nature of any such cross section will depend on which of the fluorine multiplet lines is observed; our purpose here is to illustrate the phase–antiphase behavior of these cross sections.

Results. Initial Considerations. The result of a heteronuclear two-dimensional chemical shift correlation experiment is a map or surface that displays along one axis the shifts of one nuclear species and the shifts of another along a second axis. Such representations can be rather complex in the absence of any decoupling because phase relationships of the features of the correlation map. In the experiments used in this work, the proton chemical shifts are arrayed along one axis while the chemical shifts of the fluorine nuclei of the polymer will appear along a second, orthogonal axis. For heteronuclear systems the appearance of a "slice" of the correlation surface taken in the direction of the proton shifts at a particular fluorine shift can be calculated.[20] Figure 4 shows the expected appearance for such a slice when the spin system is the *p*-fluorophenyl ring (the chemical shifts and coupling constants are those obtained from an analysis of the proton and fluorine spectra of *p*-fluorocinnamic acid; B. A. Halley, unpublished). The phase–antiphase nature of the correlation surface is apparent but for sharp resonance lines it would be possible to deduce the proton chemical shifts of the spin systems from such a pattern. However, when spectral lines are broad the phase–antiphase features tend to cancel one another and the signal-to-noise ratio in this case would be seriously degraded. The pulse sequence

$$90(\mathrm{H})\text{–}t\text{–}180(\mathrm{F})\text{–}t\text{–}\Delta_1\text{–}90(\mathrm{H})90(\mathrm{F})\text{–}\Delta_2\text{–acquire} \quad \text{(decouple)} \qquad (1)$$

can be used in small-molecule experiments to remove heteronuclear spin coupling effects in both dimensions of the two-dimensional map and, thus, eliminate the phase–antiphase peaks and their tendency to cancel one another. During the delay Δ_1 magnetization vectors initially coincident precess to become 180° out of phase so that polarization transfer can take place, while the delay Δ_2 in the sequence provides an opportunity for magnetization vectors in the transverse plane to precess 180° from each other and thus vitiate phase differences. Ideally both delays will be equal to $1/2S$, where S is the frequency separation characteristic of the two resonances. For the 4-fluorophenyl system, S will be of the order of twice the meta or ortho proton-fluorine coupling constants (5-9 Hz); Δ_1 and Δ_2 will therefore be of the order 55-100 ms. During precession times this long, appreciable transverse relaxation can take place in macromolecular systems with concomitant loss of signal in the correlation map.

During the time Δ_1 (or Δ_2) a magnetization vector of length M_0, precessing at a frequency $S/2$ in the rotating frame will precess through an angle θ given by

$$\theta = \pi S t \text{ (radians)} \tag{2}$$

in a time t and, while this takes place, transverse relaxation will diminish the length of the vector by

$$M(t) = M_0 \exp[-\pi w t] \tag{3}$$

where w is the observed line width of the resonance signal produced by M_0. Differentiation shows that the optimum projection of two magnetization vectors precessing at $S/2$ and $-S/2$ on the axis they are approaching is given when the time $t_{\max}$ is

$$t_{\max} = \arctan (S/w)/S \tag{4}$$

Knowledge of w and the separation of multiplet components (S) permit the adjustment of the delays Δ_1 and Δ_2 in the pulse sequence so that signal losses during the heteronuclear chemical shift correlation experiment with macromolecules can be minimized.

Relaxation Times. Aromatic proton and fluorine spin-lattice relaxation times were determined for the polymer sample at 300 or 282 MHz and were found to be 0.7-1.1 and 0.8 s, respectively. A rough estimate of the transverse relaxation time (T_2) for the aromatic protons was made by means of spin echos and gave values around 0.09 s, corresponding to a line width of about 4 Hz. While not highly precise because the effects of echo modulation by homonuclear spin coupling were not taken into account, this result is adequate for the present purposes. The fluorine transverse relaxation time (0.009 s) was roughly estimated from the apparent line width (35 Hz) of the fluorine resonance of the polymer at 94 MHz. Finally, the $^{19}F[^1H]$ nuclear Overhauser effect was determined to be -0.12 ± 0.02 at 282 MHz. Calculations showed that the T_1 and Overhauser effect measured at 282 MHz were consonant with results obtained by Matsuo et al.[10] at lower frequencies and support our assumptions about the molecular weight of the polymer used in this work.

Chemical Shift Correlations. A proton-fluorine chemical shift correlation experiment using the pulse sequence shown in eq 1 in which the delays Δ_1 and Δ_2 set equal to 55 ms was attempted. These delays correspond to the optimum values if transverse relaxation can be neglected and the precessional frequency difference between the antiphase resonances is equal to 9 Hz, the largest proton-fluorine coupling constants in the fluorophenyl ring. There were no detectable correlation peaks obtained in this experiment, and one computes using the relaxation times mentioned above that >50% of the proton magnetization is lost by transverse relaxation during a Δ_1 delay of this magnitude and >99% of the fluorine magnetization is lost during the Δ_2 delay; the lack of detectable features in the correlation map under these conditions is, therefore, understandable.

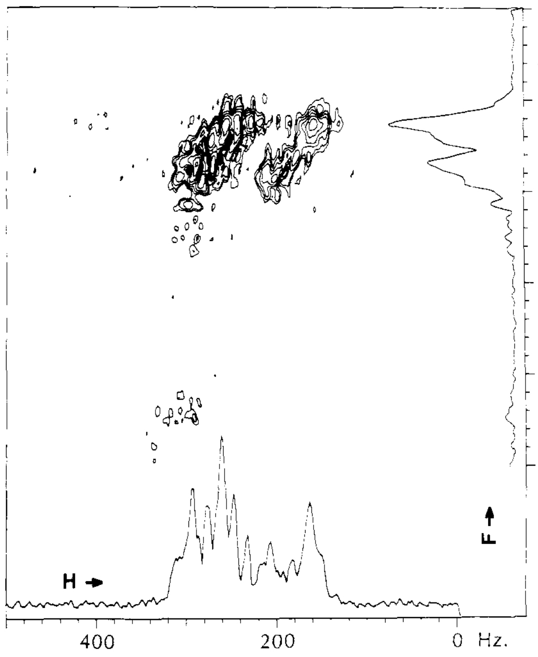

Figure 5. Proton-fluorine chemical shift correlation map obtained with the delays Δ_1 and Δ_2 set to 34 and 8 ms, respectively. The fluorine observation frequency was 282 MHz.

Calculations using eq 4 and the experimental relaxation data indicate that the optimum time for the delay Δ_1 would be around 40 ms while Δ_2 should be set to 9 ms. Examination of the dependence of the optimum delay on transverse relaxation time and the separation S shows for the kinds of coupling constants present in the fluorophenyl ring that the optimum delay time is relatively insensitive to w when $w > 20$ Hz and that a missetting of Δ_1 and Δ_2 of ±25% would have little effect on the final shift correlation map. Using the optimized delays, the pulse sequence produced the shift correlation map shown in Figure 5. A large number of correlations are indicated; cross sections of the map at various positions along the fluorine axis (Figure 6) show that many molecular environments for fluorophenyl rings are possible in this polymer. (The signal-to-noise ratio is not especially favorable in the ^{1}H dimension and some of the apparent signals may be artifactual.)

Projections of the correlation map to each shift axis are compared in Figures 1 and 2 to the directly observed fluorine and proton spectra of the polymer. It is clear that the shift correlation experiment is most responsive to those species in the sample with the sharpest lines (slowest transverse relaxation), and molecular forms represented by the fluorine chemical shifts at lower field do not appear prominently in the correlation map. Thus, additional environments for the fluorophenyl ring are likely present in the polymer but are not reported in this experiment.

Discussion. If a fluorophenyl ring is in an environment that is asymmetric, each proton of the ring could have a unique chemical shift and thus, at any given fluorine chemical shift of this sample of poly(p-fluorostyrene), as many as four correlated proton chemical shifts could be detected in cross sections such as those shown in Figure 6. Although there is ample evidence for slow rotation of phenyl rings in protein structures,[21] relaxation data for poly(p-fluorostyrene) indicate that aromatic ring rotation in this polymer takes place on a nanosecond time scale[11]

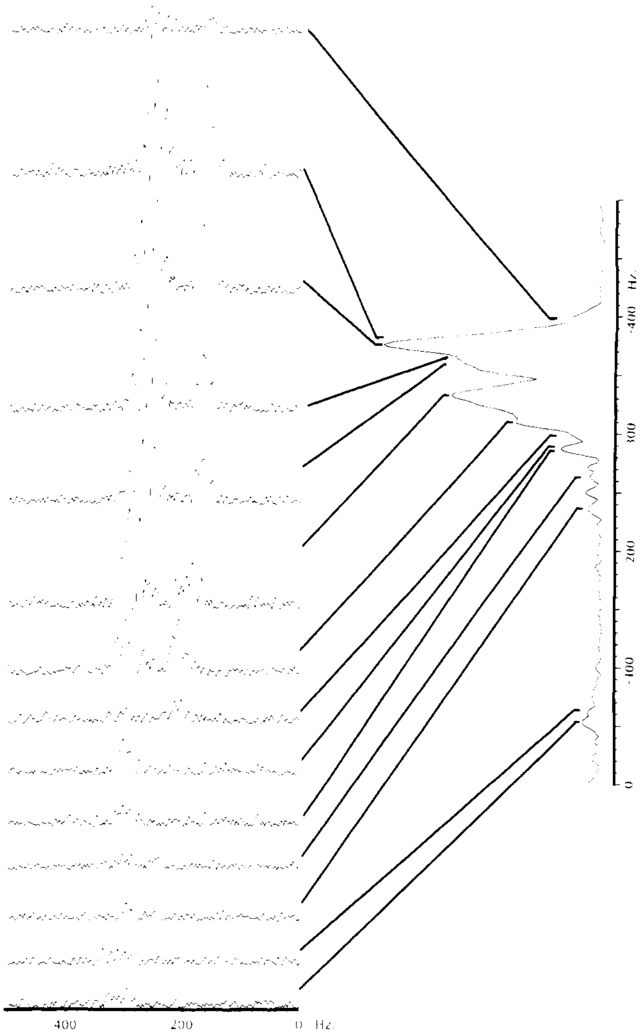

Figure 6. Cross sections in the proton shift dimension of the map shown in Figure 5 taken at the fluorine shift indicated. The spectrum is decoupled in both shift dimensions.

and is surely fast enough to average the chemical shifts of the chemically equivalent protons of the fluorophenyl ring. We did not observe any significant change in the correlation map when the experiment was carried out with a sample temperature of 50 °C, a change that should accelerate phenyl ring rotation. Only two proton chemical shift correlation peaks are expected, therefore, for each unique fluorine chemical shift.

The experiments reported here suggest a large number of magnetically distinguishable environments for the fluorophenyl rings of the polymer. Presumably these correspond to the influence of stereochemical configuration on fluorine shifts. Our maps are not sufficiently resolved to clearly indicate exactly how many of these localized structural possibilities are represented in the correlation map but it is apparent that several fluorophenyl rings with similar fluorine chemical shifts are characterized by detectably different proton shifts. Further work with this system is needed, including the examination of specifically deuterated polymers, before it will be possible to assign the various resonances or correlation peaks observed. A detailed study of the effects of transverse relaxation will also be needed to quantitate the amounts of each of these forms that are present.

Our work to date suggests the power of two-dimensional heteronuclear chemical shift correlations in polymer systems; experiments involving carbon–proton correlations may also be rewarding.

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Registry No. Poly(*p*-fluorostyrene) (homopolymer), 24936-47-8.

References and Notes

(1) Schaefer, J. *Top. Carbon-13 NMR* **1974**, *1*, 150.
(2) Carmen, C. J.; Baranwal, K. C. *Rubber Chem. Technol.* **1975**, *48*, 705–718.
(3) Schaefer, J. In "Structural Studies of Macromolecules by Spectroscopic Methods"; Ivin, K. J., Ed.; Wiley: New York, 1976.
(4) Pasika, W. M., Ed. *ACS* Symp. *Ser.* **1979**, *No. 103.*
(5) Woodward, A. E.; Bovey, F. A., Eds. "Polymer Characterization by ESR and NMR"; American Chemical Society: Washington, DC., 1980.
(6) Randall, J. C. *J. Polym. Sci., Polym. Phys. Ed.* **1975**, *13*, 889–899.
(7) Jasse, B.; Laupretre, F.; Monnerie, L. *Makromol. Chem.* **1977**, *178*, 1987–1992.
(8) Randall, J. C. In *ACS Symp. Ser.* **1979**, *No. 103*, 291–318.
(9) Tonelli, A.; Schilling, F. C.; Cais, R. E. *Macromolecules* **1982**, *15*, 849–853.
(10) Matsuo, K.; Kuhlmann, K. F.; Yang, H. W.-H.; Geny, F.; Stockmayer, W. H.; Jones. A. A. *J. Polym. Sci., Polym. Phys. Ed.* **1977**, *15*, 1347–1361.
(11) Jones, A. A. *J. Polym. Sci., Polym. Phys. Ed.* **1977**, *15*, 863–872.
(12) Hull, W. E.; Sykes, B. D. *J. Mol. Biol.* **1975**, *98*, 121–153.
(13) Bax, A. "Two-Dimensional Nuclear Magnetic Resonance in Liquids"; D. Reidel Publishing Co.: Boston, 1982; p 54 et seq.
(14) Gagnaire, D. Y.; Taravel, F. R.; Vignon, M. R. *Macromolecules* **1982**, *15*, 126–129.
(15) Chan, T. M.; Markeley, J. L. *J. Am. Chem. Soc.* **1982**, *104*, 4010–4011.
(16) Matsuo, K.; Stockmayer, W. H. *J. Polym. Sci., Polym. Phys. Ed.* **1973**, *11*, 43–50.
(17) Freeman, R.; Kempsell, S. P.; Levitt, M. H. *J. Magn. Reson.* **1980**, *38*, 453–479.
(18) Hahn, E. L. *Phys. Rev.* **1950**, *80*, 580.
(19) Pegg, D. T.; Bendall, M. R.; Doddrell, D. M. *J. Magn. Reson.* **1981**, *44*, 238–249.
(20) Bolton, P. H. *J. Magn. Reson.* **1981**, *45*, 239–253.
(21) Jardetzky, O.; Roberts, G. C. K. "NMR in Molecular Biology"; Academic Press: New York, 1981; pp 449–454.

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Relationship between Renormalization Group, Two-Parameter Theory and Blob Models of Polymer Excluded Volume

The description of polymer excluded volume has been approached by a variety of different methods, including renormalization group theory,[1] scaling[2] and blob methods,[3-5] the two-parameter theory,[6] and lattice enumeration and Monte Carlo methods. Each is claimed to have a useful range of validity, but the interrelationships between the different approaches have not been established, making it difficult to compare the predictions of the different

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